The spatial variation of weathering and soil depth across a Triassic sandstone outcrop.

*A.M. Tye, R.L. Lawley, M.A. Ellis, and B.G. Rawlins

British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham, NG12 5GG.

*Author for correspondence

e-mail: atye@bgs.ac.uk

Fax: 0115 9363264

Keywords: Sherwood Sandstone Group, Soil thickness, Weathering, Geostatistics,

Abstract

In this study, we used an archive of borehole logs from the British Geological Survey to collect information on the spatial structure of weathering that extends from the surface to competent bedrock across the Triassic Sherwood Sandstone Group outcrop (750 km^2), in the East Midlands, U.K. The borehole logs were used to estimate the thickness of the soil (n = 280) and soil & saprolite (S&S) to competent rock (n = 500). The weathering profile of the sandstone consisted of soil (median thickness ~1.5m) overlying a transition zone of compacted and weakly cemented weathered sandstone saprolite over bedrock. Topographic analysis using a NEXTMAP 5 x 5 m digital elevation model revealed no significant relationships between slope properties (relief, flow length, flow accumulation or slope angle) and soil or S&S thickness. A weak, but statistically significant correlation was found between the thickness of the soil and S&S (r_s = 0.25, $P<0.001$, n = 192). The variation in soil thickness may be related to changes in current and historic and landuse, variation in sandstone properties and the influence of glacial/periglacial processes. The thickness of the saprolite was more variable towards the southern part of the study area, where it increased to a maximum 40m. We hypothesise and provide evidence that the greater weathering thickness is related to the occurrence of increased faulting in this part of the study region, allowing increased access to meteoric waters. A possible source of increased water supply is meltwater from Quaternary ice sheets; the overburden of ice may have increased sub-glacial pore water pressure, with the fractures and faults acting as a drainage system for the removal of dissolved weathering products.

1. Introduction

In this paper, we examine the spatial distribution of soil and soil-saprolite (S&S) thickness over an area >750 km^2 in Triassic sandstone of eastern UK. Increasingly, a systems-based approach is used to study the ecosystem-soil-geology continuum of the 'critical zone' as this enhances our understanding of the processes which interact between its various components (Brantley et al., 2007; Anderson *et al.*, 2007). One area of the 'critical zone' that requires greater understanding is the spatial variation of the weathered zone (Soil and Saprolite) across large areas of similar geology. Soil thickness represents a critical resource as a potential carbon store (Denman *et al.*, 2007) whereas the combined soil and saprolite thickness (S&S) – from the land surface to competent bedrock - is important for water storage, groundwater flow and filtration as well as the biogeochemical cycling of elements. Compliance to legislation, such as the European Water Framework Directive (EC, 2000) requires improved understanding of systems and processes throughout the near surface environment. For engineers, knowledge of S&S thickness is essential for understanding ground stability.

Considerable work examining soil thickness has been undertaken by geomorphologists, who since the early work of Davis (1892) and Gilbert (1909) have recognised its importance in landscape evolution. The principal interacting factors influencing soil thickness being the rate of bedrock lowering or soil production, slope angle and hillslope transport flux (erosion). In particular, the properties of convex hillslopes and whether they exist in 'steady state' have been widely investigated. Convex hillslopes are described as 'steady state' when both the hillslope form and the thickness of the soil stay the same as the landscape lowers in a uniform manner. A steady state hillslope will have a topographic profile that fits a parabolic function and will have defined characteristics. Firstly, soil discharge per unit width of the slope will increases linearly with distance downslope; this being caused by a linear increase in topographic gradient as distance from the crest increases. Secondly, there will be diffusive transport of soil and a uniform soil production rate. If soil production rate depends on soil thickness, then the 'steady-state' hillslope will have uniform soil thickness. These processes are described using the 'conservation of mass equation' and 'geomorphic transport laws' (Deitrich *et al*., 2003). Physical models describing hillslope transport processes (e.g. soil creep) that influence soil depth, envisage the surface horizons of soils acting as conveyor belts, transporting material downslope through 'diffusion-like' processes (Fernandes & Dietrich, 1997; Yoo *et al*. 2009). Mudd and Furbish (2004) included the role of chemical denudation in their diffusive model of soil development on slopes. Increasingly, these processes are modelled so that soil thickness, bedrock lowering and slope properties can be incorporated. For example, Braun *et al*. (2001) used field data to parameterise a transport model with an exponential soil production law to capture spatial variations in soil thickness on hillslopes. Model outputs suggest that steady state soil distribution would take ~50000 yrs to develop.

One of the recognised factors that will determine soil or regolith thickness is a negative feedback mechanism whereby bedrock weathering rates decrease as soil thickness increases. This occurs because of reduced moisture penetration and thermal variation occurring with the accumulation of weathered rock (Small *et al*., 1997). This process is parameterized as the 'Soil Production Function' (Heimsath *et al*. 1997; Densmore *et al*., 1998; Ellis *et al*., 1999; Humphreys and Wilkinson, 2007) and is either an 'inverse exponential' or 'humped' function. Heimsath *et al*. (1997, 1999 & 2001) tested models of equilibrium soil thickness using cosmo-radiogenic isotope analysis (e.g. ^{10}Be & ^{26}Al) and demonstrated an exponential decline of soil production with soil thickness. A recent example of the use of cosmo-radiogenic isotopes in determining soil production is work carried out on sandstone bedrock in Arnhem Land, Australia, where analysis revealed that maximum soil production occurred at a depth of ~35 cm (Heimsath *et al*., 2009).

Recent advances in calculating accurate bedrock lowering rates using cosmo-radiogenic nuclides have been incorporated into landform evolution models, whereby the effects of different transport mechanisms (simple creep, depth-dependent viscous creep and overland flow) on soil thickness have been identified (Braun *et al*. 2001). Models have also confirmed field observations relating soil thickness to negative curvature (Heimsath *et al*. 1997; Braun *et al*. 2001). Ahnert (1987) demonstrated through modelling that the negative feedback relationships between the various components of geomorphological process and response systems produce landforms that have a tendency towards 'dynamic equilibrium' within the landscape.

Additional factors contributing to the variation in soil thickness include non-linear transport processes such as shallow landsliding (Roering *et al*., 2001), glacial / periglacial processes (Carter and Ciolkosz, 1986), tree throw (Carter and Ciolkosz, 1991) and bioturbation by burrowing animals such as pocket gophers (Yoo *et al.* 2005). Misasny and McBratney (1999) demonstrated the role that differing bedrock properties may produce on soil thickness through a rudimentary mechanistic model of soil production and landscape development. By introducing initial randomness and irregularities in the form of bedrock that weathers at different rates, chaos or instability is introduced into the system leading to non-uniform soil thickness.

These issues of soil generation provide the fundamental scientific motivation for the current investigation. There also exists, however, a compelling applied science driver to the present study related to the management of groundwater in this important regional aquifer. The study area comprises the Sherwood Sandstone Group outcrop (>750 km^2) in Nottinghamshire, U.K., which has been drilled intensively because the Permo-Triassic sandstones of the UK represent the country's second most important freshwater aquifer, supplying approximately 25 % of licensed groundwater abstractions (groundwater, industry and agriculture) in England and Wales

(Allen *et al*. 1997; Brewerton and Smedley, 1997). It is heavily pumped at boreholes in both the unconfined and confined aquifer at depths up to 500 m to the east of the Trent Valley and about 20 km from outcrop (Bath *et al*., 1979; Edmunds *et al*., 1982; Andrews *et al*., 1984; Downing *et al*., 1986). The input of water to the aquifer is predominantly through diffuse infiltration or recharge from influent rivers (Brewerton and Smedley, 1997). The age of the groundwater in the unconfined aquifer can be less than 100 years (Allen *et al*., 1997). As a consequence of the rapid groundwater transit time, the unconfined aquifer is susceptible to both diffuse pollution, such as contamination from agricultural (it is designated as a nitrate vulnerable zone (DEFRA, 2008)), and/or point sources such as industrial sources, sewage effluent and discharge from the underlying Carboniferous strata that have been mined extensively (Beamish and Klinck, 2006; Wilson *et al*., 1994). Thus, in the context of groundwater management, there is an important need to understand the spatial structure of weathering of the Sherwood Sandstone.

Few studies have examined the depth of soil and S&S spatially across such large areas. Two such surveys are those by Phillips *et al*. (2005) and Hren *et al*. (2007). The former examined regolith thickness in the Ouachita Mountains on Paleozoic sedimentary rocks whilst Hren *et al*. (2007) surveyed 225 locations including soil pits, soil cores and exposed soil-rock surfaces at road cuts or landslides to assess weathered depth to bedrock in the Washington Cascades. Hren *et al*. (2007) found a weak relationship ($r^2 = 0.27$) between log slope angle (m/m) and log soil depth in their study. Phillips *et al*. (2005) placed their study into a framework of 'equilibrium', 'disequilibrium' and 'non-equilibrium' following the review of their applicability to geomorphology by Renwick (1992). They suggest that an 'equilibrium' state would produce an approximately uniform regolith thickness across areas with similar geology and environmental controls. They describe a 'disequilibrium' system as being one that is moving steadily towards steady state but has not had time to reach it (i.e. a regolith cover that is eroding or accumulating towards a steady state). By contrast, a ‘non-equilibrium system’ is inherently dynamically unstable or dominated by frequent disturbance, preventing the development of a steady state (i.e. a thickening or thinning of the soil thickness which continues until limited by external factors) and this results in soils/regolith of variable thickness within areas of the same geology. They found that despite individual slopes showing a relationship between slope characteristics and depth there were no significant relationships between soil thickness, slope angle and curvature in the Ouachita Mountains, suggesting that a ‘non-equilibrium’ status existed in the soil thickness.

When examining soil thickness and weathering on regional scales, other factors need to be considered. For example, tectonics can influence the chemical weathering process through the uplift and fracturing of rock (Berner *et al*. 1983; Molnar *et al*. 2007). Tectonic uplift provides new rock material for chemical weathering and can be a limiting factor in the weathering of rocks. In their study in the Washington Cascades, Hren *et al*. (2007) identified the weathering zone depth and rock exhumation rate as being important in explaining dissolved Si fluxes. Additionally, increased weathering has been found around regional faulting and associated smaller fractures in rocks as they can act as drainage networks (Milodowski *et al*. 1998; Ackhurst *et al*. 1998

Any investigation into the scales over which S&S thickness vary requires information at a sufficiently fine resolution for it to be related to landscape characteristics. Such information can be obtained where the ground has been regularly probed and observations with depth recorded in a relatively consistent manner. Logs obtained from boreholes can provide such information. The Sherwood Sandstone Outcrop in Nottinghamshire, U.K, is an important aquifer where boreholes are commonly drilled for water abstraction and engineering investigations. For over 50 years, copies of these borehole logs have been archived by the British Geological Survey. Many of the archived records for the Sherwood Sandstone Group outcrop contain data pertaining to the depth and development of the weathering process of this sandstone outcrop. In this work we examine data from the archived borehole logs to understand the spatial variation in thickness of (i) the soil and (ii) the S&S until competent bedrock was reached. We analysed the thickness data geo-statistically to estimate the dominant scales at which variation occurs and compare this to scales of topographic variation. In addition, because of the large area examined, information regarding (i) topography, (ii) groundwater levels, and (iii) local faulting patterns were examined to assess their potential role in developing S&S thickness. We present a hypothesis suggesting that the regional distribution of faults underlying parts of the study area may contribute to the variation in weathering depth to competent bedrock across the area.

2. Materials and Methods

2.1 The study area – geology and soils

Our study area is the outcrop of the Sherwood Sandstone in Nottinghamshire, U.K. The area is approximately 50 km long and 15 km wide, and is largely characterised by a gentle, undulating low relief landscape, with much of the area lying between 50-70 m above sea level. Maximum elevation is ~130m in the south of the study area. It is part of the sequence of Permo-Triassic sandstones extending from NW and NE England (Fig.1), through the Midlands to SW England. Detailed accounts of the geological history of the Permo-Triassic sandstone can be found in Allen *et al*. (1997) and in the local geological memoirs by Edwards (1967) and Smith *et al*. (1973). The Sherwood Sandstone Group consists of the Nottingham Castle and Lenton Sandstone Formations. The Lenton Sandstone Formation is the lower geological unit and consists of fine sandstone with a thickness of 10-50 m and the upper Nottingham Castle Formation consists of coarse pebbly sandstone between 50-200 m thick (Allen *et al*., 1997). The Sherwood Sandstone Group conformably overlies, to the west, Permian units consisting of dolomitic limestone, sandstones, mudstones and evaporites. The aquifer dips at ~1-2° to the east and crops out in Nottinghamshire to form an unconfined aquifer. The aquifer is confined to the east by the late Triassic Mercia Mudstone Group (dolomitic and gypsiferous/anhydritic mudstones and siltstones).

The study area is situated on the East Midlands shelf, the shallowly subsiding western margin of the Southern North Sea Basin. The East Midlands Shelf was considered to be a tectonically stable platform, with a history of minor burial since Triassic times, based largely on a lack of structural or stratigraphic detail. However, apatite fission track analysis and vitrinite reflectance data have provided evidence that the East Midlands shelf has experienced two uplift and erosion events during the early and late Tertiary. It has been suggested that between 1 and 2 km of sediment has been removed by Tertiary uplift and erosion (Green *et al.* 2001). The variation in the uplift and inversion of the East Midlands Shelf and the surrounding Midland Platform and Southern North Sea, has been correlated with the distributions of Palaeozoic basins. Those areas underlain by Palaeozoic basins have been exhumed to a greater extent suggesting that the underlying basement structure may have a significant role in the timing of uplift and inversion during regional events, possibly through the preferential reactivation of weaker basinal regions in response to compressional events at plate margins (Green *et al*. 2001).

The Quaternary history of the Sherwood Sandstone Group outcrop in Nottinghamshire is poorly understood. The area was last glaciated during the Anglian (450 000 BP) although two subsequent major glaciations have occurred during which the area would have been subjected to intense peri-glacial weathering. The majority of glacial deposits across the outcrop appear to have been lost to denudation processes as the few remaining Quaternary deposits identified tend to be very thin and confined to interfluves (Edwards, 1967). Thus, it is largely assumed that the Sherwood Sandstone outcrop has largely been weathered in-situ leaving a soil that is very sandy, free-draining and with a comparatively low clay content. The major soil type across the area is the Cuckney Series, part of the Cuckney 1 Association (Ragg *et al*., 1984), described as a very slightly stoney sand to a depth of ~70 cm and sand below this. Land-use on about 80 % of the outcrop is agriculture (mainly arable) and ~ 18 % is either deciduous or coniferous woodland, largely forming Sherwood Forest.

2.2 Data collection and statistical analysis

The National Geoscience Data Centre (NGDC) at the British Geological Survey holds information relating to the majority of boreholes (>10m) taken in the UK. A total of ~2500 borehole records were found for the study area; of these 500 provided relevant information pertaining to the depth of S&S to competent bedrock and 280 had information relating to the depth of the soil. Whereas the degree of weathering of the sandstone was sometimes unclear, the records used provided a strong delineation between weathered sandstone and bedrock. The borehole records were mostly produced by engineers during the construction of roads and drilling of water abstraction wells. The NGDC also inherited the UK Coal Authority borehole archive and some of these contained relevant information. However, the majority of these records were associated with deep geology and the Carboniferous coal seams that underlie the region. We used the collected data and geographic coordinates for each borehole as the basis for mapping the thickness of the weathered zone.

The identification of spatial weathering patterns was undertaken using geostatistics to produce an isarithmic map of S&S thickness to engineering rock-head, in which S&S thickness at a location $\mathbf{x}$ is regarded as a realization of a random function $Z(\mathbf{x})$ that is intrinsically stationary. This is a weak form of second-order stationarity and is met if two conditions hold. First,

$$E[Z(\mathbf{x})-Z(\mathbf{x}+\mathbf{h})]=0\,\forall\mathbf{x} \qquad (1)$$

where $\mathbf{h}$ is a separation in space, the *lag*.

The second is that the variance of the differences,

$$2\gamma(\mathbf{h}) = E[\{Z(\mathbf{x}) - Z(\mathbf{x}+\mathbf{h})\}^2], \tag{2}$$

depends only on $\mathbf{h}$ and not on $\mathbf{x}$. The function ($\mathbf{h}$) is the variogram.

$$\hat{\gamma}(\mathbf{h}) = \frac{1}{2N_{\mathbf{h}}}\sum_{i=1}^{N_{\mathbf{h}}}\{z(\mathbf{x}_i) - z(\mathbf{x}_i + \mathbf{h})\}^2 \tag{3}$$

The borehole locations are irregularly spaced and there may only be one or a very few pairs of observations that are exactly separated by a particular lag. Using the method of moments, the variogram is estimated for lag classes each centered on a distance and direction that defines the nominal lag, but comprising a range of distances and directions in each class. The second stage is to fit a continuous function of lag to the experimental variogram. This enables semivariances to be calculated for all the lags in the kriging equations. Only certain mathematical functions are suitable for this purpose; Webster & Oliver (2007) describe the most commonly used functions and how they are fitted. The spherical function is one of the most commonly fitted which when including a nugget variance (c_0) is written

$$\gamma(h) = c_0 + \begin{cases} c_1\left\{\dfrac{3h}{2a} - \dfrac{1}{2}\left(\dfrac{h}{a}\right)^3\right\} & \text{for } h \le a \\ c_1 & \text{for h} > a \end{cases} \tag{4}$$

where γ is the semi variance at lag distance *h,* c_1 is the component of spatially correlated variance and *a* is the range of the model which represents the average diameter of regions or features in the data. The nugget variance (c_0) represents the variation which occurs at scales shorter than the smallest sampling interval plus any error in the measurement process – in our study this would equate to the differences in measurements of total weathering depth in the same core log recorded by different observers. The variogram can be used in ordinary kriging to produce unbiased estimates of the variate on a regular grid which can then be used to produce an isarithmic map. The variogram is used to allocate weights to the sample data in the local neighbourhood so that the estimates are unbiased and estimation variances are minimized (see Webster and Oliver, 2007).

2.3 Topographic analyses

We investigated the role of topography on soil and S&S thickness using the digital terrain analysis software within Arc-GIS™ v9.2 (ESRI) and a Digital Elevation Model (Nextmap DEM) of the region with a 5 metre cell resolution (Intermap, 2007). We calculated a set of primary topographic attributes: (i) local relief (at the grid scale of 5m), (ii) slope angle, (iii) flow path length, (iv) upslope contributing area and (v) nearest-neighbour curvature across the study region. We overlaid the locations of the borehole observations on a grid of the topographic attributes and joined them based on their spatial location. For each of the five topographic attributes we calculated the skewness coefficients of their distributions; where these were greater than 1, we log-transformed the variable prior to further analysis. We used least squares linear regression to establish how much of the variation in soil and S&S thickness could be explained by each of the five topographic indices.

To determine the frequency distribution of slope lengths across our study region we applied the stream definition and catchment polygon processing functions in ArcHydro™ to determine the spatial distribution of drainage networks and catchment polygons, respectively, for the study region using the NextMap DTM. We converted the catchment polygons to points and made a random selection of 1000 points along the catchment boundaries covering the entire region. We then generated flowpaths to the nearest point on the drainage network using the downstream flow path tracing function in ArcHydro™. The flow paths were then truncated at the point they met the drainage network. The lengths of each slope (flowpath) were computed in the GIS and we calculated summary statistics of the frequency distribution.

2.4 Analysis of Groundwater depths

A subset of the borehole records had recorded data on the depth to water table which combined with other published data for the aquifer, was used to understand the extent to which local groundwater levels may contribute to the spatial patterns of weathering, soil and S&S thickness. However, it is likely that groundwater conditions were very different over the past few or tens of thousands of years, and so modern conditions may not provide a clear role for groundwater.

2.5 Analysis of regional faulting patterns

Geological maps and information recorded from field observations were used to determine the relative frequency of faults across the outcrop. Few faults are recorded through geological survey in the Sherwood sandstone because there are few 'marker beds' or distinctive variations in lithology that enable the mapping of 'individual beds' of rock and hence faults. Weathering of the sandstone generates relatively thick weathered deposits on an undulating landscape contributing further to the difficultly in mapping linear features such as beds and faults. As evidence of faulting at the surface is scarce, we examined historical records known as 'coal abandonment plans'. These identify coal seams that have been abandoned because of faulting in the carboniferous strata. Bailey *et al*. (2005) carried out a similar exercise in the Westpahlian A-C fluvial/deltaic strata of the East Pennine Coalfield, U.K. This paper included parts of our study area and found faults throws ranging from <1 to 180 m and lengths from 10 to 16 km. We selected those faults we identified in the carboniferous strata that were considered to have sufficient throw to affect the Triassic strata (>70m). The fact that the faulting was generated through the Palaeozoic basins would suggest that major faults in the Carboniferous would be seen in the Triassic sandstones. Finite faults in general may have displacement-length ratios of

10^{-4} to 10^{-1}, and those within the underlying carboniferous units in our work are known to be ~$10^{-1.2}$ (Bailey *et al*. 2005). Therefore many of the faults directly underlying the base of the Triassic sandstone are likely to be of regional significance and could be related to faults known to extend into the Triassic sandstones.

3. Results

3.1 Near surface Sandstone weathering in the Sherwood Sandstone Group

To illustrate the weathering process in the Nottingham Castle Sherwood Sandstone formation, we provide an outline of the weathering process and relate it to that of the engineering classification of Spink and Norbury (1993). Five distinct stages in the weathering continuum can be identified regardless of the overall thickness of the weathered zone, although not all stages may be present in any one particular profile. The stages are (i) development of an organic rich (~1 % C) topsoil, usually up to ~ 60 cm deep, (ii) a highly weathered and loose upper sand deposit or sub-soil, (iii) continued weathering of the sandstone leaving a sand deposit that becomes progressively more compact, (iv) transition from increasingly compact sand into weakly cemented sandstone before progressing into (v) hard sandstone. Core logs also reveal the presence of occasional bands of silty or thin mudstone and the more common bands of quartzite pebbles typical of the Nottingham Castle Formation. Within the engineering classification of sands and sandstone given by Spink and Norbury (1993), stages (i) and (ii) equate to soil, stages (iii) and (iv) equate to the in-between stage of non-durable rock and stage (v) the durable rock. The transition between stages (ii) and (iii) is the most marked and is demonstrated by a rapid change in penetrometer resistance. In the example shown (Fig. 3) taken from Sherwood Forest (SK60756273) the boundary occurs at ~1.5 m and the resistance is found to increase from around 1 to ~17.5 MPa across this short distance. Stages (i), (iii) and (iv) are the least well defined in the borehole logs. In some instances it was found that the Stages (iii) and (iv) were absent and that the highly weathered loose deposit was found directly on the competent rock. In Stage (iii), the dense compacted sand gradually passes into very weakly cemented sandstone (Stage iv). This is often described as 'weak' or 'inferior' and still retaining structure and is described in some records as 'easily broken by hand'. Within stages (iii) & (iv) small bands of highly weathered sand are sometimes found that have been created by preferential flow of meteoric water to groundwater via the fractures network (Wealthall *et al*. (2001).

3.2 Statistical analyses and isarithmic map of soil-weathered zone thickness

3.2.1 Total weathered zone (stages 1-4)

Thickness of the S&S (surface to competent bedrock) obtained from the borehole data (n = 500) ranged from 0.15 to 40m with a median of ~3m (Fig 4a). Depth distributions were strongly positively skewed; taking natural logarithms resulted in a more normal distribution with a relatively small skewness value of 0.03 (Fig 4b). Semi-variances (Equation 3) were estimated using the log-transformed data. The presence of non-stationary trend was investigated by fitting linear and quadratic functions to the thickness values and their spatial coordinates. These functions accounted for less than five per cent of the variance indicating there was no significant long-range trend in the thickness data. Semi-variances were estimated in each of eight directions (0°, 22.5°...157.5°) using Equation 3 with a tolerance angle of 11.25° and a lag interval of 400 metres to determine whether there was evidence for anisotropy (i.e. different magnitudes of variation in different directions) in the thickness data. The estimated semi-variances in each direction were similar, particularly at the shorter lag intervals which is important for local interpolation by kriging. We concluded that any anisotropy in the data was insignificant and so we proceeded to estimate semi-variances with no restriction on orientation (isotropic variogram) with the same lag interval up to a maximum range of 12 km. The variances increased with the lag separation and a series of authorised functions were fitted (Webster and Oliver, 2007) to the variance estimates using a weighted least squares version of the MVARIOGRAM directive in Genstat (Payne *et al*., 2005). A spherical function (Equation 4) was optimal with parameters of 4.8 km for the range and sill and nugget variances of 0.41 and 0.36 respectively indicating that around 54% of the variance is spatially correlated (Fig. 3). This means that the thickness of the S&S at any point on the landscape is, on average, correlated with its thickness within a circle of radius 4.8km around that point. Although it is difficult to relate this measurement to the physics and chemistry of the underlying weathering processes, it suggests that this is the magnitude of the scale over which the dominant processes operate to determine S&S thickness. By contrast, the median slope length (path from crest to drainage network) for 1000 random positions on catchment boundaries was 240 m (range 8 to 1414 m), which suggests that short range hillslope-scale processes cannot directly account for the observed long-range pattern of S&S thickness In other words, the evidence suggest that the broad spatial pattern of S&S thickness distributions is likely to be influenced by large scale processes, such as groundwater flow pathways controlled by the fault network, rather than the influence of shorter-scale (<240 m), hillslope processes, especially on the low topographical relief of the study area. However, this is not to imply that shorter scale hillslope processes do not contribute to the larger scale weathering process. Bogaart and Troch (2004) suggest that hillslope topography affects runoff, and subsurface storm flow mechanisms; the controls being surface and subsurface topography that control the divergence and convergence of flow paths, gradient which controls the effects of gravity on downhill flow velocity, hydraulic properties controlling water retention behaviour, porosity and soil thickness, and hillslope size that effects maximum length of subsurface flow paths. These factors will all contribute to the flow of groundwater and the subsequent weathering process.

To produce an isarithmic map, we predicted values at the nodes of a fine grid by punctual, lognormal ordinary kriging based on the 500 thickness observations, and threaded contours through them. The fine grid (500 m) was interpolated and shaded using a greyscale based on the same class intervals (Fig. 6). In part of the study region dominated by forested land use there were too few data points for ordinary kriging; in such circumstances the mean thickness for the entire study region is likely to be as accurate an estimate as that based upon interpolation. The map highlights areas of potentially greater weathering (> 10 m) in the southern part of the study region, with one area in the south to depths > 20m. There is some evidence of a curvilinear feature extending from the region of greatest thickness in the south in a northerly direction. The pattern of S&S thickness shows considerable short-scale variability; thicknesses of 2 and 10 metres are separated by ca. 2 kilometres in the south of the study region.

3.2.2 Variation in depth of the Soil (Stages 1 & 2)

Of the 2500 borehole logs, 280 had information pertaining to the thickness of the soil (Stages 1 & 2). Figure 7 shows the frequency distribution of soil depths. This, in effect represents the depth distribution of the current soil resource across the area. The majority of soil depths are between 1 - 3m. Where borehole information existed for both the thickness of soil and S&S (n=192), analysis was undertaken to assess whether a relationship existed. The dataset consisted of two subsets of samples. Firstly, a subset where borehole logs generally followed the 5 stages of weathering outlined previously and secondly, a subset where the highly weathered part of the sandstone (Stages 1 & 2) extended to the competent sandstone, thus missing out on stages (iii) and (iv). Therefore the dataset was non parametric and correlation analysis was undertaken using the Spearman Rank correlation co-efficient (r_s). A weak correlation was found between S&S (Stages 1-4) and soil (Stages 1-2) thickness ($r_s = 0.25$, $P<0.001$, n=192). Semi-variances were estimated (Equation 3) but no spatial structure (autocorrelation) was observed.

3.3 Topographic Analysis

A series of analyses were undertaken that correlated the soil and S&S thicknesses to topographic characteristics including (i) local relief, (ii) slope angle, (iii) flow path length, (iv) upslope contributing area and (v) slope curvature using regression analyses. No significant relationships with slope characteristics were found for either the S&S or 'soil'. Table 1 summarizes these analyses.

3.4 Levels of groundwater

We investigated the potential role that current groundwater levels may have on the spatial distribution of weathering depth, particularly the deep weathering in the southern part of our study area. Several papers report on the current regional groundwater level. Bath *et al*. (1987) report the potentiometric surface as lying 10m - 40 m below the surface, running west to east, and Green *et al*. (2006) found groundwater levels to lie ~20m below the soil surface in their study site in Sherwood Forest. Thus the depth of groundwater is generally below that of the S&S weathering. In addition, an analysis of our borehole records revealed that in only 67 of the 500 boreholes was groundwater recorded. In these boreholes the recorded depth of groundwater varied between 0.9 and 17.2 m below the surface. The median depth of water was 2.7m and the average depth 3.4m. The presence of this groundwater was generally a result of thin layers of impermeable marl that are occasionally found within the sandstone stratigraphy, creating perched water-tables. Thus in these areas, a contribution to weathering may be found.

3.5 Position of underlying faults

Fig 8a shows the major faults from the Carboniferous strata that we consider are likely to affect the Triassic sandstones. Some of these appear to be continuations of faults located in the Permian rocks to the west of the study area. Fewer faults appear in the northern section of the outcrop as there are fewer coal abandonment records for this area. Therefore, a complete picture of the major faults in the carboniferous strata of this area may not have been fully realized. However, Bailey *et al*. (2005) present maps of faults where the throw > 1m and it is apparent that there are numerous smaller faults throughout the study area. There is reasonable agreement between areas where large faulting is predominant (Fig. 8a) and areas of deep weathering (Fig. 8b), although the correspondence is not perfect. This may be due to (i) a lack of borehole records in some areas and (ii) the mapping of the faults at depth being projected vertically to the surface as the fault dip was not known.

4. Discussion

Spatial and statistical analysis of our borehole log data revealed that (i) there was spatial autocorrelation in the S&S thickness to competent rock, (ii) that a significant yet weak correlation existed between the thickness of soil and S&S and (iii) there was no significant topographic influence on the thickness of soil or S&S. Phillips *et al*. (2005) found a similarly high degree of local spatial variability in soil depth unrelated to topography in a dataset of Ouachita Mountain soils. In the following discussion we assess a number of potential factors that may have influenced the spatial variation of soil thickness and we propose a hypothesis that may explain the spatial distribution of S&S weathering.

The primary chemical weathering process in the Sherwood Sandstone is the dissolution of anhydrite, gypsum, dolomite and calcite cements (Bath *et al.*, 1987; Burley and Kantorowicz, 1986). Thus the soil represents material where the cement has been largely removed, whilst the saprolite stills retains sufficient cement to maintain some strength and structure. Analysis of the current potentiometric groundwater levels across the study area (Bath *et al*. 1987) suggests that currently the S&S generally sits above the groundwater level. The role of groundwater is difficult to assess, because the age of soils across the area is largely unknown and groundwater conditions are likely to have been very different over the past tens of thousands of years. However, infiltration of fresh meteoric water will continue chemical weathering within the soil and saprolite. Precipitation across our study area is ~ 650 mm a^{-1} so it is unlikely that spatial differences in soil and S&S thickness are a result of variability in weathering rates due to variations in precipitation.

Land-cover and the soil ecosystem will influence soil thickness across the study area. Until ~1200 AD, when clearances began, the study area was largely forested. Trees can play a role in soil thickness by enhancing chemical weathering through the release of root exudates, by increasing physical weathering through the bioturbation caused by tree roots, and by enhancing soil transport by tree-throw (Gabet *et al*., 2003; Roering *et al*., 2003). When cleared, tree throw can create new pathways for water flow as the soil is physically disturbed. Carter and Ciolkosz (1991) suggested that tree throw may mask slope gradient effects when examining soil thickness in sandstone in Pennsylvania. Differences in land-cover may also cause infiltration heterogeneity leading to variation in weathering depth. Calder *et al*. (2003) used neutron probe analysis to assess recharge under different vegetation sites within a small part of our study area (Clipstone Forest). They reported that average annual recharge plus runoff to be 136 ± 11 for grass, 122 ± 3 for heath, 76 ± 5 for oak woodland and 34 ± 8 mm for pine woodland. Although differences in recharge are found with different land cover, we do not consider that land-cover has had a major effect on the depth of soil found as for the most significant period of the Holocene land-cover across the study area was all predominantly woodland. To demonstrate this we examined soil depth on arable and woodland (n = 5) sites that were close together. Little variation in soil depth (~200 cm) was found in both the arable and forest soils.

A further factor that could influence soil and S&S thickness is natural variation in the sandstone properties and how these may respond to weathering. Misasny and McBratney (1999) demonstrated that differences in rock weathering rates can create chaotic effects in soil thickness. It is probable that some small scale variation in the weathering rates and soil / saprolite thickness may be a result of the geochemical variability of the sandstone cement. However, Lovelock (1977) described the Nottingham Castle Sandstone as having only slight lithological variation; principally associated with grain size and bedding structure. Whilst we acknowledge the potential role of all the above in both the historical and current weathering of the sandstone, we do not consider that they fully explain the spatial variation in the weathering to bedrock.

To account for the variation in soil and S&S thickness, we propose a hypothesis whereby much of the variation, especially the deep weathering in the southern region, is a consequence of (i) periglacial freeze-thaw and (ii) the infiltration of glacial and/or peri-glacial meltwater. It is acknowledged that during the Last Glacial Maximum (LGM), approximately 10000 yrs BP, the Midlands and southern England remained unglaciated (Howard *et al*., 2007), leaving the Anglian glaciation (430,000 – 480,000 yrs BP; Marine Isotope Stage (MIS) 12) as the last time ice covered our study area. The major evidence that glacial meltwater may have been a significant influence on chemical weathering and therefore soil and saprolite depth, is that our study area is the major recharge area of the Sherwood Sandstone Aquifer in the East Midlands. There is considerable paleohydrological evidence that the aquifer was recharged by peri-glacial water between 10-35 000 yrs BP. Bath *et al*. (1979) carried out a major isotopic analysis of waters in the East midlands Sherwood Sandstone aquifer and demonstrated that recharge waters now present in the confined aquifer to the east are periglacial waters, characterised by $\delta^{18}O_{SMOW}$ values between -9.1 to -9.8 and low Cl^- values (7-21 mg l^{-1}), consistent with low temperatures (Bath *et al*. 1979; Edmunds *et al*. 1982).

The variability of the soil thickness (0.15 – 9m; median 1.5m) is probably a result of a succession of glacial or peri-glacial activity through the Pleistocene. This may indicate why soil thickness was not found to be related to topography and why there was only a weak relationship between soil and S&S depth. Dietrich *et al*. (1995) suggested that their model of colluvial soil thickness may not be suitable to glaciated areas, probably because of the number of factors that have already been imposed on the 'soil production function' and subsequent weathering rates. For example, for our area of interest, the scattered remnants of the Anglian glacio-fluvial sand, gravel and tills found today are believed to be the few remains of a much more extensive deposit (Howard *et al*. 2007). This suggests that extensive denudation of the outcrop must have occurred following the Anglian Glaciation as the ice sheet retreated, or through periglacial mass-wasting events during successive cold stages in the middle to late Pleistocene between the Anglian and the LGM (MIS 12-2) (Howard *et al*. 2007). Evidence of major transport of material from the Sherwood sandstone outcrop are found in the major river terraces adjacent to the River Trent that occur to the south of the study area. These terrace deposits include, for example, the Eagle Moor sand and gravel (Marine Isotope Stage (MIS) 12)), the Balderton sand and gravel (MIS 6) and the Holme Pierpoint sand and gravel (MIS 2). Thus, although a denudation of the Anglian till deposits is suggested we do not know how much of the underlying weathered sandstone was removed as well. Evidently, uneven accumulations of weathered debris across the study area will affect moisture and thermal inputs and hence subsequent bedrock lowering.

During cold periods subsequent to the denudation, freeze thaw processes would be a major contributory factor in breaking the rock surface and re-starting soil production, prior to chemical weathering. Infiltration of melt-water during peri-glacial times would also not be consistent across the study area, with aspect, slope and snow/ice coverage important local factors. These factors may initiate different weathering rates as suggested by Misasny and McBratney (1999).

In addition periglacial geli/solifluction processes could influence soil thickness on slopes and hence future bedrock weathering rates. Variable soil thickness has been identified on slopes as a result of periglacial activity on sandstones in the Appalacian Mountains (Carter and Ciolkosz, 1986). They identified lobate terraces created by solifluction processes on both gently sloping (2-5%) and steep (20-40%) slopes. Similar processes could have occurred in our study area although they have not been identified, possibly because of anthropogenic influence on landuse. These could have helped create differences in weathering rates across the outcrop as a result of changing soil thickness.

Whilst recent glacial events are likely to have contributed to the variation in soil depth across the outcrop, it is not known at what time the deepened weathering of the S&S in the southern section of the study area occurred. It is possible that the input of glacial water could have taken place through (i) increased pore pressure due to the overburden of ice during the Anglian glaciation or (ii) the infiltration of meltwater during peri-glacial stages. Regardless of the source of water, we suggest that the weathering occurred as a result of drainage being controlled by the regional faulting pattern. The role of fractures in rock weathering and soil formation is recognised at local scales (Schoeneberger and Wysoki, 2005; Taylor and Eggleton, 2001). However, at regional scales, jointing, and faulting can control drainage development, particularly in homogenous rocks such as sandstones (Taylor and Eggleton, 2001). Molnar *et al*. (2007) suggested that one of the principal effects of tectonic deformation was that it 'riddles the upper crust with fractures which provide avenues for water flow'. We demonstrated in Figure 8 that there is a considerable match between faults and deeper weathering. One of the reasons why the southern part of our study area was more susceptible to faulting is its geographical position. It is situated on the East Midlands shelf which is sited on the western margin of the subsiding Southern North Sea Platform (Section 2.1). The highly weathered zone located through our borehole study, is itself situated on the western margin of the East Midlands Shelf. During the tertiary uplift of the East Midlands shelf the geology on the edge of the basin may be more susceptible to faulting as the rock is thinner. Howard *et al.* (In Press) states that the Sherwood Sandstone Group, increases in thickness at it extends northwards across our study area. This trend is consistent with a regional north eastwards thickening of the sandstone, extending across the Eastern England shelf. In the southern, highly weathered part of our study area the thickness of the Sherwood Sandstone Group is ~80 m, yet 25 km to the north east it is 168 m thick. Therefore, because the rock is thinner in the southern part of our study area, proportionally more of the rock could have been affected by faulting as the basin subsided.

Regional faults, such as those mapped in Figure 8a are likely to have a series of smaller faults splaying off them, creating a more extensive drainage network. Increased fluid flow through this drainage network would be likely to lead to enhanced dissolution of the cements and greater weathering. There is evidence within the Triassic sandstones of the U.K. that faulting zones can enhance the depth of weathering. The Sherwood Sandstone Group in the Sellafield area of west Cumbria was studied extensively as part of the UK Nirex program to find geology suitable for a high level nuclear waste repository. The depth of weathering was assessed by identifying the type of mineralisation found. Within the St Bees Sandstone, part of the Sherwood sandstone Group, depths of weathering were found to be ~ 270 - 440m in the proximity of the potential repository zone. However, close to the Fleming Hall Fault Zone area (~1 km away), mineralisation by weathering had extended to ~ 660m (Milodowski *et al*. 1998; Akhurst *et al*. 1998). Further evidence pointing to extensive fracturing of the sandstone in the deeply weathered area which our study located, can be found in transmissivity values calculated from borehole pumping tests. Many values in this area have transmissivity values

(T) between 800 and 1500 m^2 d^{-1} which is indicative of flow through highly fractured rock (Allen et al. 1997).

5. Conclusions

We examined the thickness of the (i) soil and (ii) S&S to competent bedrock across the Sherwood Sandstone outcrop in Nottinghamshire, U.K. using information from archived borehole logs. We found a spatial pattern of saprolite thickness to bedrock that was found to extend to depths of 40 m. There was no indication that the depth of weathering was related to topography, although there was a weak correlation between soil and total weathered depth to bedrock. However, we consider that glacial or periglacial processes may have been influential in the development of the spatial pattern of weathering thickness. The current study not only provides a valuable dataset on soil thickness across the Sherwood Sandstone outcrop in Nottinghamshire, but also increases our understanding of the soil-geology system of this important aquifer in England. It presents information that may enhance our conceptual understanding of groundwater flow within the upper aquifer which could be considered when developing groundwater models. The work also adds to other recent work that has started to demonstrate the previously unknown complexity of the Sherwood Sandstone Group aquifer including the structural controls on compartmentalisation (Mohamed and Worden, 2006) and the role of sediment filled fractures (Wealthall *et al*. 2001) in water movement.

Acknowledgements

This paper is published with the permission of the Executive Director of the British Geological Survey (NERC). The authors would like to thank Dr Jonathan Lee for useful discussions. We would also like to thank the Associate Editor and two anonymous referees for their suggestions on improving this manuscript.

References

Akhurst, M.C., Barnes, R.P., Chadwick, R.A., Millward, D., Norton, M.G., Maddock, R.H., Kimbell, G.S. & Milodowski, A.E. 1998. Structual evolution of the Lake District Boundary Fault Zone in west Cumbria, U.K., *Proceedings of the Yorkshire Geological Society,* **52**(2), 139-158.

Allen, D.J., Brewerton, L.J., Coleby, L.M., Gibbs, B.R., Lewis. M.A., MacDonald A.M., Wagstaff, S.J. & Williams, A.T. 1997. The physical properties of major aquifers in England and Wales. *British Geological Survey Technical Report WD/97/34 and E.A. R&D 8,* 312pp.

Anderson, S.P., von Blanckenburg, F., White, A.F. 2007. Physical and chemical controls on the Critical Zone. *Elements*, **3**, 315-319.

Andrews, J.N., Balderer, W., Bath, A.H., Clausen, H.B., Evans, G.V., Florkowski, T., Goldbrunner, I., Ivanovich, M., Loosli, M. & Zojer, H. 1984. Environmental isotope studies in two aquifer systems: a comparison of groundwater dating methods. In *Water Resources Development*, *Proceedings of the Symposium on Isotope Hydrology,* IAEA, Vienna.

Anhert, F. 1987. Approaches to dynamic equilibrium in theoretical simulations of slope development. *Earth surface Processes and landforms*, **12**, 3-15.

Bailey, W.R., Walsh, J.J. & Manzocchi, T. 2005. Fault populations, strain distribution and basement fault reactivation in the East Pennines coalfield, U.K. *Journal of Structural Geology*, **27**, 913-928.

Bath, A.H., Edmunds, W.M. & Andrews, J.N. 1979. Palaeoclimatic trends deduced from hydrochemistry of a Triassic sandstone aquifer, United Kingdom. In *Isotope Hydrogeology 1978*, IAEA, Vienna.

Bath, A.H., Milodowski, A.E. & Strong, G.E. 1987. Fluid flow and diagenesis in the East Midlands Triassic sandstone aquifer. In *Fluid Flow in Sedimentary Basins and Aquifers*. Goff, J.C. & Williams, B.P.J. (eds), Geological Society Special Publications, No. 34, 127-140.

Beamish D. & Klinck, B. 2006. Hydrochemical characterisation of a coal mine plume detected by an airborne geophysical survey. *Geofluids*, **6**, 82-92.

Berner, R.A., Lasaga, A.C., Garrels, R.M. 1983. The carbonate-silicate geochemical cycle and its effect on atmospheric carbon dioxide over the past 100 million years. *American Journal of Science*, **283**, 641-683.

Bogaart, P.W. & Troch, P.A. 2004. On the use of soil-landscape evolution modelling in understanding the hillslope hydrological response. *Hydrology: Science & Practice for the 21st Century*, **1**, 251-259.

Brantley, S.L., Goldhaber, M.B. & Ragnarsdottir, K.V. 2007. Crossing disciplines and scales to understand the critical zone. *Elements*, **3**, 307-314.

Braun, J., Heimsath, A.M. & Chappell, J. 2001. Sediment transport mechanisms on soil-mantled hillslopes. *Geological Society of America*, **29**, 683-686.

Brewerton, L.J &. Smedley, P.L. 1997. The Natural (Baseline) Quality of Groundwaters in England and Wales. Part 2: The Triassic Sherwood Sandstone of the East Midlands and Yorkshire. *British Geological Survey Technical Report WD/97/52 (Hydrology Series)*, pp. 43.

Burley, S.D. & Kantorowicz, J.D. 1986. Thin section and S.E.M. textural criteria for the recognition of cement-dissolution prosity in sandstones. *Sedimentology*, **33**, 587-604.

Calder, I.R., Reid, I., Nisbet, T.R. & Green, J.C. 2003. Impact of lowland forests in England on water resources: Application of the Hydrological Land Use Change (HYLUC) model. *Water Resources Research,* **39**, 1319.

Carter, B.J. & Ciolkosz, E.J. 1986. Sorting and thickness of waste mantle material on a sandstone spur in central Pennsylvania. *Catena*, **13**, 241-256

Carter, B.J. & Ciolkosz, E.J. 1991. Slope gradient and aspect effects on soils developed from sandstone in Pennsylvania. *Geoderma,* **49**, 199-213.

Davies, W.M. 1892. The convex profile of badland divides. *Science*, **20**, 245.

DEFRA. 2008. Implementation of the nitrates Directive (91/676/EEC). Description of the methodology applied in identifying waters and designating nitrates vulnerable zones in England. pp 49.

Dietrich, W.E., Reiss, R., Hsu, M.L., & Montgomery, D.R. 1995. A process based model for colluvial soil depth and shallow landsliding using digital elevation data. *Hydrological Processes*, **9**, 383-400.

Dietrich, W.E., Bellugi, D.G., Sklar, L.S. & Stock, J.D. 2003. Geomorphic transport laws for predicting landscape form and dynamics. in: R.M. Iverson and P. Wilcock (editors), *Prediction in Geomorphology*, Geophysical Monograph 135, American Geophysical Union, p. 103-132.

Denman, K.L., G. Brasseur, A. Chidthaisong, P. Ciais, P.M. Cox, R.E. Dickinson, D. Hauglustaine, C. Heinze, E. Holland, D. Jacob, U. Lohmann, S Ramachandran, P.L. da Silva Dias, S.C. Wofsy and X. Zhang, 2007: Couplings Between Changes in the Climate System and Biogeochemistry. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Densmore, A.L., Ellis, M.E. and Anderson, R.S. (1998) A numerical model of landscape evolution by bedrock landslides. *Journal of Geophysical Research* **103**: 15-203-15,220.

Downing, R.A., Edmunds, W.M. & Gale, I.N. 1986. Regional groundwater flow in sedimentary basins in the U.K. In *Fluid Flow in Sedimentary Basins and Aquifers.* Goff, J.C. & Williams, B.P.J. (eds). Geological Society Special Publications, No. 34, 105-125.

Edmunds, W.M., Bath, A.H. & Miles, D.L. 1982. Hydrochemical evolution of the East Midlands Triassic sandstone aquifer, England. *Geochimica et Cosmochimica Acta*, **46**, 2069-2081.

Edwards, W.N. 1967. Geology of the country around Ollerton. Memoirs of the Geological Survey of Great Britain, HMSO, pp.297.

EC 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal L 327, 1-73.

Ellis, M. E., Densmore, A. L., and Anderson, R. S., (1999). Development of mountainous topography in the Basin Ranges, USA. *Basin Research* **11,** 21-42.

Fernandes, N.F. & Dietrich, W.E. 1997. Hillslope evolution by diffusive processes: The timescale for equilibrium adjustments. *Water Resources Research*, **33**, 1307-1318.

Gabet, E. J., Reichman, O. J., and Seabloom, E. W. 2003. The effects of bioturbation on soil processes and sediment transport. *Annu. Rev. Earth Planet. Sci.,* **31**, 249–73, doi: 10.1146/annurev.earth.31.100901.141314

Gilbert, G.K. 1909. The convexity of hilltops. *Journal of Geology*, **17**, 344-350.

Green, J.C., Reid, I., Calder, I.R. & Nisbet, T.R. 2006. Four year comparison of water contents beneath a grass ley and a deciduous oak wood overlying Triassic sandstone in lowland England. *Journal of Hydrology*, **329**, 16-25.

Green, P.F., Thomson, K. & Hudson, J.D. 2001. Recognition of tectonic events in undeformed regions: contrasting results from the Midland Platform and East Midlands Shelf, Central England. *Journal of the Geological Society, London*, **158**, 59-73.

Heimsath, A.M., Dietrich, W.E., Nishiizumi, K., Finkel, R.C. 1997. The soil production function and landscape equilibrium. *Nature*, **388**, 358-361.

Heimsath, A.M., Dietrich, W.E., Nishiizumi, K., Finkel, R.C. 1999. Cosmogenic nuclides, topography, and the spatial variation of soil depth. *Geomorphology*, **27**, 151-173.

Heimsath, A.M., Dietrich, W.E., Nishiizumi, K., Finkel, R.C. 2001. Stochastic processes of soil production and transport: Erosion rates, topographic variation and cosmogenic nuclides in the Oregon Coast Range. *Earth Surface Processes and Landforms,* **26**, 531-552.

Heimsath, A.M., Fuink, D., Hancock, G.R. 2009. The 'humped' soil production function: eroding Arnhem Land, Australia. *Earth Surface Processes and Landforms*, **34**, 1674-1684.

Howard, A.S., Warrington, G., Carney, J.N., Young, S.R., Pharaoh, T.C. & Cheney, C.S. *In Press*. Geology of the country around Nottingham. Memoir for 1:50000 geological sheet 126. HMSO, London. pp.151-170.

Howard, A.J., Bridgland, D., Knight, D., McNabb, J., Rose, J., Schreve, D., Westaway, R., White, M.J., White, T.S. 2007. The British Pleistocene fluvial archive: East Midlands drainage evolution and human occupation in the context of the British and NW European record. *Quaternary Science Reviews,* **26**, 2724-2737.

Hren, M.T., Hilley, G.E. & Chamberlain, C.P. 2007. The relationship between tectonic uplift and chemical weathering rates in the Washington Cascades: Field measurements and model predictions. *American Journal of Science*, **307**, 1041-1063.

Humphreys, G.S. & Wilkinson, M.T. 2007. The soil production function: A brief history and its rediscovery. *Geoderma*, **139**, 73-78.

Intermap (2007). NEXTMap Britain elevation data from Intermap

Lovelock, P.E.R. 1977. Aquifer properties of Permo-Triassic sandstones in the United Kingdom. Bulletin 56 of the Geological Survey of Great Britain. HMSO, London, pp.50.

Milodowski, A.E., Gillespie, M.R., Naden, J., Fortey, N.J., Shepherd, T.J., Pearce, J.M. & Metcalfe, R. 1998. The petrology and paragenesis of fracture mineralization in the Sellafield area, west Cumbria. *Proceedings of the Yorkshire Geological Society*, **52**(2), 215-241.

Minasny, B. & McBratney, A.B. 1999. A rudimentary mechanistic model for soil production and landscape development. *Geoderma*, **90**, 3-21.

Mohamed, E.A. & Worden, R.H. 2006. Groundwater compartmentalisation: a water table height and geochemical analysis of the structural controls on the subdivision of a major aquifer, the Sherwood Sandstone, Merseyside, U.K. *Hydrology and Earth System Sciences*, **10**, 49-64.

Molnar, P., Anderson, R.S. & Prestrud Anderson, S. 2007. Techtonics, fracturing of rock, and erosion. *Journal of Geophysical Research*, **112**, F03014.

Mudd, S.M. & Furbish, D.J. 2004. Influence of chemical denudation on hillslope morphology. *Journal of Geophysical Research*, **109**, F02001.

Payne, R.W., Harding, S.A., Murray, D.A., Soutan, D.M., Baird, D.B., Welham, S. J., em et al. 2005. The Guide to GenStat Release 8, Part 2: Statistics. Lawes Agricultural Trust, Harpenden.

Phillips, J.D., Marion, D.A., Lucklow, K. & Adams, K.R. 2005. Nonequilibrium regolith thickness in the Ouachita Mountains. *The Journal of Geology*, **113,** 325-340.

Ragg, J.M., Beard, G.R., George, H., Heaven, F.W., Hollis, J.M. Jones, R.J.A., Palmer, R.C., Reeve, M.J., Robson, J.D. & Whitfield, W.A.D. 1984. *Soils and their use in Midland and Western England. Soil Survey of England and Wales Bulletin No. 12.* MAFF, Harpenden, pp. 433.

Renwick, W.H. 1992. Equilibrium, disequilibrium and non-equilibrium landforms in the landscape. *Geomorphology*, **5**, 265-276.

Roering, J.J., Kirchner, J.W., Sklar, L.S. & Dietrich, W.E. 2001. Hillslope evolution by nonlinear creep and landsliding: An experimental study. *Geology*, **29**, 143-146.
Roering, J.J., K. M. Schmidt, J. D. Stock, W. E. Dietrich and D. R. Montgomery, 2003, Shallow landsliding, root reinforcement, and the spatial distribution of trees in the Oregon Cost Range, *Canadian Geotechnical Journal*, **40**, 237-253.

Schoeneberger, P.J. & Wysocki, D.A. 2005. Hydrology of soils and deep regolith: A nexus between soil geography, ecosystems and land management. *Geoderma*, **126**, 117-128.

Small, E.E., Anderson, R.S. and Finkel, R. (1997) Erosion rates of summit flats using cosmogenic radionuclides. *Earth and Planetary Science Letters,* **150,** 413-425

Smith, E.G., Rhys, G.H. & Goossens, R.F. 1973. Geology of the Country around East Retford, Worksop and Gainsborough. Memoirs of the Geological Survey of Great Britain, HMSO, pp.348.

Spink, T.W. & Norbury, D.R. 1993. The engineering geological description of weak rocks and overconsolidated soils, In *The Engineering Geology of Weak Rock.* Coulthard, J.M. & Cripps, J.C. (eds.), Balkema, Rotterdam, pp.289-301.

Taylor, G. & Eggleton, R.A. 2001. Landscapes and the evolution of the regolith. In *Regolith Geology and Geomorphology*, John Wiley & Sons, Chichester. pp. 13-57.

Webster, R., Oliver, M.A., 2007. Geostatistics for Environmental Scientists: second edition. John Wiley and Sons, Chichester.

Wealthall, G.P., Steele, A., Bloomfield, J.P., Moss, R.H. & Lerner, D.N. 2001. Sediment filled fractures in the Permo-Triassic sandstones of the Xheshire Basin: observations and implications for pollutant transport. *Journal of Contaminant Hydrology*, **50**, 41-51.

Wilson, G.B., Andrews, J.N. & Bath, A.H. 1994. The nitrogen isotope composition of groundwater nitrates from the East Midlands Triassic Sandstone aquifer, England. *Journal of Hydrology*, **157**, 35-46.

Yoo, K., Amunson, R., Heimsath, A.M., Dietrich, W.E. 2005. Process based model linking pocket gopher (Thomomys bottae) activity to sediment transport and soil thickness. *Geological Society of America*, **33**, 917-920.

Yoo, K., Mudd. S.M., Sanderman, J., Amundseon, R. & Blum, A. 2009. Spatial patterns and controls of soil chemical weathering rates along a transient hillslope. *Earth and Planetary Science Letters*, **288**, 184-193.

Table 1: Summary of regression co-efficients relating (i) soil-saprolite depth and (ii) soil to topographical variables obtained from analysis of NEXTMAP DEM with 10x10m grid cells.

Dependent Variable (y)	Independent Variable (x)	Regression Coefficients		SE of Observation	
		Constant	Slope(x_1)	n	R^2_{adj}
Log_{10}(S&S)	Log_{10} (Relief)	0.489	0.036	482	0.00
	Log_{10}(Upslope area)	0.663	-0.355	482	0.02
	Curvature	0.548	0.010	482	0.00
	Log_{10}(Slope angle %)	0.555	-0.017	482	0.00
	Log_{10}(Slope Length)	0.220	0.0791	482	0.05
Log10(Soil)	Log_{10} (Relief)	0.393	-0.138	280	0.02
	Log_{10}(Upslope area)	0.172	-0.06	280	0.00
	Curvature	0.176	0.176	280	0.01
	Log_{10}(Slope angle %)	0.167	-0.0487	280	0.03
	Log_{10}(Slope Length)	0.240	-0.034	280	0.00

Figure captions:

Figure 1: Location of the Sherwood Sandstone outcrop in the East Midlands of England with regional, solid geology. Co-ordinates show km of the British National Grid.

Figure 2: Description of sandstone weathering on the Sherwood sandstone outcrop in Nottinghamshire.

Figure 3: Plot of penetrometer resistance versus depth.

Figure 4: Histograms and summary statistics for 500 observations of: a) Soil and Saprolite (S&S) thickness to competent rock and b) $\log_e$ transformed S&S.

Figure 5: Isotropic auto-variogram of $\log_e$ transformed S&S (symbols) and fitted spherical model (line).

Figure 6: Map of S&S thickness from the surface to competent rock. Coordinates are metres of the British National Grid.

Figure 7: Frequency distribution and summary statistics of soil depth

Figure 8(a-d): Maps showing (a) the current mapped fault structures in the East Midlands of England with the Sherwood sandstone outcrop outlined, (b) faulting in the carboniferous strata underlying the Sherwood sandstone outcrop, (c) the proposed major faults that could run through the study area and those with large throws that potentially may have an effect on the weathering of the overlying Sherwood Sandstone formation and (d) how the revised faulting patterns in the carboniferous corresponds with the total depth of weathering of the sandstone as indicated by kriging and grey scale measure.

Fig 1:

Fig 1:

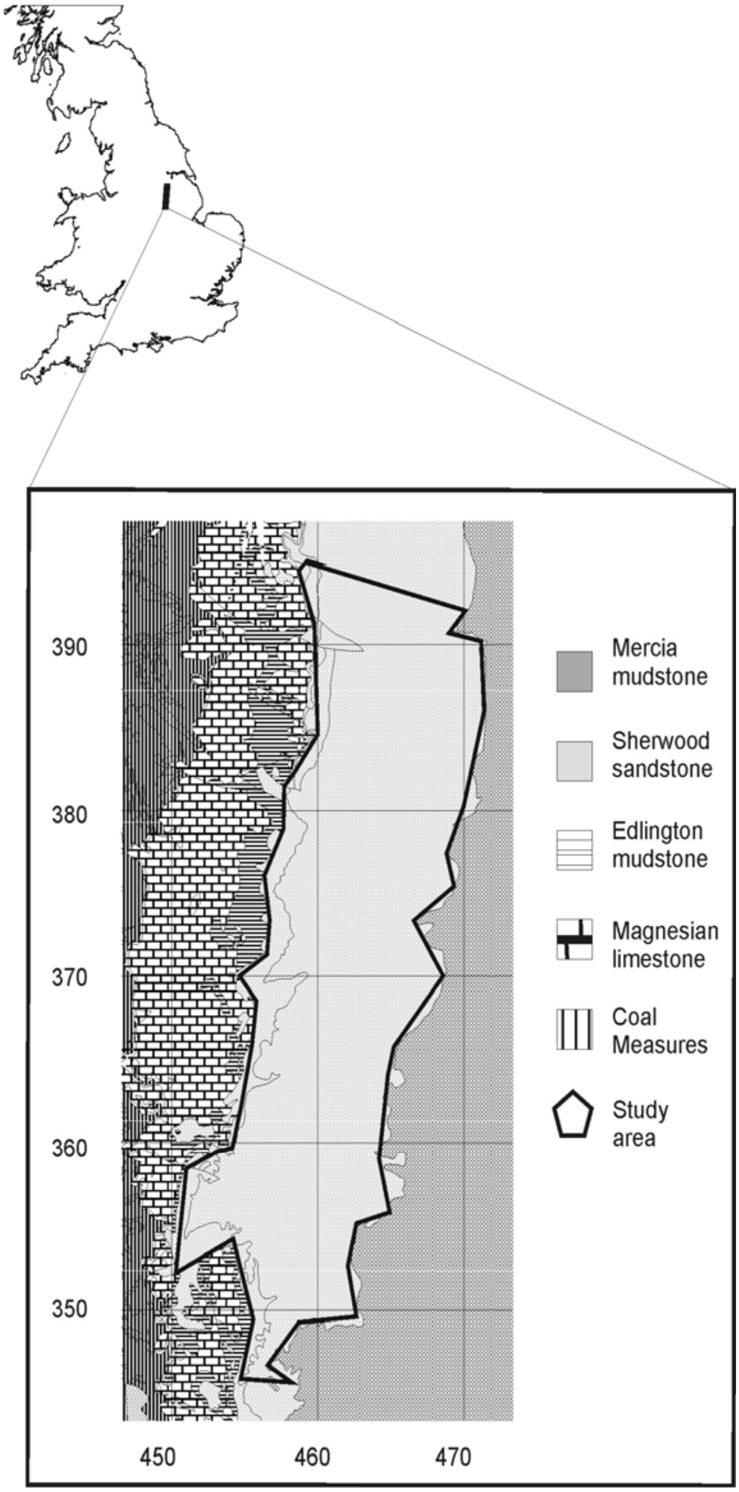

390
380
370
360
350
450
460
470
Mercia mudstone
Sherwood sandstone
Edlington mudstone
Magnesian limestone
Coal Measures
Study area

Fig 2:

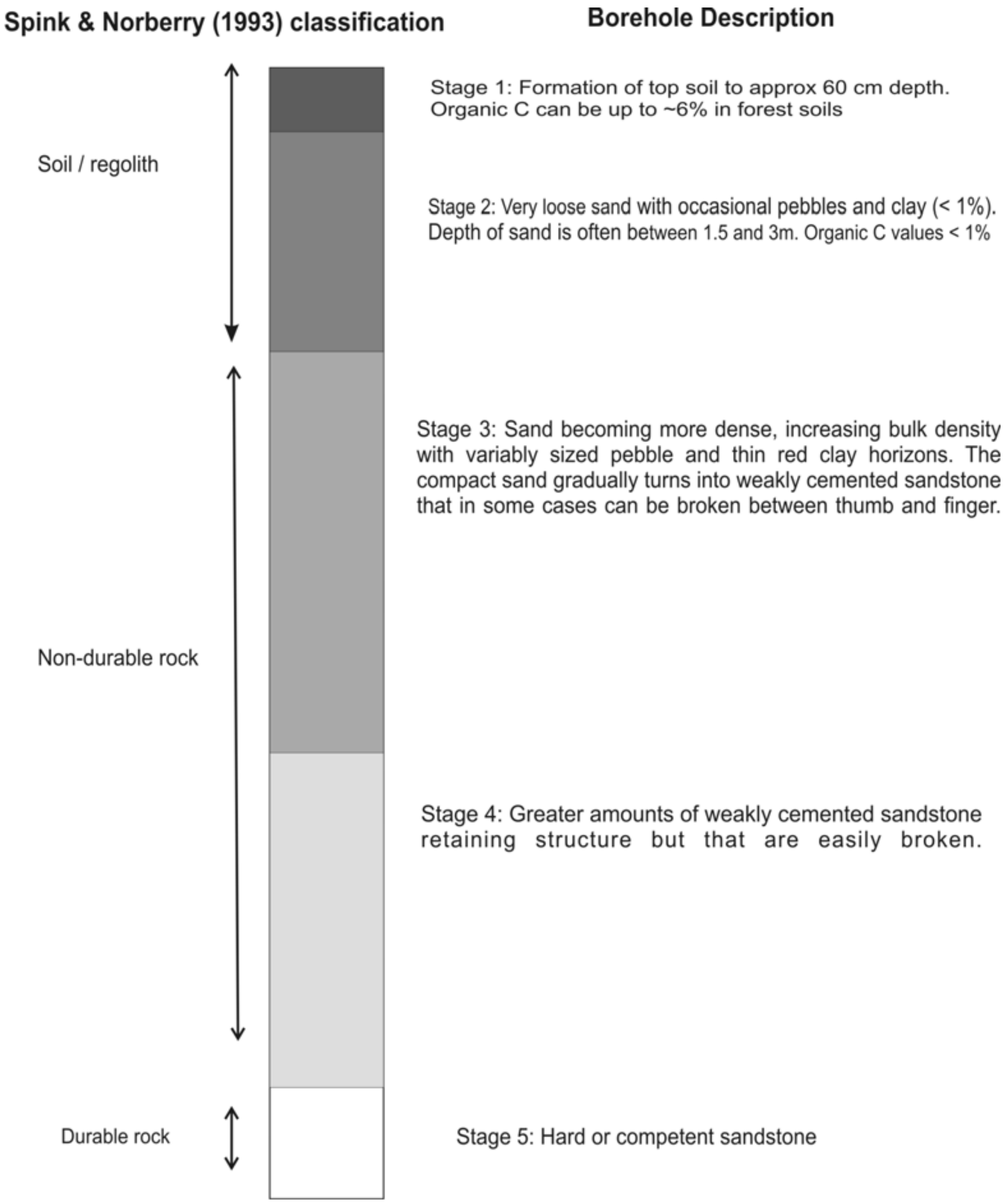

Spink & Norberry (1993) classification
Borehole Description
Soil / regolith
Non-durable rock
Durable rock
Stage 1: Formation of top soil to approx 60 cm depth. Organic C can be up to ~6% in forest soils
Stage 2: Very loose sand with occasional pebbles and clay (< 1%). Depth of sand is often between 1.5 and 3m. Organic C values < 1%
Stage 3: Sand becoming more dense, increasing bulk density with variably sized pebble and thin red clay horizons. The compact sand gradually turns into weakly cemented sandstone that in some cases can be broken between thumb and finger.
Stage 4: Greater amounts of weakly cemented sandstone retaining structure but that are easily broken.
Stage 5: Hard or competent sandstone

Fig 3:

Fig 3:

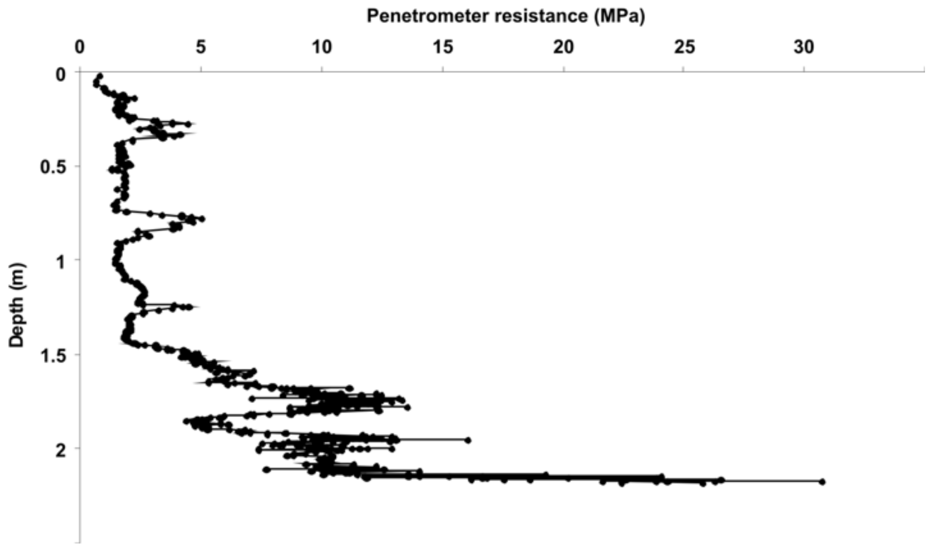
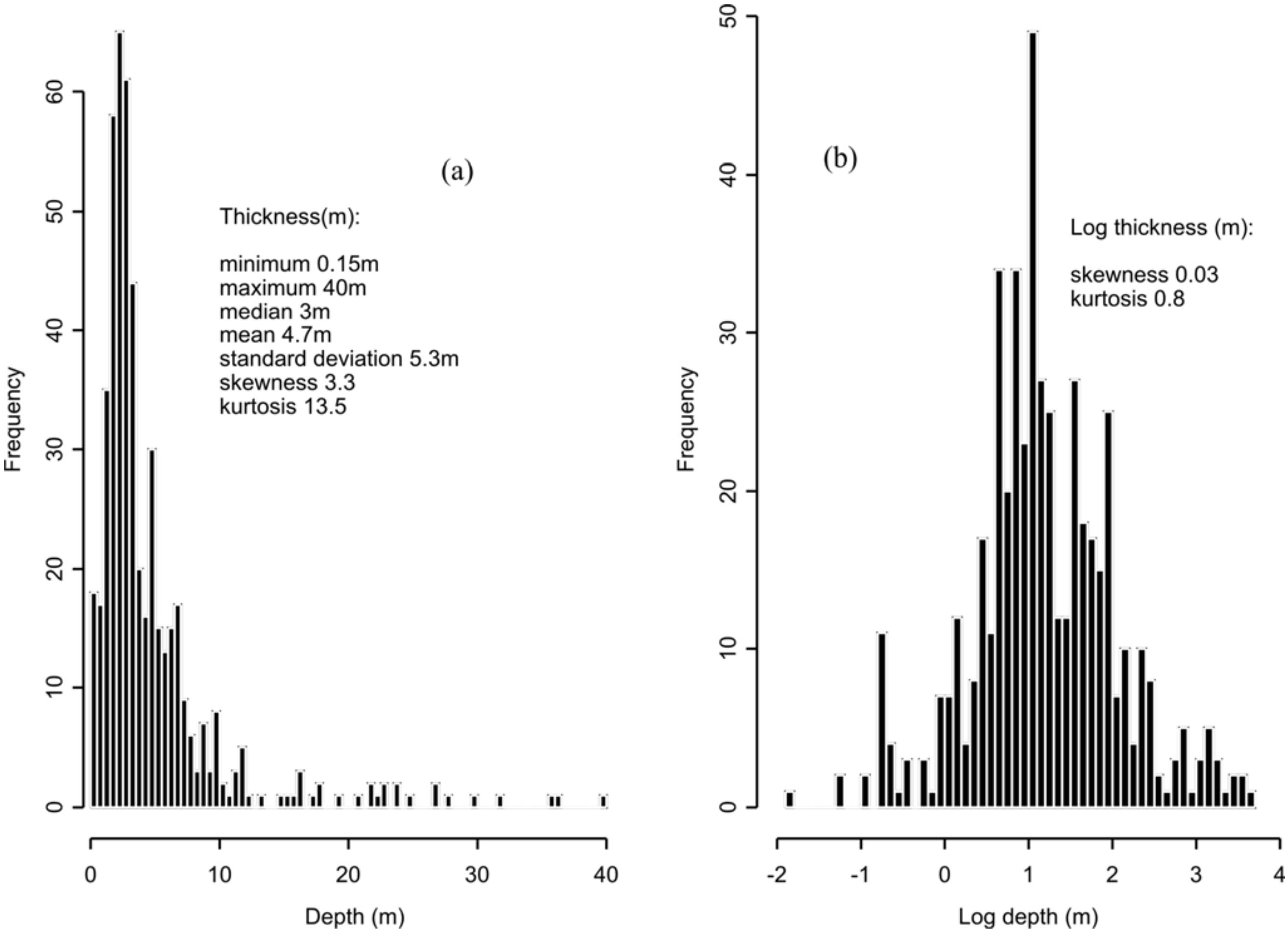

Penetrometer resistance (MPa)
0
5
10
15
20
25
30
0
0.5
1
1.5
2
Depth (m)

Fig 4:



(a)
Thickness(m):
minimum 0.15m
maximum 40m
median 3m
mean 4.7m
standard deviation 5.3m
skewness 3.3
kurtosis 13.5
Frequency
Depth (m)
0
10
20
30
40
50
60
(b)
Log thickness (m):
skewness 0.03
kurtosis 0.8
Log depth (m)
-2
-1
1
2
3
4

Fig 5:

Fig 5:

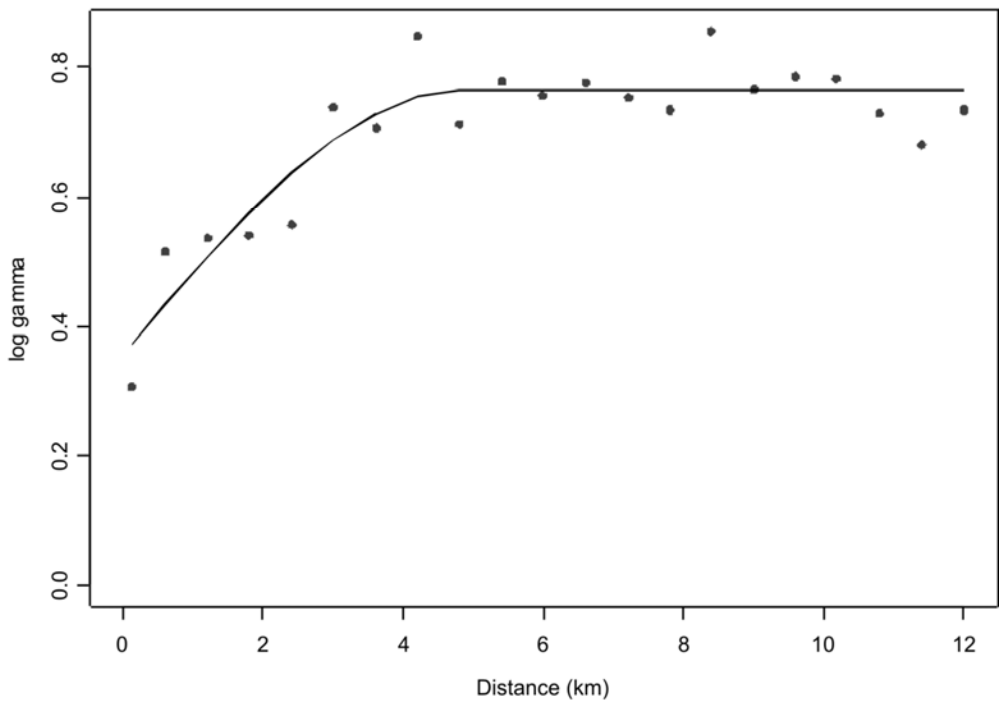


Fig 6:

Fig 6:

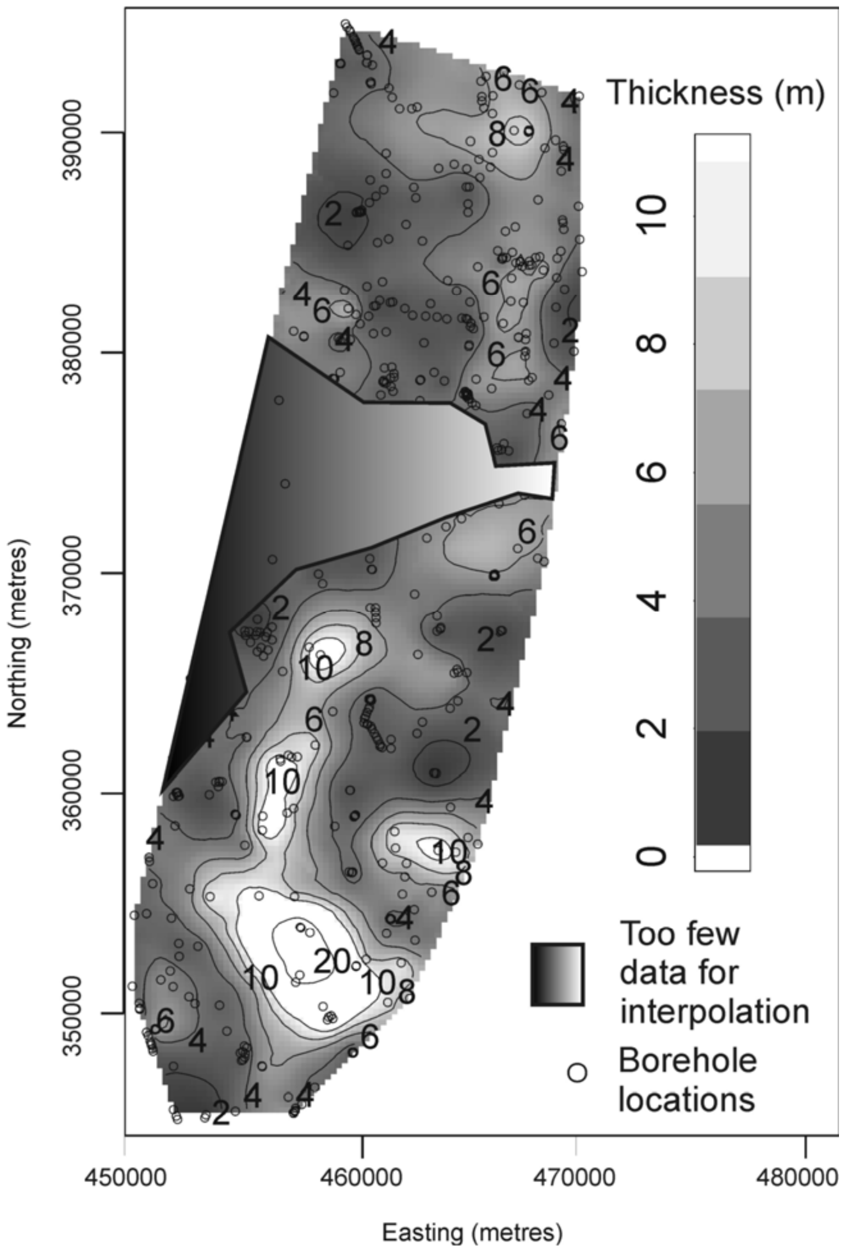

Thickness (m)
Too few data for interpolation
Borehole locations
Northing (metres)
Easting (metres)
450000
460000
470000
480000
350000
360000
370000
380000
390000
0
2
4
6
8
10

Fig 7:

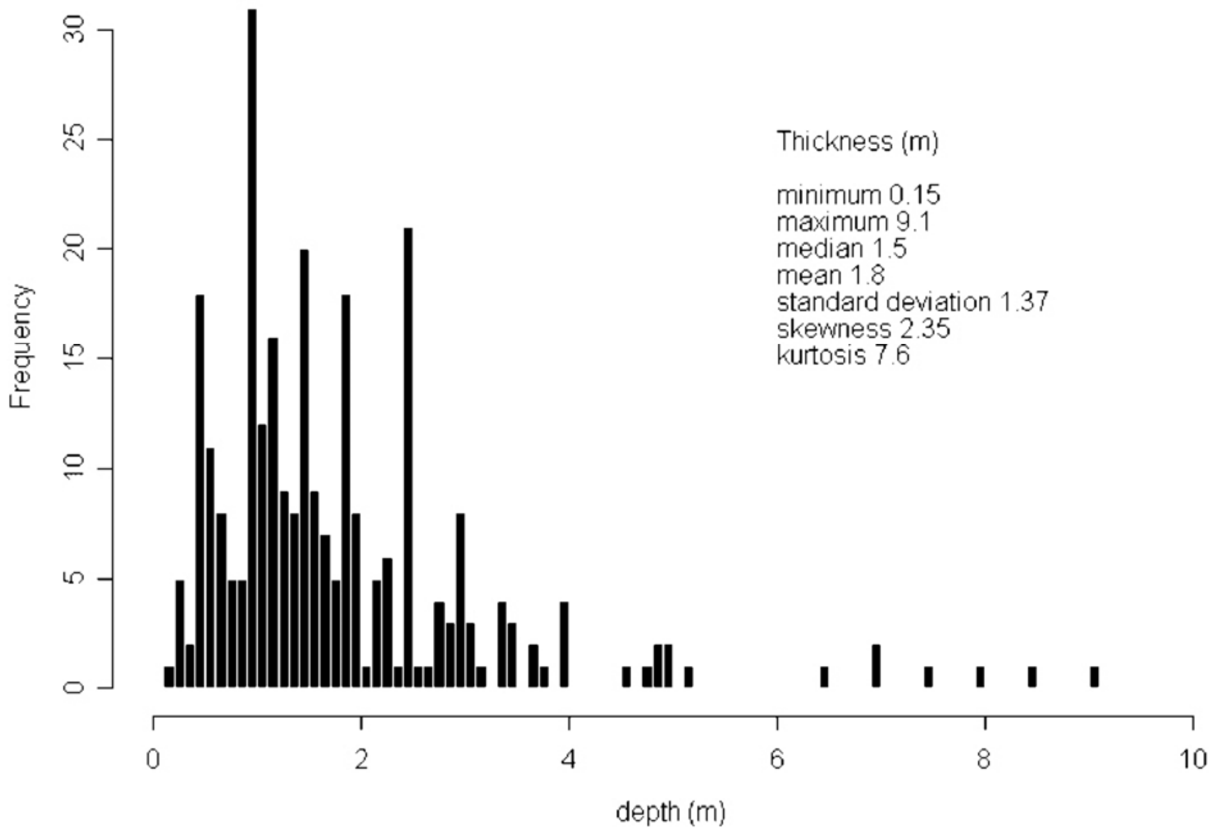
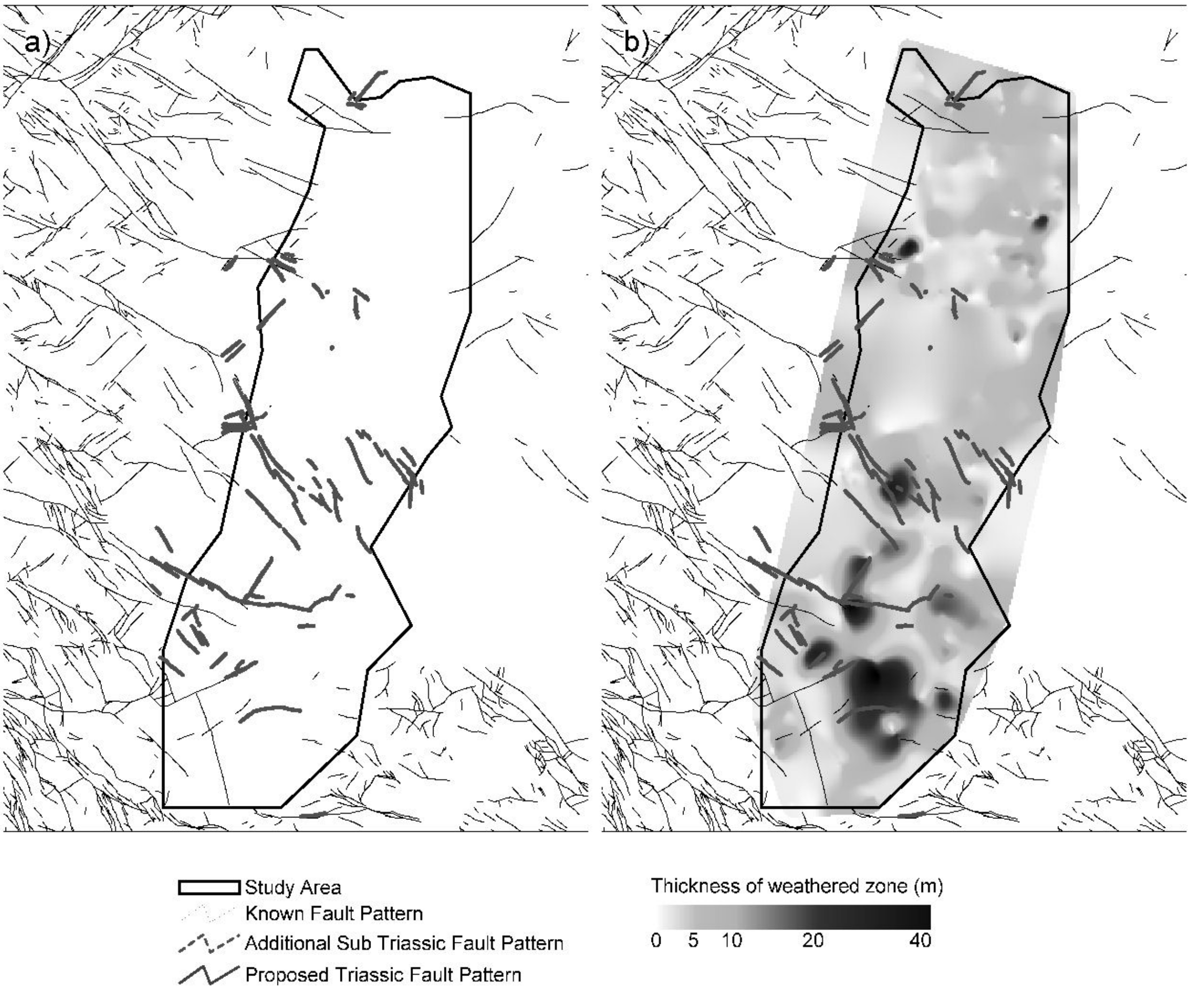

Thickness (m)
minimum 0.15
maximum 9.1
median 1.5
mean 1.8
standard deviation 1.37
skewness 2.35
kurtosis 7.6
Frequency
depth (m)
0
5
10
15
20
25
30
0
2
4
6
8
10

Fig 8:


a)
b)
Study Area
Known Fault Pattern
Additional Sub Triassic Fault Pattern
Proposed Triassic Fault Pattern
Thickness of weathered zone (m)
0 5 10 20 40