The key role of micromorphology in studies of the genesis of clay minerals and their associations in soils and its relevance to advances in the philosophy of soil science

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Abstract: Micromorphological observations from 3 different published works have been studied to aid understanding of aggregation and of colloids, both unique to soils. Saprolites in Hong Kong included ‘veins’ of different thicknesses and colours. Optical mineralogy identified them as infill from the neogenesis of clays in rock fractures. The common thicker infills resulted from weathering. Dark infill contained comminuted primary minerals whereas thin pale infill originated hydrothermally. Scanning electron microscopy (SEM) showed that the size, shape, and mineralogy of the kaolin minerals formed in infill depended on the types of cracks in the saprolites and on drying. Energy-dispersive X-ray spectroscopy analyses showed Fe and/or Mn in dark-coloured infill from comminution of primary minerals upon brecciation, or else beside pale infill in tuff, showing seasonal drying in tuff but not in granite. Pale infill gave predominantly large tubular halloysite in granite but large platy kaolinite in tuff, except that hydrothermal kaolin gave small particles. In dark infill, kaolin particles were also small and were kaolinite and halloysite mixtures. The effect of impurity Fe and Mn in constraining kaolin mineral crystallinity in infills simulates some of the effects of impure soil environments. Long-term cultivation of soils in Australia led to environmental scanning electron microscope images of large macroaggregates indicating their breakdown and loss. Transmission electron micrographs of ultrathin sections showed that macroaggregates of clay size, comprising clay minerals and oxides covering other materials, including organic matter, were predominant in virgin soil but were broken down to fine clay particles that blocked pores in cultivated soils. SEM showed a web of biological origin in long-term irrigated sandy New Zealand soil that surrounded macroaggregates but only became closely attached on drying. The nature of the macroaggregates was affected strongly by their history of drying, even during preparation for analyses. Micromorphology is especially useful for indicating the nature of aggregates in situ in soils.

Key Words: Aggregates, microaggregates, macroaggregates, aggregate stability, electron microscopy, colloids, neogenesis

1. Introduction
Micromorphology is an established sub-discipline of soil science. Its foundation probably lies in the use of hand lenses for magnifying the features of soils in the field, hence expanding the view available to the naked eye. Thin sections have been studied under optical microscopes for the understanding of soil genesis since the beginning of the 20th century (Stoops 2010), but Stoops (2010) considers that the study of micromorphology had its real start with the publication of W.L. Kubiëna’s book Micropedology in 1938.

Any study of the fine-level structures or morphology visible through microscopy, including those of non-soil materials, can be strictly characterised as micromorphology. Since the early 20th century, the scope of microscopy has advanced dramatically, mainly through the use of electron optical methods. Because the unique contribution of micromorphology to studies of soils and other natural objects comes from its ability to view these objects in situ, thereby minimising artefacts from their preparation, scanning electron microscopy (SEM) is the electron optical approach that has been used most commonly in these studies. SEM continues to be widely used in soil studies, for minerals (e.g., Churchman et al. 2010b), organic materials, and also their associations (e.g., Miltner et al. 2011). Its use with an environmental cell (as environmental scanning electron microscopy, or ESEM) means that any effects of strong drying beyond that experienced by soils in nature can be avoided during the preparation of soils for viewing. This is especially advantageous for studying biological entities in soils, as well as, potentially, for some soil aggregates (Foster 1994; Churchman et al. 2010a). Transmission electron microscopy (TEM) has also been used, especially by R.C. Foster in Australia and C. Chenu in France, to study soils using preparative techniques that leave material, in
ultrathin sections, largely physically intact for viewing (e.g., Foster & Martin 1981; Chenu 1989; Chenu & Plante 2006; Churchman et al. 2010a).

In this study, published work, largely by me and co-workers, is used to illustrate some of the uses of micromorphology at different scales to solve problems relating to the genesis of some soils and soil minerals and also to the nature of associations between soil minerals and other components in some other soils. The main use of these examples herein is to point to an important role that micromorphology may be able to play in advancing our philosophical understanding of soils. Probably the major advantage of the various micromorphological tools for the study of soils is that they can provide views of the soils in situ, as already discussed. Many methods of studying soils and their components require chemical and physical pretreatments that produce artefacts comprising materials that may have lost some of the defining characteristics that constitute soils as a unique object of study. Therefore, micromorphological studies potentially have a key role to play in understanding the unique and important characteristics of the materials we call soils.

This study is mainly concerned with the contributions that micromorphology can make to discovering the characteristics of soils that make them unique among materials for scientific study. Micromorphological studies by their very nature have also made, and continue to make, contributions to discerning important characteristics of soils. It may be argued that the most useful explanation in soils reside at the level of plant roots, biota (including microbes), and water and nutrients. Explanations at the atomic level are not of much use in soils (e.g., Churchman 2010a). Furthermore, roots, biota, and water are concerned with aggregated soil, not with crushed, disaggregated, or even dried soil. The strength of micromorphological studies is that they observe aggregated, and largely undisturbed, soil.

Hence, this study seeks to ascertain the role that micromorphology, using optical, electron-optical, and also newer techniques such as those using X-ray microscopy (e.g., Wan et al. 2007) and computer-assisted tomography (Tracy et al. 2010), may be able to play in better defining soils as a philosophical entity. The philosophical framework for the study was established by Churchman (2010a). According to Churchman’s (2010a) analysis, soils have 3 aspects that mark them as unique objects of study. These are: (i) the formation and properties of horizons, (ii) the occurrence and properties of aggregates, and (iii) the occurrence and behaviour of unique colloids. Respectively, these may be defined as the unique macro-, micro-, and nano-characteristics of soils. It is already evident from the literature that each of these has been the subjects of study by micromorphological techniques.

In the pedological context, micromorphological studies, generally at the macro-level using optical microscopy, have been carried out on different horizons of soils. The micromorphology of distinctive horizons including gypseous, spodic, mollic, takyric, and yermic, as well as the commonly named A, B, and C horizons, has been the topic of many studies (see, for example, many of the chapters in Stoops et al. (2010)). Characterisation of their micromorphological features has enhanced the understanding of their genesis and that of their constituent soils. In this study however, emphasis is given to studies of aggregates and colloids at the micro- and nano-levels, respectively.

2. Outline of the studies
The micromorphological results from 3 studies are presented here. The studies are:

1. Saprolite weathering, Hong Kong (Churchman et al. 2010b). Among micromorphological techniques, this study employed mainly optical microscopy of this section and SEM of whole (rock) samples.

2. Long-term effects of agriculture on an Alfsol soil, South Australia (Churchman et al. 2010a). This study employed the micromorphological techniques of ESEM of intact aggregates separated from soils and TEM of ultrathin sections of resin-embedded sections of whole soils.

3. Effects of irrigation on an Inceptisol, New Zealand (Churchman & Tate 1986). This study employed only SEM for micromorphology.

Most of the details of the setting of the samples and preparative techniques can be found in the references cited, but some are summarised and illustrated herein under ‘Materials’.

3. Materials
3.1. Saprolite weathering
Since the project including this study was carried out with the major objective of explaining the role played by kaolin-rich vein-like zones within saprolites on slopes in Hong Kong in causing or enhancing landslides, the study mainly focused on samples comprising these ‘veins’. The saprolites have formed within either granite or volcanic tuff as a result of weathering under a very high rainfall. It had been established that they could include either or both halloysite or kaolinite and therefore their analysis was able to add to our understanding of the conditions under which halloysite or kaolinite were formed authigenically from the products of weathering of granite or volcanic tuff. Figure 1 shows a kaolin-rich ‘vein’ within volcanic tuff on a slope in Hong Kong.

For the study, block samples of approximately 100 × 100 × 50 mm in size were collected from the saprolites at
20 sites, 10 of them from granite and 10 from volcanic tuff, and were transported to the laboratory without drying. While some sub-samples were removed from ‘vein’ and surrounding material on the blocks for SEM and other studies, the largest part of the block was impregnated with a resin following air-drying and thin sections were cut for optical microscopy. SEM was conducted with an energy dispersive X-ray (EDX) detector. Samples were coated with gold for SEM imaging and with carbon for EDX analyses.

3.2. Long-term effects of agriculture

In this study, samples of the same soil type, which had been subjected to common, and sometimes also experimentally controlled, agricultural practices over periods of time of up to approximately 120 years, were compared for the effects of these practices on the nature of the soils, and particularly on the associations between their constituents. The study was enabled by the availability of a virgin site adjacent to a recently cultivated and farmed site, also quite close to rotation and tillage trial sites located on land that had been formed for ca. 100 years. The site of the virgin soil was located within a plot of land that had been occupied by a church building from the beginning of the settlement of this region in 1869 until 1949 and which had remained fenced off and never cultivated since. The terrain is quite flat over the area comprising all sites. The area including the virgin site and the recently cultivated site, and also the location of the trial sites, are shown in an aerial photograph in Figure 2.

Generally, samples for micromorphological analyses were taken from cores removed from the soils at intervals ranging from 0.01 m at the tops of the profiles to >0.1 m at greater depths.

3.3. Effects of irrigation

The availability of 2 sites, about 8 km apart, on the same sandy soil type, where soil had been irrigated with effluent from an abattoir and kept moist for 25 years at one site while it had been irrigated with water to maintain a 20% moisture content at an irrigation research station at the other site for 30 years, enabled this study. The soils were maintained under permanent grass-clover pasture, which was grazed by sheep or cattle. There were control sites at each site and these both dried out each summer. The main object of the study had been to determine the effect of the disposal of the abattoir effluent upon aggregation in the soil, and the inclusion of the soil which had been irrigated with water alone for a similar period of time was aimed to enable the separation of the effects of water alone in the abattoir effluent from that of the water inevitably added along with this effluent. SEM was carried out on 3.4-2.0 mm aggregates separated from the soils by wet sieving. The aggregates were examined by SEM both before air-drying and after freeze-drying, and also after air-drying.

4. Results and interpretations

4.1. Saprolite weathering

While optical microscopy was carried out on both matrix and ‘vein’ material, the most useful information was obtained from the latter. Nonetheless, it was observed that kaolin alteration was ubiquitous and extensive throughout the host rocks studied. In saprolites from both granite and volcanic tuff, feldspars showed the greatest degree of alteration. Alteration of biotite and sometimes also of muscovite was observed in the matrix of the saprolite, although some muscovite remained unaltered. Quartz appeared to be unaltered throughout.
The ‘veins’ varied in colour from white through pink, shades of yellow, and brown, and, in some cases, were black. Their colours have been identified more objectively using the Munsell scheme (see Churchman et al. 2010b). Even so, they could be separated into pale or dark. The textures also varied, ranging from clayey to sandy silt. Pale veins were either clay or silty clay in texture, while dark veins covered a wider range, including the coarser grades of sandy, silty clay, and sandy silt. Veins also varied in thickness or width between samples, but were generally >10 mm at their thickest in any one sample, although some were as thick as 55 mm. They also varied in thickness within samples, as seen in Figures 3-7. In 2 samples, both in saprolite from tuff at the FNS (Fei Ngo Shan) locality, the white veins were notably narrow; they were always narrower than 5 mm. A further point of distinction between the veins in these 2 samples and those from all other samples was that those in FNS occurred as broad networks of intersecting veinlets, characterised as ‘box-work’, in stark contrast to each of the veins in all other 18 samples, which were in a parallel or sub-parallel alignment with other veins where they occurred in the same sample. This distinction pointed to a genetic difference that was explored (see below) between the origin of the veins in the FNS samples and those at all other sites.

Overall, the nature of the kaolin clay minerals – and other minerals – occurring in the veins appeared to have a direct association with the thickness and colour of the veins, although thick white veins differed also according to their lithologies, whether granitic or tuffaceous. Samples were therefore separated into 4 types according to the thickness and colour of their included veins. These types and their optical analyses, as well as their clay mineralogies, from SEM were as follows:

1. Thick white veins (a) in granite: These are represented in Figure 3 by sample TKL2 from Tiu Keng Leng.
   (b) in tuff: These are represented in Figure 4 by sample SSR DS1 from Sai Sha Road.
2. Thin white veins. These are represented in Figure 5 by sample FNS N from Fei Ngo Shan.
3. Thick brown veins. These are represented in Figure 6 by sample TKL3 from Tiu Keng Leng.
4. Thick black veins. These are represented in Figure 7 by sample STC S1A from Sha Tin College.

The major features of the images and analyses in Figures 3-7 and the others of similar types that they represent (Churchman et al. 2010b) that require explanation include:

1. The reason why veins are either 'white' (or other light colours such as pink) or dark, including shades of brown, yellow, red, or black.
2. The reason for the different sizes and shapes of clay-sized particles in SEM.
3. The reason why the veins in samples from one location (FNS) are much thinner than the veins in samples from other locations and that they have a unique random or box-work configuration among the other samples in the study.

The explanations are detailed by Churchman et al. (2010b) but, in summary, they are explained by the origin of the veins. Fresh rock, whether granite or tuff, has undergone alteration on the slopes. This has occurred either by weathering, or by hydrothermal alteration. Alteration has led to the replacement of the most easily altered primary minerals by secondary minerals. X-ray diffraction analyses, as well as previous studies on samples from the slopes of Hong Kong (Kirk et al. 1997; Campbell
et al. 1998) indicated that either halloysite or kaolinite constituted the bulk of the secondary minerals formed. The rocks have become weakened as a result of alteration of their constituent minerals. Especially because of the load imposed by materials upslope, the weakening of the rocks has led to their fracture. This has occurred either along intergranular contacts within the rocks or else by shearing of crystals. Fracturing that occurred along intergranular contacts would lead to clean, uncontaminated fracture surfaces between rock fragments while that occurring with shearing of crystals would lead to a brecciation of these crystals. The brecciation would lead to the comminution of primary minerals into finer fragments and hence to their easier dissolution, to give especially oxides and hydroxides of iron and manganese. The veins are explained generally by the neogenesis of kaolin minerals from solutions that have leached from the rocks during their alteration. They are more correctly described as ‘infill’. On the basis of this genetic mechanism, the explanations of the particular features of Figures 3-7 identified here are proposed as follows:

1. Colour of infill. Infill is white when rock fracture has occurred largely along intergranular contacts, leaving clean surfaces for neogenesis to occur in the newly formed void, devoid of coloured contaminants. This is so in the representative samples described in Figures 3-5. The EDX analyses in Figure 3 show almost no peak for the colouring elements Fe and Mn. Apart from that for the covering Au, the analyses are dominated by those for Al and Si, with Si > Al, consistent with the composition of the kaolin minerals. That in Figure 4 is similar but shows very small peaks for Fe and Mn, as well as minor peaks for K and Ti. The analyses in Figure 5 are essentially the same, although there are significantly stronger peaks for Fe, especially, along with small peaks for K and Ti, in this case (sample FNS N). These may arise from the bulk of

Figure 5. Top left: Block sample FNS N (approx. 100 mm²), showing thin white veins throughout sample. Top right: Microfabric of white vein within sample FNS N; the scale bar is 1 mm long. Lower left: SEM of white vein in FNS N at high magnification. Lower right: EDX analysis of the vein in FNS N. Partly reproduced from Churchman et al. (2010b) with permission from the Clay Minerals Society.
this sample bordering especially narrow infill (Figure 5), as already noted. The resolution of the beam for analysis may be insufficiently small to include just infill materials so that primary minerals such as K-feldspar and titanium oxide contribute to the analyses. The dominant infill in the 3 samples shown in Figures 3-5 is largely monochrome, although there are textural differences, especially between that in FNS N (Figure 5) and those in TKL2 (Figure 6) and SSR DS1 (Figure 7), as will be explained further below. The black infill alongside the dominant white infill in SSR DS1 (Figure 6) has another origin (see below).

By contrast, coloured infill may include considerable Fe, as in TKL3, and this contributes to the various shades of red, yellow, and brown in the infill in this sample (Figure 6) and/or Mn, which is largely responsible for the dominantly black infill in STC S1A (Figure 7). K and Ca are also present in notably high proportions, indicating the incorporation of substantial primary minerals in the infill in this sample (STC S1A). The optical micrograph for TKL3 (Figure 6) and STC S1A (Figure 7) shows that infill in these samples is very heterogeneous in terms of colour, at least. That for STC S1A also shows great heterogeneity, and also a high concentration of small comminuted particles that have resulted from the brecciation of primary minerals upon rock fracture occurring within mineral grains.

2. There is a huge difference between the sizes of the dominant particles in the different infills. Those shown in the SEMs in Figures 3 and 4 within thick white infills...
are large, although they differ from each other in their dominant shape. They comprise very long tubular particles in TKL2 infill (Figure 3) and quite large platy particles, assembled together in the shape of rosettes, in SSR DS1 infill (Figure 4). In these, and in all other samples, X-ray diffraction (XRD) analyses have identified tubular particles as halloysite and platy particles as kaolinite. In TKL2 and SSR DS1, differential thermal analyses (DTAs) showed that kaolin minerals comprised at least 80% of the infill (Table 2 in Churchman et al. 2010b). XRD showed that 100% of the kaolin minerals in TKL2 infill are halloysite, while 80% of them in SSR DS1 infill are kaolinite (Tables 2 and 3 in Churchman et al. 2010b).

Figure 7. Top left: Block sample STC S1A (approx. 100 mm$^2$), showing black veins throughout the sample. Top right: Microfabric of black veins within STC S1A; the scale bar is 1 mm long. Lower left: SEM of black vein in STC S1A at intermediate magnification. Lower right: EDX analysis of the vein in STC S1A. Partly reproduced from Churchman et al. (2010b) with permission from the Clay Minerals Society.

By contrast, the particles of kaolin minerals in the infills in FNS N, which is white, and in both TKL3 and STC S1, which are highly coloured, are much smaller than those in TKL2 and SSR DS1. They appear to be highly tubular in TKL3 (Figure 6), platy in FNS N (Figure 5), and a mixture of shapes in STC S1 (Figure 7). XRD analysis confirmed abundant halloysite in TKL3, although kaolinite was present in nearly as high a concentration, and it indicated a significantly higher concentration for halloysite than for kaolinite in FNS N. This confirms that electron microscopy is probably too selective and/or misleading when one shape (tubular in this case) is visually dominant for good quantitative analyses. For STC S1A, DTA shows that the proportion of infill that comprised kaolin minerals was very low. XRD showed a crystalline manganese oxide, todorokite, to be present and other SEM images showed this to comprise quite large platy particles.
Therefore, the SEM in Figure 7 shows tubular halloysite, platy kaolinite, and also platy todorokite. The evidently substantial occurrence of the latter is consistent with the high proportion of Mn shown in the EDX analysis of this sample (Figure 7).

The explanation for the comparatively larger sizes of particles in TKL2 and SSR DS1 (Figures 3 and 4) than in others lies in the relatively clean environment (open cracks) in which kaolin minerals formed by neogenesis in these samples. The reason why kaolin minerals formed in the coloured infills are small comes from the constraints that the other ions in solution (those of Fe and/or Mn, mainly) imposed upon crystal growth in the contaminated environments resulting from the brecciated fractures.

The explanation why halloysite is formed rather than kaolinite, or vice versa, in the various samples of infill was suggested by the appearance of manganese oxide, as black veins or black spots, and/or iron oxides in or alongside the infill many of the samples, especially SSR DS1 (Figure 4), TKL3 (Figure 6), and, of course, STC S1A (Figure 7). Only those samples containing infill including or bordering on black spots or veins of manganese oxide and/or red, yellow,
or brown colouring from iron oxides or oxyhydroxides contained kaolinite. Otherwise, where these features did not appear, the kaolin minerals in infill were predominantly halloysite. The white infill in TKL2 (Figure 3) contains only halloysite among the kaolin minerals. Manganese and iron oxides or oxyhydroxides both require drying for their formation, so it is concluded that their occurrence indicates that the infills containing or bordering these oxides have undergone periods of drying. Halloysite is formed in its hydrated state (Churchman & Carr 1975), so it can be concluded that, when drying occurs, kaolinite is favoured as the newly formed kaolin mineral, whereas halloysite only forms when the environment remains wet. Drying is only intermittent, and probably seasonal, in the high rainfall zone of Hong Kong, so it appears that mixtures of halloysite and kaolinite, such as in all samples examined here except TKL3, result from different hydration regimes occurring cyclically in the corresponding sites.

3. The exceptional infill in FNS samples. Both the optical evidence and that from SEM suggest that FNS samples, represented by FNS N (Figure 5) here, have a different origin from the other samples in this study. The microfabric by optical microscopy in Figure 5 appears to be unstressed, showing randomly disposed micro-vermiform shapes, unlike those in the other samples in Figures 3, 4, 6, and 7, which reflect processes of shearing and/or brecciation having taken place in their formation and development. The clay particles also differ in their

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Figure 9. Scanning electron micrographs (SEMs) of the surfaces of macroaggregates of 2-3.4 mm in size from a soil: (a) (top left) Irrigated with water to 30% moisture content for 30 years; aggregate studied freeze-dried. (b) (top right) From control site adjacent to water-irrigated soil; aggregate studied freeze-dried. (c) (lower left) Irrigated with effluent from an abattoir and kept moist for 25 years; aggregate studied freeze-dried. (d) (lower right) Irrigated with water to 30% moisture content for 30 years; aggregate studied air-dried. Reproduced from Churchman and Tate (1986) by permission from CSIRO Publishing.
alignment and association with one another from the other samples studied. They comprise relatively small particles, which are randomly interlocked and reasonably tightly packed. These characteristics mark them as typical products of hydrothermal processes, according to Keller (1976). Weathering, by contrast, tends to give looser arrangements of particles (Keller 1976). A hydrothermal origin is possible in Hong Kong, especially close to fault zones (Irfan 1996). The infill in the FNS samples may not have formed by complete fractures of rocks as in the other samples studied.

4.2. Long-term effects of agriculture

In this study, described in detail by Churchman et al. (2010a), micromorphology was carried out using ESEM on air-dried aggregates and with TEM, which was applied to ultrathin sections of resin-treated samples of topsoil. While many other measurements were made on the soil samples, micromorphology proved crucial in understanding the effects on the soil studied of different extents of agricultural management. The micromorphological data enabled explanations of the differences between soils with different histories that were recorded in particle and pore size distributions, surface spectral analyses, and various measures of aggregate stability to be made in terms of observable changes in the nature and extent of aggregation.

Examples of observations made with ESEM and TEM of soils with different land-use histories are given in Figure 8.

The ESEMs in each case (virgin, newly cultivated, and long-term cultivated soils) show more-or-less rounded microaggregates that are each just a few micrometres (generally <10 µm) in diameter mixed in with larger primary particles, which are identified by XRD as largely comprising quartz. Quartz is identified in each of the ESEM images. Clusters of microaggregates, often approximately

![Image](https://via.placeholder.com/150)

**Figure 10.** Transmission electron micrographs (TEMs) of ultrathin sections (right) of samples from within the upper 0.05 m of an Alfisol from South Australia, showing dark mineral matter surrounding (a) (top) plant cells, probably fine roots (pale), and also quartz shards; (b) extracellular polysaccharide (identified by staining); and (c) bacteria. The scale bar in each case represents 1 µm. Partly reproduced from Churchman (2000) with permission from CRC Press.
50 µm in size, may themselves be characterised as larger microaggregates, following the widely-accepted Tisdall and Oades (1982) hierarchical model of aggregation in soils. The ESEMs of the different samples in Figure 8 differ mainly in the relative proportions of microaggregates of various sizes, on the one hand, and quartz particles on the other. Microaggregates tend to cover the surfaces of quartz particles, but to different extents in each case. While electron micrographs necessarily provide selective views, a surface-sensitive technique with a wider scope, photoacoustic infrared spectroscopy, confirmed that more quartz was exposed at the surface of the long-term cultivated soil than the newly cultivated soil whereas there was considerably less quartz exposed at the surface of the virgin soil than in both of the cultivated soils. One reason why the greatest amount of quartz was exposed at the surface of the long-term cultivated soil than in that of both the virgin and newly cultivated soil was revealed by the particle size distributions, which showed a lower clay content in the long-term cultivated soil than in either the virgin or newly cultivated soil, each of which had the same content of clay. Loss of clay by erosion, likely to be by wind, is suggested by this result.

The effects of soil management at the micrometric level are shown by the TEMs in Figure 8. In the virgin soil (Figure 8a), virtually all of the fine material occurs within microaggregates which are approximately 2 µm across; 2 µm is one of the basic sizes for microaggregates that are postulated in the Tisdall and Oades (1982) hierarchical model. Although microaggregates also dominate the TEM image for the newly cultivated soil (Figure 8b), these are generally greatly reduced in size from those shown for the virgin soil in Figure 8a. Many are submicron in size. In the TEM image of the conventionally cultivated soil (Figure 8c), however, there appears to be much dispersed submicron material that is characterised as fine clay in the image. The high concentration of fine clay in the conventionally cultivated soil blocks pores (Figure 8c), but more pores are open in the newly cultivated soil (Figure 8b), while they appear to be generally free of fine clay in the virgin soil (Figure 8a). The pore size distribution determined by mercury intrusion porosimetry confirmed these indications from TEM by showing a peak in pore volume for pores in the 10-100 µm range for the virgin soil that decreased in height for the newly cultivated soil, but had disappeared from the pore size distribution for the long-term cultivated soil. Furthermore, it may be deduced from Figure 8c that the dispersed fine clay is easily available for loss from erosion by wind or water. The series of TEMs in Figure 8 show that the source of deterioration of the soil by long-term agricultural practices lies in the loss of microaggregates. A measure of the stability of aggregates to a disrupting force, in this case osmotic pressure, confirmed the micromorphological observations, especially by TEM, of the breakdown of aggregates.

Churchman et al. (2010a) also studied the effects of the introduction of no-till management practices to the soil following its cultivation by conventional practices for ~100 years. The soil was examined by all the same micromorphological and other analytical techniques as samples from the other sites after no tillage had been used for 18 years. It yielded similar images in ESEM and TEM to those shown in Figure 8c for long-term conventional cultivation and similar results from photoacoustic infrared spectroscopy, for particle and pore size distributions and for aggregate stability, to those for this latter soil. There was no evidence for any effect of no-till management on the nature and extent of microaggregation at any scale below ~100 µm of soil that was already cultivated conventionally for ~100 years.

4.3. Effects of irrigation

In this study, described in detail by Churchman & Tate (1986), micromorphology as carried out using SEM enabled identification of a mechanism to explain the results of macroaggregate stability determinations that were made using the traditional wet-sieving approach that is common in soil structural studies. According to these determinations, air-dried macroaggregates 2-3.4 mm across following long-term irrigation with water only were more stable to immersion in water with mechanical agitation, as assessed by wet sieving, than were those from long-term irrigation with organic-rich abattoir effluent. When wet-sieving was carried out on field moist soils without prior air-drying, although those from both water- and effluent-irrigation were weaker than the air-dried macroaggregates, the macroaggregates from the water-irrigated soil were even less stable than those from the air-dried soil. The SEMs of the surface of the macroaggregates following the various irrigation treatments are shown in Figure 9.

The outstanding feature of the SEMs in Figure 9 is the appearance of a web, with an organic appearance, surrounding the aggregates. In the aggregates that had been irrigated with water alone but never air-dried either over the preceding 30 years or prior to SEM analysis (Figure 9a), the web was incomplete and only partially attached to the soil particles. By contrast, the web appeared to be closely attached to the soil particles in the aggregates from the control site alongside the soil that was irrigated with water. In the macroaggregates from the effluent soil (Figure 9c), the web was even more complete, although this soil was also examined without prior drying, either throughout its treatment or prior to SEM analysis. When the water-irrigated soil had been air-dried prior to analysis (Figure 9d), no distinct web was apparent over the particles.
It is likely that the web observed in Figure 9 consisted of a polysaccharide, which is commonly involved in the stabilisation of macroaggregates, e.g. Tisdall and Oades (1982). The SEMs show incomplete binding by the web of components in wet macroaggregates, especially when these were from irrigation by water alone, but the closer association of the components in dried macroaggregates helps to explain the generally lower water stability of macroaggregates prior to air-drying and especially the lower stability of water-irrigated rather than effluent-treated macroaggregates when drying was not allowed to occur. This supports an earlier study by Reid and Goss (1981), who found that stabilisation of soils by polysaccharides may not become effective until soils dried out.

5. Discussion
In discussing the implications of the contributions made by the various micromorphological techniques employed in these 3 studies to a better philosophical understanding of soils, it should first be noted that the study of saprolites is not concerned with soils per se. In terms of the unique characteristics of soils proposed by Churchman (2010a), the saprolites do not comprise horizons or aggregates. However, they show a variety of forms of their constituent minerals, which are mainly either halloysite or kaolinite, and this aspect has a bearing upon the origin of the unique character of colloids in soils. In inorganic saprolites, the colloids comprise clay minerals. The study of the saprolites showed that, when formation of these clay minerals occurred, by the process of neogenesis that is common in soils (Churchman & Lowe 2012), the size, especially, of the product minerals was greatly influenced by the presence of impurities in the environment in which formation took place. As pointed out by Churchman (2010b), using other examples from the same Hong Kong study, clay minerals in soils are generally much smaller than their counterparts that have formed in less heterogeneous non-soil environments. The contrast between the minerals in the white infills from weathering (samples TKL2 and SSR DS1, Figures 3 and 4) and those in the coloured infills (samples TKL3 and STC S1A, Figures 6 and 7) simulates something of the comparison between, respectively, clay minerals formed in a non-soil environment and those formed in soils. The main difference between the simulated soil-like environments in these coloured infills and those in soils lies in the influence of biology on soils. Biology tends to exacerbate the heterogeneity of the environments for neogenesis in soils. Of course, clay minerals in soils have many other characteristics that make them somewhat exceptional compared with those from non-soil environments, but the work described here makes no particular contribution to their origin. Note, however, that micromorphological techniques, especially high-resolution TEM, can show the nature of interstratifications and point to their origin (see, e.g., Churchman et al. 1994).

The micromorphological study of the long-term effects of agriculture on a soil showed the effects of common agricultural practices on microaggregates, generally regarded as aggregates which are <250 μm in equivalent spherical diameter (Tisdall & Oades 2006). These are the most stable constituents of the structure of soils (Tisdall & Oades 1982; Churchman et al. 2010a) and their breakdown signifies a loss of structure and hence of agronomically important pores that is essentially irreversible by farming practices (Churchman et al. 2010a). Furthermore, the loss of the smallest microaggregates implies the release of very fine particles, as seen in Figure 8c, that leads to their easy loss from the soil system and hence erosion by wind or water. Furthermore, close examination of TEMs that were obtained in this particular study, including that in Figure 8a, showed that the essential nature of microaggregates was made up of mineral material, identified by Churchman et al. (2010a) as both crystalline clay minerals and oxides, surrounding organic matter of various types. Figure 10 is a composite of images from TEM that shows this feature of some microaggregates in the soil studied. It is very likely that the coating minerals serve to protect the organic matter in the core of the microaggregates from breakdown through either predation by microbes or oxidation. This mechanism is likely to constitute the main method of sequestration of carbon in soils generally (e.g., Lehmann et al. 2007; McCarthy et al. 2008).

The micromorphological effects found in the study of the effects of irrigation on soils point to a biologically derived mechanism for the association of particles and microaggregates together to give macroaggregates. It is the pores between macroaggregates that are most important for the anchoring of plant roots in soils and for the transport of essential nutrients, water, and air to them (Tisdall & Oades 1982). The micromorphology of the soil in this study also showed strong effects of air-drying upon soil structure.

Aggregation has been identified as a unique characteristic of soils, even though there is no clear-cut, widely accepted definition of aggregates (Churchman 2010a). This is exemplified by a discussion by Weinhold et al. (2005) of the factors involved in assessing soil quality. Soil quality itself is defined as “the capacity of a soil to sustain biological productivity, maintain environmental quality and promote plant and animal health” (Weinhold et al. 2005, p. 349). Weinhold et al. (2005) then concluded that aggregation accounts for almost all of the physical properties, many of the biological properties, and also some of the chemical properties that relate to the assessment of soil quality.
In practice, measures of the stability of aggregates to disruptive forces such as water have been generally used to define the status of aggregation in soils, and the important contributions of aggregates to soil properties have been discussed in terms of those of, for example, ‘water-stable aggregates’. The stability of macroaggregates is often determined by their resistance to disruption by immersion in water through wet-sieving (e.g., Kemper & Roseneau 1986), but this technique, besides being limited because it does not represent all possible disruptive forces encountered by soils in the field (for example, that of wind), is also limited and probably compromised by the methods chosen for soil preparation, and particularly those of drying and re-wetting. Air-drying is usually adopted, but soils may also be analysed field-moist (e.g., Churchman & Tate 1986), while many studies (e.g., Kemper & Roseneau 1986; Oades & Waters 1991; Le Bissonais 1996) have shown that even the rate of re-wetting air-dried soils with water can substantially affect the result obtained. Le Bissonais (1996) suggested that an older French approach whereby re-wetting was carried out in ethanol, had merit, although he also suggested that the method adopted should reflect the disruptive forces that were most relevant in each situation. In general, however, soils, and particularly macroaggregates, are likely to become disrupted in the course of making any measurement of, for example, their size distribution. Generally, soils and their aggregates comprise a range of stabilities and the weakest are easily disrupted; hence, studies of those that are stable to a defined level of a disruptive force may neglect important characteristics of their unstable counterparts. For example, they may neglect aggregates bound, however loosely, by the network seen in pre-dried soils in Figure 9a. In order to properly represent the nature of the aggregates encountered by, for example, plant roots, microbes, and nutrients and pollutants in soils, it would be preferable to be able to study aggregation and aggregates as they occur in situ in soils.

As seen here and elsewhere (e.g., Chenu 1989; Oades & Waters 1991; Foster 1994; Stoops et al. 2010), modern approaches to micromorphology, especially using electron-optical techniques, offer the promise of being able to advance our understanding of the nature of aggregates in situ. The promise is encouraged by the quite recent development and use in soil studies of such techniques as scanning transmission X-ray microscopy (STXM) (Wan et al. 2007) and X-ray computer tomography (CT) (Tracy et al. 2010). STXM has enabled mapping elements as they occur spatially in microaggregates (Wan et al. 2007) while X-ray CT enables 3-dimensional imaging of undisturbed aggregates as well as roots (Tracy et al. 2010) in soil.

In summary of the central role played by aggregation in soils, it may be argued that the most important properties of soils, including the protection they offer for their constituent microorganisms (e.g., Bruns 2002), are directly attributable to those of their aggregates and to the nature and extent of their aggregation. Insofar as materials in soils, e.g., quartz sands and fine clays, are not aggregated together with other soil components (e.g., Figure 8c), they will behave similarly to these particular materials in other contexts, e.g., quartz sands in river courses and beaches, and fine clays in saprolites, regoliths in general, and mineral deposits. Otherwise, aggregates demand close and careful attention by current and future micromorphological approaches if we are to advance our knowledge of soils as unique and important materials.

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