THE DEVELOPMENT OF HIGH PLASTICITY CLAY SOILS THROUGH WEATHERING OF DEVONIAN SLATES IN SOUTH DEVON

A. C. CATTELL

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Clay-rich subsoils are developed from Devonian slates across south Devon. Weathering of the slate causes a progressive disaggregation to silty clay, with little change in the clay mineralogy. Although the clay size fraction (and hence plasticity) of individual soil samples varies with the degree of breakdown of slate clasts, the plasticity of completely weathered material is controlled by the mineralogy of the parent slate. Soils on Lower Devonian slates almost all have low to intermediate plasticity, those developed on Upper Devonian slates have intermediate to high plasticity, whilst very high plasticities soils only occur on Middle Devonian slates. These types are geographically widespread: Upper Devonian purple slates in Plymouth and Newton Abbot produce indistinguishable soils 40 km apart, and pale yellow high plasticity soils are developed on Middle Devonian slates in Torquay, Dartington and Plympton. Previous work has shown that most slates, including Middle Devonian, have the clay assemblage illite + chlorite +/- kaolinite. New data presented here show that the highest plasticity soils are restricted to particular Middle Devonian slates which have low Fe and Mg and high Al, and consequently have the assemblage illite + kaolinite. The non-chloritic slate unit is widespread but its extent remains to be determined.

A.C.Cattell, Rodney Broom Associates, 15 Courtenay Park, Newton Abbot, Devon, TQ12 2HD

INTRODUCTION

There has been much recent research into the geotechnical properties of the highly plastic sedimentary clays of Mesozoic and Tertiary age which occur in south-east England. In particular, recent hot dry summers have emphasised the high shrinkage potential of these clays and have led to widespread damage to structures with shallow foundations. Published technical advice on dealing with foundation problems on plastic clays is based on these sedimentary clays (BRE, 240: 1993).

In Devon, west of the River Exe, sedimentary clays of this type occur in the Tertiary Bovey Formation, and foundation problems associated with them occur where the clays are not mantled by colluvial material, for example in the Liverton area in the Bovey Basin. However, these clays are of restricted extent. Much more widespread are plastic clay soils formed on the Devonian and Carboniferous slates and shales. These are produced by weathering of the bedrock, and form a mantle often only a metre or so in thickness, underlain by non-plastic weathered rock. This contrasts with the Mesozoic and Tertiary clays of south-east England, where the plastic clay can be tens of metres thick.

This contribution is based on data collected during engineering site investigations in south Devon. The nature of the work means that the data are much more extensive in the urban areas than elsewhere. Also, there is a probable bias towards sites on high plasticity clays, since these give rise to foundation problems and hence require investigation. This contribution looks at the development of high plasticity clays on the Devonian slates; similar clays are developed on the Crackington Formation shales of Upper Carboniferous age (Grainger and Harris, 1986).

GEOLOGY

The study area consists of the Devonian outcrop south of the Dartmoor Granite, and north of the Start Complex. The sequence consists predominantly of argillaceous sediments, which are interbedded with arenaceous sediments, limestones, volcanic rocks and some intrusive bodies. The geology of the area is described in more detail by Selwood and Durrance (1982).

The Geological Survey sheets covering the area are of very different vintages, and the sub-division of the Devonian slates varies from sheet to sheet. To be consistent across the area, in this contribution the slate bedrock is divided simply into Lower, Middle and Upper Devonian, based on the mapping divisions used on the turn-of-the-century sheets and also in the more recent 1:250 000 compilations. Dartmouth Slate, Meadfoot Beds and Staddon Grits are combined into a single Lower Devonian unit because there are too few data from these rocks to warrant subdivision.

Mudrocks occur throughout the succession. The Lower Devonian (Dartmouth Group, Meadfoot Group) consists of mudrocks interbedded with varying proportions of more arenaceous sediments, and some volcanic rocks. The Middle Devonian sequence contains a considerable thickness of mudrocks, known as the Nordon Slate in the east of the area, which contain limestones and volcanic complexes. The Upper Devonian contains a variety of mudrocks (the Whiteway, Gurrington, Rora and Kate Brook Slates in the east), which are locally interbedded with volcanic rocks, and deposition of mudrocks continued into the early Carboniferous. The Upper Devonian mudrocks include a distinctive purple (locally purple and green) variant; which often forms a mappable unit separate from the surrounding grey slates (e.g. Selwood *et al.,* 1981; British Geological Survey, 1997).

All the strata were deformed during the Variscan orogeny. This led to the development of east-west trending folds of various amplitudes and orientations, and the dislocation of the original stratigraphy by northward displacement along low-angle southerly-dipping thrusts. The result is that the Devonian strata are now divided into a series of east-west trending zones, with a general increase in age of the sediments toward the south.

Regional metamorphism accompanied the deformation, producing a well developed cleavage in the mudrocks, which are best described as slates. The original detrital clay mineral assemblage in the mudrocks has been transformed to a low-grade regional metamorphic assemblage of illite +/- chlorite +/kaolinite. Studies of illite and chlorite crystallinity show that the metamorphic grade of the slates in the area varies from the uppermost part of the diagenetic zone, through the anchizone to the lowermost part of the epizone (Warr, 1995). The diagenetic zone is restricted to a few localities in the north of the area, and the epizone to a single locality in the south.

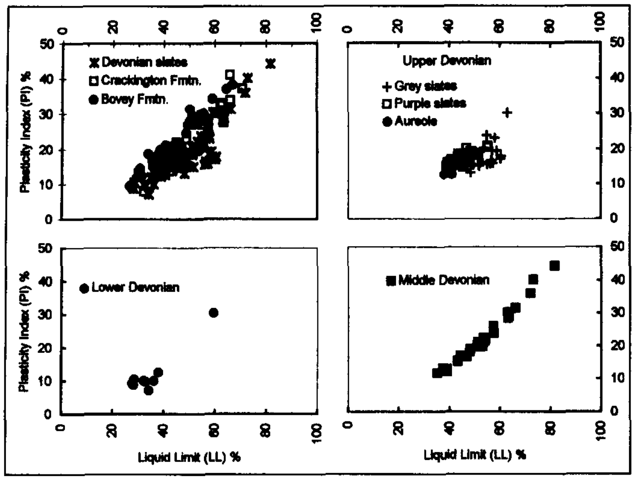

Figure 1. Plasticity of soils developed on Devonian slates in south Devon. (a) Comparison with other local high plasticity soils; the similarity with the Crackington Formation reflects their similar illite-dominated mineralogy compared with the kaolinitic Bovey Formation clays. (b) soils on Lower Devonian slates, (c) soils on Middle Devonian slates, (d) soils on Upper Devonian slates.

All the data presented here are from sites where the slate bedrock is shown by the reconnaisance mapping of Warr (1995) to be at anchizone grade. Regional metamorphism was followed by intrusion of the Dartmoor granite, with the development of a narrow aureole of contact metamorphic rocks: one site in this study lies at the edge of the aureole near Hemerdon.

SOILS

The slates of the region have been exposed to weathering at various times since their formation (e.g. during the Permian and again in the early Tertiary), and some soil was formed at these times. However, except in very exceptional circumstances the weathered material formed at these times has been stripped off by subsequent erosion, probably during periglacial conditions in the Pleistocene (c.f. Grainger, 1984, Findley *et al.,* 1984). The current subsoil was generated during late Pleistocene and Holocene times (Findley *et al.,* 1984).

Although the materials in the soils developed on the slates are of local origin (shown by the ubiquitous presence of clasts of local bedrock), there is abundant evidence of downslope movement of material. Much of this was active in past colder climates, but there is evidence of creep and some local landslip under current conditions. Above the more indurated units - such as the Dartmouth Slates - a stony head is developed on sloping sites, and clay-rich soils are rare. On the more easily weathered Middle and Upper Devonian slates, thick sequences of clay-rich soil are developed through accumulation on lower hillslopes. In the Plymouth area these deposits can be 8 m or more in thickness. Such thick soils are homogeneous, with no evidence of layering or progressive change with depth.

On steeper sections of the concave-convex slopes typical of the area, discrete slip planes may be present separating silty clay from relatively unweathered slate beneath. The slips are normally inactive but their presence is indicated by a narrow layer of softer wetter clay at the base of the soil profile. The profiles on the steeper slopes are similar to those described by Grainger and Harris (1986) on the Crackington Formation, except for the lack of the interbedded sandstones and consequent absence of sandstone cobbles in the soils.

Residual clay-rich soils are developed on gently sloping upper

sample	13524R	14034R	11366	14183	14146	14034S	13524S	SW4	SW6
material	rock	rock	soil	soil	soil	soil	soil	rock	rock
bedrock age	Middle Devonian	Upper Devonian	Middle Devonian	Middle Devonian	Upper Devonian	Upper Devonian	Middle Devonian	Middle Devonian	Upper Devonian
location	SX 924 610	SX 493 556	SX 789 617	SX 553 557	SX 845 721	SX 493 556	SX 924 610	SS 199 031	SS 047 862
SiO2	61.59	57.01	63.7	50.48	55.24	53.53	57.18	55.92	56.16
Al2O3	24.29	20.05	21.82	25.07	23.27	19.66	25.49	22.4	21.22
TiO2	1.09	0.82	1.3	1.04	0.98	0.83	1.16	0.86	0.9
Fe2O3	3.3	8.03	3.07	9.09	8.53	8.17	3.81	8.32	9.09
MgO	0.55	2.97	0.48	0.73	1.21	2.53	0.55	2.77	3.48
CaO	0.15	0.21	0.33	0.15	0.32	2.09	0.26	0.24	0.22
Na2O	0.26	0.84	0.86	0.3	0.78	1.19	0.53	0.8	0.53
K2O	5.05	4	3.44	4.86	3.66	3.94	5.23	4.75	4.47
P2O5	0.1	0.1	0.06	0.07	0.05	0.15	0.07	0.15	0.13
MnO	0.05	0.28	0.01	0.02	0.03	0.28	0.02	0.06	0.12
LOI	4.8	4.44	5.89	8.3	6.36	8.36	6.89	4.96	4.35
TOTAL	101.23	98.75	100.96	100.11	100.43	100.73	101.19	101.23	100.67
Clays (XRD)	ill+kaol	ill+chl	ill+kaol	ill+kaol	ill+chl	ill+chl	ill+kaol	ill+chl	musc+chl
Liquid Limit	63.2	81.8	63.1	44.2	66.1				
Plastic Limit	34.8	37.6	33	26.4	34.7				
Plasticity Index	28.4	44.2	30.1	17.8	31.4				
<0.425mm	100	79.9	91.8	71.4	100				

Table 1. Geochemical data rom soil and rock samples. SW4 and SW6 are from Warr & Rice (1993). Total iron expressed as ferric iron, oxidation ratio not determined.
Analysis by standard XRF technoques at earth Resources Centre, University of Exeter.
Plasticity data by standard engineering test methods at stunt Drilling Services, Taunton.

parts of hillslopes. The soil thickness is not usually great, and rarely exceeds 1.5 m. The lower parts of residual soil profiles often have the appearance of slate, retaining a "ghost" cleavage, but partially or completely broken down to silt- and clay- grade particles. In well exposed examples the slaty cleavage in the underlying slate can be traced up into the clay soil, clearly demonstrating the soil's residual nature. The gradational soil-rock contact is undulatory, due to the variable susceptibilty to weathering of the individual beds in the slate. Where the bedding in the slate is dipping at a moderate angle, clay soil derived from an easily-weathered layer may underlie fresh or slightly weathered slate of a more resistant layer. This relationship is clear in an excavated face, but would not be so clear in a typical site investigation borehole log.

GENERATION OF PLASTIC CLAY SOILS

The progressive weathering of slate to produce silty clay involves the gradual breakdown of gravel-sized slate fragments to their silt- and clay- sized constituent grains. Sand-size grains are rare at all stages of weathering, giving rise to bimodal particle size distributions.

The degree of weathering affects the plasticity of the soil. For engineering purposes, soils are passed through a 0.425 mm sieve prior to plasticity testing. During weathering, the proportion of soil finer than 0.425 mm increases. Significantly, the proportions of the size fractions within the <0.425 mm fraction change with weathering, mainly resulting from the break down of silt and fine-sand sized relict slate fragments into clay and silt. The result is that plasticity increases with increasing weathering, and that a large variation in plasticity is common in many soil profiles. The maximum plasticity in any one site depends both on the bedrock type (particularly its clay content) and the degree of weathering reached.

Residual soil profiles show a progressive decrease in plasticity with increasing depth, reflecting the progressive decrease in the degree of weathering. In contrast, transported profiles commonly show little or no variation in plasticity with depth.

CORRELATION OF SOIL PLASTICITY WITH BEDROCK.

Soils developed on Devonian slates show a wide range in plasticity, from low to very high. The range in, plasticity of these soils is essentially the same as that found in similar soils developed on Carboniferous shales in the region (Grainger and Harris, 1986). In contrast, the soils are distinct from the local sedimentary clays of theBovey Formation, which form a parallel trend (Figure la).

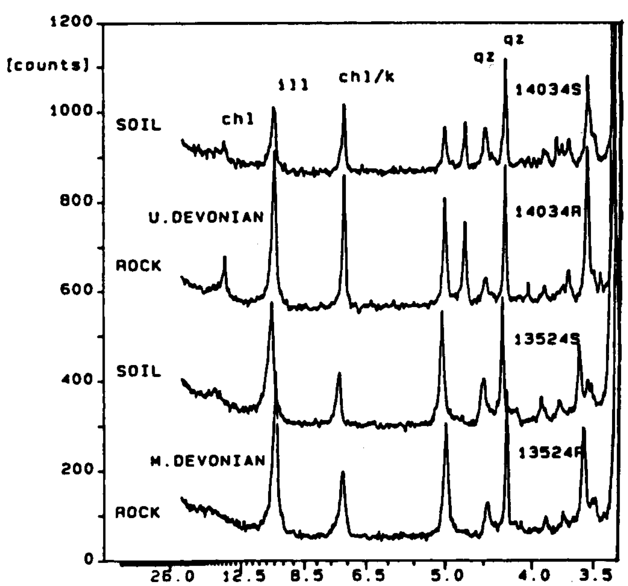

Figure 2. *X-ray diffraction spectra from soil-rock pairs.*

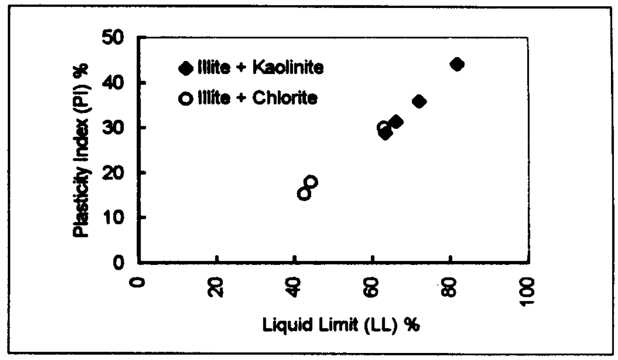

Figure 3. *Clay mineralogy compared with plasticity. In each case the sample is that with the maximum plasticity from that site. Data from this study supplemented by reinterpretation of XRD data of Hunter (1997) on samples from sites where plasticity had been determined in this study.*

There are marked differences in the properties of soils developed on the different slate bedrocks. Although the number of samples is small, the available data suggest that high plasticity soils are not commonly developed on Lower Devonian slates (Figure lb). The only sample with high plasticity is from a site in Torquay mapped as Lower Devonian (Staddon Grit) but within 50m of a faulted contact with Middle Devonian slates.

Middle Devonian slates weather to produce intermediate to very high plasticity soils, with high and often very high plasticity clays developed at most of the sites investigated (Figure 1c). A striking feature of the data is the almost perfect correlation between LL and PI ($r^2 = 0.96$). The correlation implies a common origin and by inference homogeneous source rocks along the outcrop of Middle Devonian slates from Torquay through Dartington to Plympton. Such tightly constrained trends are unusual for plasticity data (c.f. trends for other units on Figure 1).

Upper Devonian slates generate soils of intermediate to high plasticity (Figure 1d). The data form a rather diffuse cluster and do not form a well-defined trend. Subdivision into grey and purple (+/-green) variants produces distinct but overlapping 'data sets. Soils developed on the purple slates (Torpoint Formation in the Plymouth area, purple variant of the Gurrington Slate in the Newton Abbot area) have higher PI relative to LL, and also form a reasonably well-defined trend ($r^2 = 0.60$). In contrast the soils developed on grey Upper Devonian slates show no well-defined trend. The soil data imply that the grey slate bedrocks are variable, whilst the purple slates form a relatively homogeneous group. As with the Middle Devonian slates there is no evidence for variation along the outcrop: soils developed on the Upper Devonian purple slates in Plymouth are identical to those on similar rocks in Newton Abbot, some 40 km to the east. All sites sampled here are from the Whiteway and Gurrington Slates in the Newton Abbot area, or from the Saltash Formation in the urban area of Plymouth. No sites have been sampled on the Kate Brook or Rora Slates, or from the Tavy Formation to the north of Plymouth. The low PI samples which produce the scatter in the plasticity data for the grey slates are all from sites in the Plymouth-Plympton area, but there is no obvious common factor linking these sites. Too few sites have been sampled on grey slates elsewhere to be sure whether or not the low-PI type is widespread.

One site has been sampled from Upper Devonian slates just outside the mapped aureole of the Hemerdon stock of the Dartmoor Granite. The three samples of soil from this site show the lowest plasticity of any samples from Upper Devonian sites, despite the lack of macroscopic evidence of the contact metamorphism in the rock. The soils are also distinctive in having low plasticity combined with a high fines content (over 90% passing 0.425 mm sieve), other low-plasticity samples having lower fines contents. Unfortunately there are no data other than plasticity on samples from this site but it is clear that the

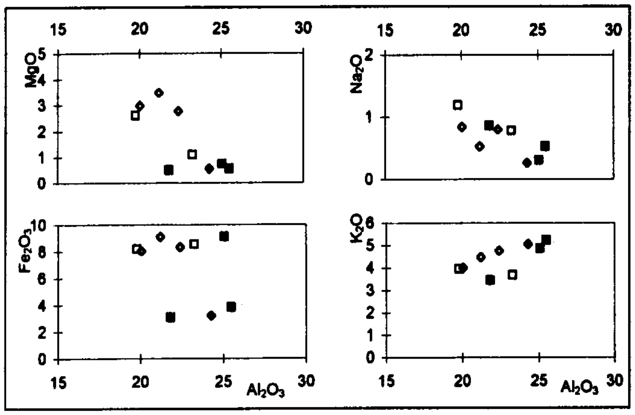

Figure 4. Chemistry of soil and rock samples, from this study and from Warr & Rice (1993). Filled symbols indicate non-chloritic samples, open symbols indicate chloritic samples. Square symbols indicate soil samples, diamond symbols indicate rock samples.

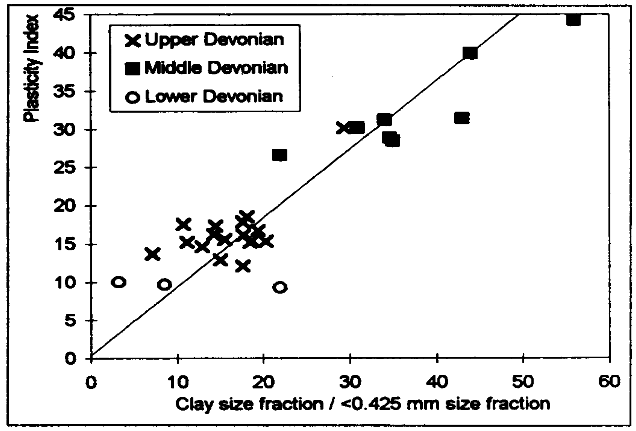

Figure 5. Activity of soils developed on Devonian Slates. Note the the clay size fraction is corrrected for the presence of particles larger than 0.429 mm, since it is the <0.425 mm fraction on which the plasticity is determined. A line of activity — 0.9 (the activity of illite) is shown for reference.

mineralogy of the slate has been affected by the metamorphism, causing a lowering of plasticity. This could result from coarsening of clay mineral grain size, or from a change in clay mineralogy. More work is required, but it is interesting to note that the effects of low grade contact metamorphism are recorded in the physical properties of the soils at a distance from the intrusion where the effects are not immediately obvious in the rock. It should be possible to map out an aureole even where outcrop is absent, by inexpensive soil testing.

CORRELATION OF SOIL PLASTICITY WITH CLAY MINERALOGY.

Seven samples, 5 of soil and 2 of slate bedrock, have been analysed by X-ray diffraction (XRD) at the Earth Resources Centre, University of Exeter. In addition, original X-ray diffraction traces from slates and overlying soils at 2 sites (Hunter, 1997) and from slates at 15 sites (Warr, 1995) have been examined. Soil plasticity data are available from the sites studied by Hunter (1997), but no information on the soils is available from the sites sampled by Warr (1995).

The clay mineralogy of the slates and overlying soils has been determined at four sites, two where high plasticity soils are developed on Middle Devonian slates, and two where moderate plasticity soils are developed on Upper Devonian slates. At all four sites, the clay mineralogy of the soils is the same as that of the underlying rock (Figure 2). The clay peaks may be slightly broader in the soils than in the underlying slate, but more careful analysis is required before any conclusion can be drawn from this. It is concluded that the clay mineralogy of the soil is inherited from the underlying slate with little modification. A similar conclusion was reached by Grainger (1984), who looked at soils developed on Crackington Formation mudrocks.

Although the sample numbers are small, the available XRD data show a clear connection between clay mineralogy and soil plasticity. At the four sites where the highest plasticity soils are developed, slate bedrock and clay soil contain the assemblage illite + kaolinite, whilst soil and slate samples from the three sites with lower plasticity soils have the assemblage illite + chlorite +? kaolinite (Figure 3). It should be noted that only the highest plasticity soil samples from each site were analysed by XRD, and it is not true to say that soils with illite + kaolinite all have high plasticity. Both chlorite-bearing and chlorite-free soils will show a wide range in plasticity, but the maximum plasticity found in chlorite-free soils (LL=82) is higher than that found in chlorite-bearing soils (LL=63). A similar division was noted by Grainger and Harris (1986) who recorded higher maximum plasticities on non-chloritic shales (LL=82) than on chloritic shales (LL=63) in the Crackington Formation to the east of Exeter. The exact match between the data from the two areas must be purely coincidental, but the similarity suggests a similar underlying control.

All Middle Devonian sites investigated here and by Hunter (1997) have the assemblage illite + kaolinite. In contrast Upper Devonian sites all have chlorite-bearing assemblages. At first sight this suggests a simple subdivision into Middle Devonian non-chloritic slates and Upper Devonian chloritic slates. However, this is not correct. The data of Warr (1995) show that illite + chlorite is the commonest assemblage in both Middle and Upper Devonian slates. Middle Devonian slates with the illite + kaolinite assemblage do occur, for example at Gerston, south of Totnes, but generally the Middle Devonian slates are chloritic (Warr, pers. comm.). The new data show the presence of a subordinate but geographically widespread unit of non-chloritic slate within the Middle Devonian. The unit was probably preferentially sampled in this study, because the high plasticity clay soils developed on it lead to foundation problems which require investigation.

GEOCHEMISTRY.

The seven samples (2 rock, 5 soil) analysed by XRD have also had their major element chemistry determined. Compositions were obtained by standard X-ray fluorescence techniques at the Earth Resources Centre, University of Exeter. Data from the same laboratory from 2 other Devonian slates, whose clay mineralogy is known, were presented by Warr and Rice (1993) and are also used here for comparison. The chemical data, together with XRD data and available plasticity test results are shown on Table 1.

Data are available from 4 samples of slate, 3 of which are chloritic. The non-chloritic slate, which contains the assemblage illite+kaolinite, is distinguished by very low Fe_2O_3 and MgO, and also shows slightly low Na_2O, slightly high K_2O and high Al_2O_3 (Figure 4). The whole-rock chemistry readily explains the different mineralogy of the non-chloritic slates and shows that the absence of chlorite is due to bulk rock composition rather than the effect of metamorphic grade. The chloritic purple slate has higher MnO than the greyish green chloritic slates, but otherwise its major element chemistry is indistinguishable.

The soils have generally similar chemistry to their parent slates and to soils developed on slates of similar mineralogy (Figure 4), although there are some anomalies whose origin is unclear (e.g. elevated CaO in sample 6, elevated Fe_2O_3 in sample 4). All soils have elevated loss-on-ignition.

The chemical data show that the non-chloritic slate unit within the Middle Devonian has a distinctive chemistry, particularly low Fe, Mg and high Al, that distinguishes it from other slates in the succession. The different chemistry must reflect a different source of detritus, but analysis of this is beyond the scope of this paper.

DISCUSSION

From the data presented above, it has been shown that the highest plasticity soils (with plasticity indices greater than 65) occur only on non-chloritic slates, whilst weathering of chloritic slates leads to less plastic soils. The most obvious explanation of this is that the non-chloritic slates are more clay-rich, and therefore on weathering give rise to more clay-rich and hence more plastic soils. In order to assess this, it is important to be clear what is meant by "clay-rich". In engineering usage clay refers to a size fraction (less than 2 μm), irrespective of the mineralogy of the grains. To avoid ambiguity this is referred to below as the clay size fraction. In contrast it is possible from chemical and mineralogical data to estimate or calculate the weight fraction of clay minerals present in a soil or rock, irrespective of whether or not the grains are bound in larger aggregates. This is referred to below as the clay mineral content. The XRD data show that apart from the clay minerals, the only significant minerals present are quartz with minor oxides and rare calcite; these minerals are non-plastic and simply dilute the effect of the plastic clay minerals.

The clay size fraction is not routinely measured in fine soils in engineering investigations, but data are available for some 20 samples of soils developed on Devonian slates in the area. The clay size fraction can be plotted against the plasticity index, and for genetically-related soils, i.e. soils with similar clay mineralogy, a good positive correlation is expected. The ratio (plasticity index / clay size fraction) is referred to as the *activity* of the soil. Soils developed on Devonian slates have activities close to 0.9 (Figure 5), which is the experimentally-determined activity of illite (Skempton, 1953). There is no detectable difference in the activity of the chloritic and non-chloritic soils. There is however a sharp distinction in the clay size fraction of the two types: on nonchloritic slates, soils have clay size fractions ranging up to maxima of 35 to 50%, whilst on chloritic slates the maxima are usually less than 25%, and do not exceed 30%.

The particle size data show that the higher maximum plasticity of the non-chloritic soils can be correlated with their greater clay size fraction; the maximum clay size fraction in soils on nonchloritic soils is typically double that of soils on chloritic slates. However, the chemical and mineralogical data show that the non-chloritic slates do not have exceptionally high clay mineral contents. It is not possible to quantify precisely the mineralogy from the available data because the oxidation state of iron is not known, but rough calculations show that the chloritic and non-chloritic slates have broadly similar clay mineral contents. The non-chloritic samples have slightly elevated illite contents but these are certainly not sufficient to explain the large difference in plasticity index and certainly do not explain the large differences in clay size fraction in the soils.

The inference is that the non-chloritic slates break down more completely to their constituent grains, whilst a significant proportion of the clay minerals in the chloritic slates remain bound in silt-size aggregates. The reason why the chloritic slates are more resistant is not known. However, it is interesting to note that recent transmission electron micrscope studies show that in the chloritic slates, chlorite and illite are interlayered in phyllosilicate stacks and do not occur as discrete grains (Warr and Nieto, in press). Whatever the cause, the presence of chlorite seems to prevent the development of the highest plasticity clay soils. As noted above, Grainger (1984) and Grainger & Harris (1986) noted similar relationships in soils developed on the shales of the Crackington Formation. These similarities suggest that the relationship may be general and applies to the development of highly plastic residual clays from very low-grade metamorphic mudrocks elsewhere.

From the limited data available, it is not clear whether the non-chlotitic slates are isolated occurences, or form part of a more widespread and potentially mappable unit similar to the non-chloritic Ashton Shale within the Crackington Formation. The alternative is that the non-chloritic slates, all analysed samples of which are kaolinite-bearing, represent slates affected by deep weathering during the Tertiary. Work is in progress to discriminate between these possibilities.

CONCLUSIONS

1. Residual clay soils inherit the clay mineralogy of their parent slate.
2. Highly plastic clay soils are locally developed on a non-chloritic slate within the Middle Devonian.
3. The presence of chlorite inhibits the development of high plasticity soils.
4. A non-chloritic, low Fe, Mg, high Al unit is present in the Middle Devonian slates in three areas across south Devon. It is not known if these are isolated occurences or represent part of a more widespread stratigraphic unit.

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