VARIATIONS IN SOIL DISPERSIVITY ACROSS A GULLY HEAD DISPLAYING SHALLOW SUB-SURFACE PIPES, AND THE ROLE OF SHALLOW PIPES IN RILL INITIATION

HAZEL FAULKNER1*, ROY ALEXANDER2, RICHARD TEEUW3 AND PAUL ZUKOWSKYJ4
1 Flood Hazard Research Centre, University of Middlesex, Queensway, Enfield, Middlesex, EN3 4SF, UK
2 Environment Research Group, Department of Geography, University College Chester, Chester, CH1 4BJ, UK
3 School of Earth & Environmental Sciences, University of Portsmouth, Burnaby Building, Burnaby Road, Portsmouth, PO1 3QL, UK
4 Division of Geography and Environmental Sciences, University of Hertfordshire, College Lane, Herts, AL109AB, UK

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ABSTRACT

A small bifurcating gully head displaying shallow pipe development was surveyed to explore how far three-dimensional patterns of geochemistry and sediment size can be related to hydraulic gradients in the local marl bedrock (Almería, SE Spain).

The crust, sub-crust and parent materials were sampled every 20 cm across a 2 m by 3 m grid, and then analysed for dispersive and granulometric characteristics. Spatial patterns of sodium adsorption ratio (SAR) for each layer were plotted separately. In-situ material at depths of 5–10 cm was only weakly dispersive, and the thin (0–2 cm depth) crust is also found to be mostly non-dispersive, paralleling findings from other field sites in Almería. However, the ‘signature’ relating SAR to electrical conductivity for each layer shows that in places the immediate sub-crust layer (2–5 cm) is highly dispersive. The pattern is not random; rather the SAR of this sub-crust layer follows inferred hydraulic gradients, the dispersive ‘hot spots’ being located in the most incised part of the small gully, exacerbating the erodibility of that position.

Patterns of sediment particle size and sorting do not correlate with inferred hydraulic gradients but surface material is slightly siltier than the sub-crust. Clay fraction increased with depth, and SAR is shown to have a weak inverse relationship to particle size. This association between SAR and the increased clay fractions in the lower layers supports the inference that massive pipe enlargement in the Messinian-Rich Unit is suppressed by sub-surface swelling. Since a reduction in infiltration capacity ($f_i$) with depth can be inferred from these results, infiltrating water must be deflected into the already vulnerable sub-crust layer during rainfall events, explaining the development of shallow pipe forms at preferential depths.

It is concluded that calcium replaces sodium in the crust during leaching, leaving a calcic crust, and a sub-crust that is sodic and prone to subsequent pipe enlargement. Rill morphology in these materials also suggests that rills develop from these pipes when pipe roofs collapse (i.e. rill discontinuity; bridges; steep headwalls; and rills with excessively high depth-to-width ratios). Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: piping; dispersion; SAR; rills; surface crust

INTRODUCTION

Dispersive soils have a high sodium adsorption ratio (SAR generally > 3), and electrical conductivity (EC) below a threshold value for flocculation (Rengasamy et al., 1984; Naidu et al., 1992). Where topographic gradients are suitable, they are prone to pipe or tunnel erosion along macropores during infiltration (Heede, 1971; Yaalon, 1987; Fitzpatrick et al., 1992; Gutierrez et al., 1997). However, an impermeable sub-soil may restrict pipe enlargement. In certain sodic clays with a susceptible mineralogy, dispersion and deflocculation of clays cause a swelling during infiltration, reducing the permeability within the whole soil mass (Rengasamy and Olsson, 1991). In soils with a significant clay percentage in their composition, infiltration capacity rates ($f_i$) in affected soils are very adversely affected (Emerson and Bakker, 1973; Frenkel et al., 1978; So and Aylmore, 1995;
Nelson et al., 1998). In sandy/silty soils, however, dispersion merely renders soils more erodible as a result of the loss of their only structuring agent, in which case infiltration rates are less affected, and soils will continue to pipe at depth along macropores (Faulkner et al., 2000).

At the surface, dispersive soils can slake and seal at very low rainfall intensities. This effect is usually held responsible for the development of ‘hard-set’ crusts (Mualem and Assouline, 1992; Singer and Le Bissonnais, 1998), which further restrict surface infiltration (Sumner and Stewart, 1992; Robinson and Phillips, 2001). However, other work suggests that even in soils with a dispersive signature at depth, there can be a loss of sodium at the surface of these materials through time, eventually rendering the crust non-dispersive (Faulkner et al., 2000, 2003b). Torri and Bryan (1997) likened these non-dispersive crusts to a weathered ‘rind’, although they may be polygenetic, as for instance on the Tortonian marls in Tabernas (Sole-Benet et al., 1997). In the presence of a vegetation cover, surface stabilization occurs when free hydrogen ions in organic acids allow hydrogen exchange with sodium. When vegetation is not present, stabilization is usually conceptualized as occurring during leaching, when calcium replaces sodium on the exchange complex (Armstrong et al., 1998), although there is no doubt that some calcium carbonate must also be moved up and redeposited or exchanged within the crust during evaporation. Both processes are probably involved in the development of a calcic crust, but the evidence from most sites is that a ‘top-down’ model explains soil development best. For example, Lopez-Bermudez and Romero-Diaz (1989) record not only a loss of dispersive status in the topsoils on marls in SE Spain, but also a translocation of clays down-profile.

It is interesting to speculate as to the effect of these processes on the geochemistry of the immediate sub-crust zone. If infiltration is persistently reduced at depth, and we have a cracked, calcic, non-dispersive crust, it is possible to argue that infiltration remains fairly good at the surface but is deflected into a shallow sub-soil zone, which may preferentially erode. This was the inferred explanation for shallow pipes in dispersive marls in the Ebro basin, Spain, given by Benito et al. (1993), and would fit the logic of the arguments given by Torri et al. (1994) and Torri and Bryan (1997) for shallow pipe development in the biancana badlands in Tuscany. In the Tabernas badlands in Almería, which has a generally non-dispersive upper soil with little evidence of piping, Sole-Benet et al. (1997) noted that wetting during infiltration was restricted to a shallow upper soil layer. It was also noted that the crust (of various kinds in Tabernas) was relatively resistant to erosion, and that sediment was preferentially produced from micro-rills in the regolith, rather than from the surface. So it may be hypothesized that shallow sub-surface dispersion is operating even in materials that are only potentially dispersive (SAR < 3) at depth.

Layering in pipe-prone materials is commonly referred to in the literature. In Australia, pipes are commonly noted to locate at significant sub-surface textural discontinuities in so-called ‘duplex’ soils (Rooyani, 1985; Fitzpatrick et al., 1992), an effect also noted in southern Africa by Reinks et al. (2000). Our hypothesis, developed from the above literature and from field observations of micro-pipes and rills across a range of Almerian badland types, is that layering in the top horizons of dispersive marls can commonly occur by translocation of ions and clay minerals along infiltrating pathways, and that these layers play a role in the erosion of the site. Since small-scale variations in dispersive character of materials with shallow pipes and well-developed crusts have not previously been investigated, our field research was undertaken to explore these possibilities.

THE STUDY AREA

Previous work in our study area (Figure 1) described how the dispersive Triassic-Rich Unit (TRU; Mather and Stokes, 1996) of the Gochar formation which lies along the southern and eastern-central parts of the Mocatan catchment near Sorbas, in Almería, southern Spain, has developed massive pipes where hydraulic gradients allow (Faulkner et al., 2000, 2003a). Faulkner et al. (2000) described SAR values in the TRU ranging up to 400 mmol l \(^{-1}\). However, from visual inspection alone, the Messinian-Rich Unit (MRU), which overlies the TRU in the basin, appears to be far less prone to piping. In fact, the greater extent of erosion on the TRU compared to the MRU matches the lithological division on air photographs of the basin flown by the UK’s Natural Environment Research Council (NERC Airborne Remote Sensing Facility) in 1996 and 2001. In confirmation, provisional test values of SAR on the MRU parent materials found SAR values only up to 20 mmol l \(^{-1}\), a value
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Figure 1. The location of the study site on the Messinian-Rich Unit within the Barranco del Mocatan, near Sorbas, Almería, Southern Spain.

Close to the boundary of Rengasamy et al.'s (1984) class 2a = 'potentially dispersive'. Nevertheless, there is evidence in places of shallow pipe development in the MRU sub-crust, especially around gully heads, which frequently demonstrate a ‘hammer-head’ form (Figure 2). Thus, simple visual inspection alone suggests that small-scale variations in dispersivity are involved in the physical erosion of the landscape, even on marls with only borderline dispersivity.

AIMS

This study explores the hypothesis that even at a small scale, translocation of mobile cations (particularly sodium) can occur along inferred hydraulic gradients in potentially dispersive materials. Data will be explored to indicate how far this translocation leads not only to small-scale crust/sub-crust differentiation of the soil (affecting erosional sensitivity), but also determines the location and subsequent enlargement of micropipes and rills.
Figure 2. Photo-mosaic of the 3 m by 2 m gully head before excavation (there is some distortion due to non-vertical alignment of camera). Boxed area on main photo is shown enlarged on right-hand side

APPROACH AND METHODS

In an initial pilot stage of this investigation, the micromorphology of the MRU was sampled to a depth of 30 cm in order to determine the type and depth of hydraulic activity. During the second period of field investigation, a small gully head (2 m by 3 m) displaying shallow sub-surface pipes was selected adjacent to the original micromorphological sample pit, and topographically surveyed on a grid basis, allowing the production of a digital elevation model (DEM). For each soil layer separately identified in the field, data from the laboratory examination of the samples were plotted on the DEM and examined for spatial patterns in particle size (micrometres), SAR (in mmol L$^{-1}$), pH, and EC (mhos cm$^{-1}$), especially in relation to the inferred hydraulic pathways towards the gully bed.
Micromorphology and hydraulic conductivity of the MRU

Three resin-impregnated sub-soil samples were explored for general porosity/depth variations, and for gypsum crystals and microspar in the pores, which would supply evidence of up-mobility or down-mobility of ions in the material. Given the impossibility of establishing very small scale vertical variations in sub-surface hydraulic conductivity, and in order to have some indication of how porosity may be affecting water movement within this material, a pit was dug away from the proposed sample site and material sampled and subjected to micromorphological examination to a depth of 30 cm. Three samples were collected: 0–10, 10–20 and 20–30 cm. Because of the hard yet friable nature of the soil, samples were collected as blocks (c. 10 × 6 × 6 cm), wrapped in plastic and then masking tape. The samples were impregnated with resin and then thin-sectioned to produce large-format slides (10 × 6 cm). Unfortunately, the 0–10 cm sample was disturbed during preparation. However, although the original pore and passage orientations and sizes of that sample were destroyed, the general positions of its concretions and lithoclasts were unaffected and the fabric of undisturbed peds could still be examined. The samples were examined for porosity under a petrological microscope, using incident, transmitted and crossed-polar light (Figure 3). The micromorphology nomenclature of Fitzpatrick (1993) was used.

Inferred hydraulic gradients

To consider the potential spatial variation in hydraulic gradients, a 2 m by 3 m grid was established across the single bifurcating gully head shown in Figure 4. Elevations were levelled across this grid on horizontal transect lines 0.5 m apart, proceeding every 20 cm for height data (every 40 cm for material sampling). A DEM was then produced from these data in the ArcView 3.1 Geographical Information System (GIS), using the
Spatial Analyst extension. Subsequent processing, overlay and three-dimensional views were undertaken in ERDAS Imagine 8.4. Hydraulic gradients were inferred from this map using both the micromorphological information and contour spacing.

Field sampling the dispersive character of the gully head

In order to examine and sample small-scale variations in the geochemical components of the crust and sub-crustal zone around the gully head feature more intensively, a grid was progressively excavated from the downslope end across horizontal transects (Figure 5). Field samples were collected at three to five depths every 40 cm across each of the seven transects (48 locations). Since the 0–10 cm micromorphological sample had been disturbed during thin-section preparation, observations on the microstructure of the crust and sub-crust were not possible. Since the micromorphological data also suggested that material was very impermeable below 10 cm, depth sampling for particle size and geochemistry in the field concentrated on the more friable top 10 cm. Samples of 10–20 g were extracted from the visible crust (c1, 0–2 cm), from the friable immediate subcrust material (d1, 3–5 cm), and from the sub-crustal non-friable zone beneath (d2, 5–7 cm). Where present, any further horizons were sampled either on the basis of textural variation or colour (d3 and d4 often undifferentiated, 7–10 cm). Samples were retained in polythene bags for subsequent laboratory analyses.

Laboratory analyses: site geochemistry and particle size determination

For water-soluble cation determination, samples were prepared as in Faulkner et al. (2001). Sample size was again kept to 5 g soil, which was pre-weighed, shaken, and centrifuged. Calcium and magnesium concentrations
were determined by flame absorption spectrometry (adding lanthanum solution for calcium determinations as advised in Hendershot et al., 1993). Potassium and sodium concentrations were determined by flame emission spectrometry. Soil concentrations of cations were expressed in milligrams cation per 100 g of soil. Having extracted cations using a 1:10 soil:water dilution, sodium adsorption ratio (SAR) was calculated using:

$$\text{SAR} = \frac{[\text{Na}]}{([\text{Ca} + \text{Mg}]/2)^{0.5}}$$

(1)

cations normally as mmol l$^{-1}$.

We note here that there are some difficulties with comparability between the SAR values derived from a saturated paste method, and those derived using 1:5 and 1:10 dilutions respectively. The convergence between our methodology and the more conventional use of a saturation paste extract for SAR was consequently explored in a separate experiment (Faulkner et al., 2001). Although different absolute values of cation concentrations were found in the saturation paste extract when compared to the 1:10 soil:water extraction method, when the values for both experiments were converted back to a concentration in the original soil, convergent SAR predictions were generated, partly because SAR is a ratio of concentrations. Using dilutions of 1:10 produces a more accurate replication of cation concentrations, so in general this method was retained. Whilst undertaking the cation analyses in the laboratory, the pH of the soil/water mix was determined using standard protocols (Carter, 1993).

For particle size determination, a dried homogenized 10 g sample, previously having passed a 2 mm test sieve, was placed in a large glass jar, brushing residual dust from the plastic bags in which they were stored. After rotating the jar a minimum of 20 times, a small sample was extracted from the bottle and subjected to laser diffraction analysis using the method as developed in Buurman et al. (1997). Electrical conductivity (EC, mmhos cm$^{-1}$) of each sample was calculated using methods discussed in Carter (1993).

**Data analysis and error minimization**

Using topographic data, a DEM was created using the ArcView 3.1 Geographical Information System with the Spatial Analyst extension, which allows isolines (contours) and flowlines to be constructed. Subsequent analysis involved exploring patterns of SAR (mmol l$^{-1}$), EC (mmhos cm$^{-1}$), mean and sorting of particle size distributions (micrometres), and pH and sediment particle size across each layer, using values from the
48 sampled points. This was completed in ERDAS Imagine 8·4, allowing the creation of overlays of these parameters as three-dimensional views. These spatial patterns were explored for convergence with hydraulic gradients inferred from the topographic DEM. Next, we examined whether crust, sub-crust and parent material (i.e. each layer, $c_r$, $d_1$ to $d_4$) were significantly different in terms of EC, SAR and pH across the site, using a parametric difference test (two-tailed).

Finally, the SAR/EC and particle size/SAR plots and pH/SAR plots (the dispersivity ‘signatures’) of crust, sub-crust and parent material were examined. These plots were developed in a previous investigation as tools for morphological diagnosis in dispersive materials (Faulkner et al., 2000). In that study, these transformed site geochemical relationships discriminated between three contrasting badland morphologies in Almería: the SAR/EC signature was used to characterize dispersive state; the SAR/particle size relationship to characterize swelling and $f_c$ reduction potential of layer material; and the SAR/pH plot to characterize the buffering properties of material samples. In the present study, these signatures are used to identify how far the layers ($c_r$, $d_1$ to $d_4$) are behaving separately in terms of critical differences in the same key functions in ways that could affect the subsequent physical erosion of the site.

The total site variations in particle size and in water-soluble cation concentrations were found on pilot tests to be within a narrow range. To ensure that experimental errors associated with the laboratory analyses would be of the lowest possible order of magnitude, laboratory analyses for water-soluble cation concentrations and textural class determination using laser diffraction analysis were undertaken in triplicate. The best estimate for all parameters was assumed to be an average of the two most convergent values (defining convergent error as an error less than 10 per cent of the total within-test variability). Where no two such values could be found, tests were repeated. Additionally, in an attempt to reduce unintended operator bias and machine ‘drift’, all laboratory analyses were undertaken ‘blind’, i.e. samples were allocated to dummy labels by a third party before tests were undertaken.

RESULTS

Layer differentiation

Student’s $t$-tests conducted on the SAR and EC data sub-sets (transformed values to normalize) demonstrate that the layer $d_1$ has a significantly higher EC and SAR than the crust, but differed only at the 0·01 probability level from the sub-soils. In terms of pH, the crust and layer $d_1$ were significantly more acidic than the subsoil layers $d_2$ to $d_4$. Exploring the mean particle size data, we found that the crust was significantly siltier than the lower layers, but these lower layers were not further differentiated by particle size (Table I). Particle sorting was undifferentiated by layer.

Micromorphology of the pilot sample of the MRU

The micromorphological information for the MRU is summarized on Figure 3. Three distinct pedogenic process domains can be identified. Firstly, below 25 cm the fine-grained dense sub-zone displays a massive structure and is relatively impermeable, apart from along hairline fissures associated with fine roots. There are no signs of repetitive wetting and drying in this zone. Secondly, immediately above this dense sub-zone, a zone of angular blocky and wedge structures is apparent (13–25 cm). This zone appears to undergo periodic wetting and drying, and possibly experiences high pore-water pressures, leading to slippage. The middle of the zone (17–22 cm) shows some evidence for enhanced precipitation of calcite, and the top of the zone (13–27 cm) shows signs of calcrete dissolution.

The top 13 cm of the profile appears polygenetic: pedogenic processes dominate, but it is not possible to rule out inputs from colluvial processes and residual weathering. The pedogenic processes involve repetitive wetting and drying, with indications of gas release, via alveolar pores, between 13 cm and 5 cm. There is some equivocal suggestion from calcrete concretions and gypsum ($\text{CaSO}_4$) microspar in the pores that the top 5 cm may experience precipitation of $\text{CaCO}_3$ from evaporating soil water; however, little further could be inferred from this disaggregated sample. The apparent high porosity of the top 10 cm of the soil suggests that the most important hydraulic activity is restricted to this depth, or even shallower.
## Patterns of SAR and particle size across the gully head in relation to hydraulic gradient

By drawing flowline widths proportional to topographic gradient, the hydraulic gradient intensity around the gully head can be suggested (Figure 4a and b). From this interpretation, hydraulic gradients increase towards the gully bed during rainfall, and as the micromorphological data showed that the top layers of the soil are substantially more porous, throughflow is inferentially focused in the shallow sub-surface along these gradients. When the SAR data are plotted by layers on the same grid, the top two layers display a strong relationship with these inferred hydraulic gradients (Figure 6). In layer \(d_1\), dispersive ‘hotspots’ appear to have developed by translocation of sodium, corresponding to the most incised part of the small gully. Thus, dispersion is at its highest where the hydraulic gradient is also greatest.

The process of translocation of ions appears to result in the development of some textural layering, as a slightly siltier crust (Figure 7). However, patterns of sediment size do not correlate with inferred hydraulic gradients (nor does sediment sorting – not shown); nor do systematic patterns of either SAR or particle size occur in the subsoil layers \(d_2\) to \(d_4\). This is what would be expected intuitively in an undifferentiated soil below the level of principal throughflow activity. Given that the clay fraction increases slightly even within the shallow zone sampled here, the layer of principal throughflow activity in these relatively impermeable materials may be very shallow indeed, i.e. within \(d_1\).

### Dispersivity ‘signatures’ for differentiated soil layers

Although parameter variability across a single site like this is inevitably restricted, the \(t\)-tests show several layers to be distinguishable simply on a single parameter basis alone (Table I). This justified the use of the SAR/EC and particle size/SAR plots and pH/SAR plots to characterize differences between the four layers identified within the gully head. On Figures 8 to 10, these signatures have been separately explored for each layer, and correlation tests performed with data transformed as required (\(p\) values for these tests are in Table II).

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**Table I. Student’s \(t\)-tests exploring significance levels of difference between soil layers across the gully head**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Untransformed</th>
<th>Transformed</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>... is crust diff from (d_1)?</td>
<td>0.000002 (&lt;0.001)</td>
<td>0.000000 (&lt;0.001)</td>
</tr>
<tr>
<td>... is (d_1) diff from (d_2)?</td>
<td>0.000990 (&lt;0.001)</td>
<td>0.817572 no diff</td>
</tr>
<tr>
<td>... is (d_2) diff from (d_3 &amp; d_4)?</td>
<td>0.223699 no diff</td>
<td>0.307830 no diff</td>
</tr>
<tr>
<td>(SAR of layer (d_1) exceeds that of the crust)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>... is crust diff from (d_1)?</td>
<td>0.112073 no diff</td>
<td></td>
</tr>
<tr>
<td>... is (d_1) diff from (d_2)?</td>
<td>0.039498 (&lt;0.05)</td>
<td></td>
</tr>
<tr>
<td>... is (d_2) diff from (d_3 &amp; d_4)?</td>
<td>0.006495 (&lt;0.01)</td>
<td></td>
</tr>
<tr>
<td>... are crust &amp; (d_1) diff?</td>
<td>0.000004 (&lt;0.001)</td>
<td></td>
</tr>
<tr>
<td>(crust and (d_1) are more acid than (d_2) to (d_4))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>... is crust diff from (d_1)?</td>
<td>0.000019 (&lt;0.001)</td>
<td>0.000001 (&lt;0.001)</td>
</tr>
<tr>
<td>... is (d_1) diff from (d_2)?</td>
<td>0.000065 (&lt;0.001)</td>
<td>0.004448 (&lt;0.01)</td>
</tr>
<tr>
<td>... is (d_2) diff from (d_3 &amp; d_4)?</td>
<td>0.310360 no diff</td>
<td>0.847480 no diff</td>
</tr>
<tr>
<td>(conductivity of layer (d_1) exceeds that of the crust)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particle size ((\mu)m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>... is crust diff from (d_1)?</td>
<td>0.000000 (&lt;0.001)</td>
<td></td>
</tr>
<tr>
<td>... is (d_1) diff from (d_2)?</td>
<td>0.376769 no diff</td>
<td></td>
</tr>
<tr>
<td>... is (d_2) diff from (d_3 &amp; d_4)?</td>
<td>0.942547 no diff</td>
<td></td>
</tr>
<tr>
<td>(crust is coarser than (d_1))</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 6. Isoline distributions of SAR (in mmol l\(^{-1}\)) of soil sampled at indicated points (shown as spots) across the gully head. Data for samples located in the crust (c\(_r\)), and at three sub-surface depths d\(_1\) to d\(_3\) are shown separately.
Figure 7. Isoline distributions of particle size (in micrometres) of the same samples as in Figure 6
The SAR/EC ‘signatures’ for each layer \( c_r \) through to \( d_{3/4} \) (Figure 8) show the subsoil layers (\( d_2 \) to \( d_{3/4} \)) are only weakly dispersive, being largely undifferentiated by this function. The crust layer (\( c_r \)) is distinctive but still largely non-dispersive. However, layer \( d_1 \) has a contrasting dispersive signature, with most SAR and EC values plotting in Rengasamy’s (1984) class I = ‘dispersive’ domain. Taking the SAR/particle size ‘signatures’ for each layer (Figure 9), SAR is shown to have a weak inverse relationship to particle size for the top two layers, whereas the lower layers are again largely undifferentiated. Finally, taking the pH of the soil mix as a measure of the buffered state (Faulkner et al., 2000), the pH/SAR relationship was also plotted (Figure 10). There is only very slight evidence of effective buffering on the crustal layer, and none in the other layers.

DISCUSSION

These results show that the crust layer (\( c_r \)) of the MRU is mostly non-dispersive, paralleling findings from other field sites in Almería (Lopez-Bermudez and Romero-Diaz, 1989; Faulkner et al., 2000). Since the relative abundance of sodium in the sub-crust layer \( d_1 \) is unlikely to be sourced from the parent material, it is inferred that calcium replaces sodium in the crust during leaching, leaving a calcic crust, and a sub-crust that is sodic, and prone to subsequent pipe enlargement.

As was the case in previous investigations using these signatures, the association between SAR and the increased clay fractions in the lower layers (Figure 9) usefully links SAR to the changes in permeability down-profile. As the clay fraction becomes more important down-profile, so the sodium on the exchange complex can have more of a physical effect, by enhancing clay swelling. This physical process is fundamental to geomorphic activity, but requires not so much a highly sodic soil but a sodic, clay-rich soil (So and Aylmore, 1995). Given the relatively high infiltration rates assumed to occur on the silty crust surface in the study area, our results suggest that throughflow will be deflected by this sub-surface swelling into the relatively silty, but dispersive layer \( d_1 \) (suggested in a schematic way on Figure 11). Being somewhat less clay-rich, the swelling of the clay fraction in layer \( d_1 \) does not render it impermeable, rather (as it loses its only structuring agent), it is rendered vulnerable to erosion. Previous research has shown how the combined influence of high relief and lack of significant clay content in the TRU has allowed it to develop a more substantial three-dimensional sub-surface pipe network (Faulkner et al., 2000). This argument also supports the inference that massive pipes are not present in the MRU because less infiltration penetrates to depth. Not only are macropores less frequent, but also any water that does infiltrate causes sub-surface swelling in layers \( d_2 \) to \( d_{3/4} \).
Figure 8. The log/log relationships between EC (in mmhos cm$^{-1}$) and SAR (in mmol l$^{-1}$) of the crust ($c_r$) and of the three subsurface layers $d_1$ to $d_{3/4}$. Pearson’s correlation coefficient ($r$) shown on graph face (see Table II)
Figure 9. The log/normal relationships between particle size (micrometres) and SAR (in mmol l\(^{-1}\)) of the crust (cr), and of the three subsurface layers \(d_1\) to \(d_{3/4}\). Pearson’s correlation coefficient \((r)\) shown on graph face (see Table II).

Figure 10. The log/normal ‘buffering’ relationship between pH and SAR (in mmol l\(^{-1}\)), of the crust (cr), and of the three subsurface layers \(d_1\) to \(d_{3/4}\). Pearson’s correlation coefficient \((r)\) shown on graph face (see Table II).
The existence of calcite microspar developing along pores in these materials (Figure 3) suggests that upward mobilization of calcite plays a role in the crust development of the MRU, at least between rainfall events. This argues for a ‘bottom-up’ model of site chemical mobilization driven by evaporation, in which calcium carbonate is moved up and redeposited or exchanged within the crust during evaporation. Whilst both processes are probably involved in the development of a calcic crust, nevertheless the data presented here suggest that a predominantly ‘top-down’ model is needed to explain the development of shallow pipe forms at preferential depths in these materials. We have already argued from the particle size data that throughflow must be preferentially occurring in layer $d_1$. But layer $d_1$ is a dispersive layer within a lithological unit which itself is much less dispersive (Figure 8). Also, most of the crust samples tested for this site mapped within Rengasamy’s class $2a$ = ‘potentially dispersive’ domain, yet layer $d_1$ has ‘hot spots’ of much higher dispersivity. During rainfall events, the strong shallow sub-surface hydraulic gradients described in the previous paragraph must force chemical transfer of mobile ions towards the lowest topographic positions in the gully head, within layer $d_1$. This is confirmed by the finding that the pattern of SAR ‘hot spots’ in the $d_1$ samples was not random, but correlated strongly with hydraulic gradients. It cannot be a coincidence that this topographic ‘low’ is the preferential location of shallow sub-surface pipe development.

Limitations: inferences of process from material properties

It has been recognized for some time that the parameter SAR, in combination with the EC of the soil water, is a good indicator of soil dispersion, and that the ability of the sodium to render the soil dispersive in water will automatically render the material more sensitive to erosion (Gerits et al., 1987). However, it is emphasized here that because the SAR of the soil/water solution will be very variable during storms (as suggested by Torri et al., 1987), the interplay between SAR of soil/water solution and the dispersive status of the soils in these narrowly defined layers may be more temporally complex that this present spatial study has suggested. Nevertheless, it is implied here that the translocation of sodium that we have documented must be important in the
spatial variability of the sensitivity of materials to erosion, and from this perspective, it is possible to infer that the patterns described can give insight into rill initiation mechanisms.

**Rill initiation**

The three-dimensional patterns displayed on Figures 8, 9 and 10 have allowed us to infer a non-random variability in material sensitivity with topography that we believe can be used to explain the development of a certain kind of crusted rill. Figure 11 shows how secondary hydrological translocation of mobile cations (specifically sodium in this study) occurs along infiltrating pathways into the gully bed. The geochemical erosional sensitivity of layer $d_1$ in these ‘hot spots’ is a consequence of these hydraulic and geochemical processes being focused on this layer for much of the year, certainly during the most significant rainfall events. The erosional sensitivity of the landscape is therefore very spatially variable, creating a kind of antecedent sensitivity for the next time rainfall occurs. Since the erosional sensitivity is in a shallow sub-surface layer and at its peak in topographic ‘lows’, the action of hydraulic processes that already perturbate the stream power function within hollows and gully head locations is reinforced here (Kirkby and Bull, 2000). This possibility can be used to explain the over-sized character of rill cross-sections in dispersive materials right from their earliest expression.

In fact, field evidence of microscale bridges on rill long-profiles is often suggestive of a ‘pipe-roof-collapse’ origin, as are other micro- and macrolandform characteristics (i.e. rill discontinuity; bridges; steep headwalls; and rills with excessively high depth-to-width ratios). Figure 12 illustrates a rill on an agricultural field of a type commonly identified in southern Spain. Given the wide presence of sodic marls in SE Spain, the rill’s micro-morphology suggests that there may be many situations outside the study area where rills initiate after infiltration, starting as shallow sub-surface micropipes beneath a coarse, relatively permeable, non-dispersive...
crust. The implication for rill initiation models is that in some circumstances it may be inappropriate to concentrate modelling effort entirely on an infiltration excess algorithm.

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