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Metamorphic alteration of a Precambrian (2.2 Ga) paleosol from South Africa revealed by backscattered electron imaging

Gregory J. Retallack and David H. Krinsley
Department of Geological Sciences, University of Oregon, Eugene, OR 97403-1272, USA

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ABSTRACT

Like many Precambrian paleosols, the 2200-Ma-old Waterval Onder clay has been metamorphosed to the greenschist facies of regional metamorphism. The extent of metamorphic alteration of the fine-grained uppermost horizons of the paleosol is assessed here using optical and backscattered electron microscopy. In hand specimens and under low-power optical examination the paleosol shows surficial lamination (cumulic horizon of soil terminology), rounded clasts coated with opaque sesquioxides (manganoferriargillans), cracks defining a fitted breccia of blocks that were evidently soft in places (blocky angular peds), cracks filled with multiple generations of material from above (illuviation argillans) and zones of unusually highly birefringent clay (climobimasepic plasmic fabric). With backscattered electron microscopy, however, at a resolution of less than about 10 μm, the fine structure of originally colloidal parts of the paleosol (mangans, argillans, matrix and plasma separations) is shown to be extensively recrystallized to illite and berthierine. Original soil structure has been obscured at this resolution by crystal growth at random across original microscopic discontinuities. Preferred orientation of metamorphic crystals can still be seen along what are presumed to be highly birefringent zones of oriented clay similar to those in modern soils, but the matrix itself shows random clusters of crystals suggestive of an advanced stage of illitization by Ostwald ripening.

The style of recrystallization of laminae in the surface horizon is similar to that seen lower in the profile where recrystallized beds are thicker and coarser grained. Thus the paleosol probably formed on an upward thinning and fining sequence of sandstone and shale, rather than on basalt. On this assumption, the profile has gained iron compared with its shaly parent material, rather than lost iron compared with basalt. This may be an indication of greater oxygenation of the atmosphere than previously thought. Possible microbial traces can be seen in thin section but because of pervasive recrystallization, these remain dubiofossils.

Introduction

Paleosols are now widely recognized in Precambrian rocks and can be regarded as evidence for terrestrial paleoenvironments of the distant geological past (Holland, 1984; Retallack, 1986a, 1990; Zbinden et al., 1988; Holland et al., 1989). Unfortunately almost all Precambrian paleosols are metamorphosed to some extent, and some also may have suffered hydrothermal alteration. This study is a contribution to the rapidly growing literature on burial diagenesis and metamorphism of paleosols (Barrientos and Selverstone, 1987; Luc et al., 1989; Golani, 1989; Nesbitt and Young, 1989; Krois et al., 1990; Lander et al., 1991; MacFarlane and Holland, 1992; Melcher, 1991; Rainbird et al., 1991). Paleosols are distinctive, often very alumina-rich materials (Reimer, 1986) which can be metamorphosed to equally distinctive rocks rich in corundum and andalusite.

The degree to which alteration after burial may have obscured the paleoenvironmental signals of ancient soil formation is currently a matter of controversy (Beeunas and Knauth,

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Correspondence to: Gregory J. Retallack, Department of Geological Sciences, University of Oregon, Eugene, OR 97403-1272, USA.

1985; Vahrenkamp and Rossinsky, 1987; Palmer et al., 1989; Holland and Feakes, 1989; Retallack, 1989). A variety of chemical and petrographic techniques has been applied to the problem of untangling the effects of alteration during soil formation and after burial (Retallack, 1991). In this study we use an additional approach involving examination of polished sections at very fine scales using backscattered electron microscopy. This technique provides images of minerals with varying contrast that correspond to atomic number and thus chemical composition at much finer scales of resolution than visible in conventional optical microscopy (Huggett, 1984; White et al., 1984; Pye et al., 1986; Burton et al., 1987; Krinsley and Manley, 1989). In this work it has proven of great use in determining the scale and scope of metamorphic alteration in a fine-grained paleosol.

The paleosol whose fine crystalline structure was examined with this powerful technique is perhaps the best studied of Precambrian paleosols: the Waterval Onder clay paleosol in the eastern Transvaal Basin of South Africa. This is one of the few Precambrian profiles that has been studied by many independent investigators who agree that it is indeed a paleosol, but differ in their interpretations of its paleoenvironmental significance (Button, 1979; Button and Tyler, 1981; Holland, 1984; Retallack, 1986b, 1990; Holland and Zbinden, 1988; Pinto and Holland, 1988). Was it developed in shale overlying basalt, or only in basalt? Was it oxidized or reduced in its interaction with the atmosphere during soil formation? Did it support microbial life or was it weathered abiotically? These three critical questions can also be reassessed from the evidence of backscattered electron microscopy presented here.

Geological setting

The Waterval Onder clay paleosol (of Retallack, 1986b) is exposed in a deep road cut immediately west of a bridge over the Elands River, 2.7 km west of the small hamlet of Waterval Onder on national road 4, Transvaal, South Africa (Figs. 1, 2). This paleosol, as well as others above the Hekpoort Basalt, such as that exposed near the Daspoort Tunnel near Pretoria, have also been referred to as the "Hekpoort paleosol" (Holland, 1984). The Hekpoort Basalt is a widespread continental flood basalt that underlies the fluvial Dwaal Heuvel Formation of the Pretoria Group. The basalt has been radiometrically dated using the Rb/Sr method at 2224±21 Ma, and the stratigraphically equivalent Ongeluk Volcanics in the Griqualand West Basin have been dated by the Pb/Pb method as 2238±90 Ma (Walraven et al., 1992) and by the Rb/Sr isochron method on whole rock as 2145±40 Ma (Cahen et al., 1984).

The Waterval Onder clay paleosol has prominent clastic dikes that have been ptygmatically folded during burial (Fig. 2). Unravelling of this deformation allows reconstruction of its chemical composition before burial compaction (Button, 1979). Along with other features of the paleosol, this evidence of deep cracking and good drainage mark it as a Vertisol (Retallack, 1986b). This is just one of many distinct paleosol profiles at this same stratigraphic level which collectively can be termed the post-Hekpoort Geosol. This extensive alumina-rich altered zone has been recognized over all but the northwestern and extreme southern parts of the Transvaal Basin (Button, 1979; Button and Tyler, 1981). Its chemical composition and petrography have also been examined in detail at the Daspoort Tunnel in Pretoria (Hart, 1986). There is an equally widespread geosol above the Ongeluk Basalt of the Griqualand West Basin (Wiggering and Beukes, 1990; Holland and Beukes, 1991).

The Waterval Onder paleosol is overlain by 7 km of mineralogically mature sediments of the Pretoria Group, 3 km of Rooiberg Felsite, 5 km of intrusive Bushveld Complex and 1–2 km of mafic sills. The Bushveld Complex has been radiometrically dated by a variety of

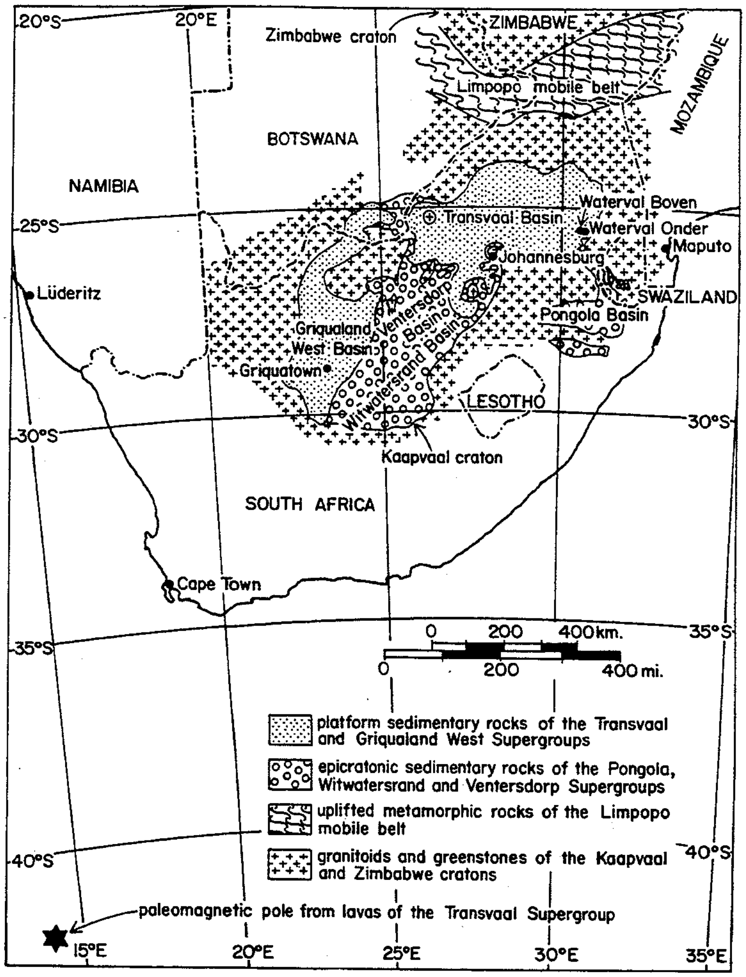

Fig. 1. Location of Waterval Onder and major tectonic units of southern Africa during the Archaean–Proterozoic transition (2900–1800 Ma: modified from Tankard et al., 1982).

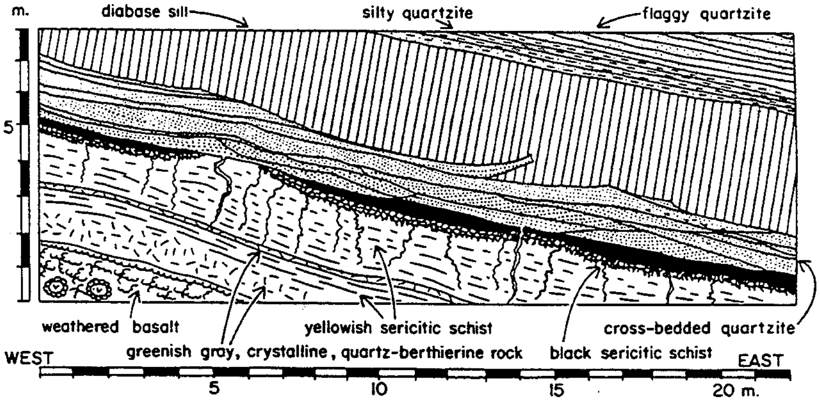

Fig. 2. Annotated field sketch of part of the south face of the road cut near Waterval Onder, South Africa.

methods including Rb/Sr isochron and U/Pb concordia plots (summarized by Cahen et al., 1984). Successive magma influxes of this enormous layered mafic intrusion are confined to a period of 2050 ± 12 Ma. Cross-cutting magmatic granophyres are of similar age (2050 ± 30 Ma) and were followed by younger intrusive granitic rocks (1920 ± 40 Ma, 1670 ± 70 Ma, 1400 ± 190 Ma). A recent Rb/Sr age determination on another paleosol on the same stratigraphic horizon as the Waterval Onder clay at the Daspoort Tunnel in Pretoria is 1925 ± 32 Ma. This is presumably when its Rb/Sr systematics were reset by metamorphic alteration associated with burial and intrusion of the massive Bushveld intrusion and associated dikes (MacFarlane and Holland, 1992). The extensive post-Hekpoort Geosol of which the Waterval Onder paleosol is a part, shows great variation in metamorphic alteration over the wide area of the Transvaal Basin in which it has been seen. Where most altered near Rustenberg on the northern margin of the Transvaal Basin, and near Zeerust on the western margin, this geosol contains large crystals of andalusite and muscovite (Button, 1979). The road cut near Waterval Onder on the eastern margin of the Transvaal Basin, is one of the least altered profiles, with relatively well preserved soil structures (Retallack, 1986b). Nevertheless, this fine-grained paleosol is indurated, with original clay minerals recrystallized to chlorite and berthierine of silt size. From this as well as the stoichiometric excess of potash, it is clear that the profile was affected by burial illitization (Retallack, 1986b). Small crystals of euhedral cubic pyrite from the two samples of the overlying Dwaal Heuvel quartzites and from a vein within the paleosol (equivalent to sample 11 of Button) were microdrilled and analyzed isotopically by Ian Lambert (pers. commun., 1987) and found to have δ^{34}S values of 6.6‰, 7.2‰, and 9.9‰, respectively. These are indications of a reducing burial environment with little or no bacterial mediation (Schidlowski et al., 1983). Also found are small amounts of chloritoid, stilpnomelane and epidote, which are commonly taken as indicators of lower greenschist facies metamorphism (Button, 1979).

Materials and methods

Oriented samples and petrographic thin sections from the Waterval Onder clay paleosol studied here were those used in an earlier study (Retallack, 1986b), and were taken to duplicate the samples of the geochemical study by Button (1979). For backscattered electron microscopy, thin section billets cut perpendicular to the ancient land surface and from near the top of the profile (black in Fig. 2) were polished with 600 grit and coated with 100 Å of carbon. These were examined under an ISI SS-40 scanning electron microscope with annular, four-element backscattered electron detectors, an Si–Li solid state energy dispersive X-ray detector, and Oats "QUANTEX" software. An accelerating potential of 20 keV was used.

Minerals were identified in the backscattered images on the basis of crystal morphology and their brightness ("Z-contrast"). Mineral identification was supported by semiquantitative analyses from the energy-dispersive X-ray unit (Krinsley and Manley, 1989). Identifications of the backscattered images also were in good agreement with observations from X-ray diffraction and optical petrography (Button, 1979; Retallack, 1986b).

Mineral composition

From X-ray diffractometry, the surface horizon of the Waterval Onder clay (black in Fig. 2) can be seen to consist largely of muscovite and quartz, with lesser amounts of berthierine, and small amounts of sphene and ilmenite. All of the phyllosilicates have the sharp peaks of well crystallized material. The following peak sharpness indices were calculated from the 10-

Å peak of muscovite: Weaver index of 12.2, Kubler index of 0.14 $\Delta°2\theta$, and Weber index of 50 (using methods reviewed by Frey, 1987). Almost all the muscovite is of the $2M_1$ polytype, considering the ratios of the 3.74 Å, 3.00 Å, and 2.80 Å peaks to the 2.58 Å peak, which are 88%, 100% and 86%, respectively. For these reasons this mineral can be identified as muscovite, rather than the less precise "sericite" of Button (1979). The "7 Å magnesian chamosite" of Button (1979), lacks a 14 Å peak and is better called berthierine, following the revision of mineral names proposed by Brindley (1982; Retallack, 1986b).

In backscattered electron micrographs, quartz is dark, often with a rimmed appearance and embayed by surrounding grains. At the other extreme of brightness are laths and some equant grains of iron and titanium oxides, only exceptionally showing evidence of manganese under energy-dispersive X-rays. The whitest grains are magnetite and the slightly grayish ones are ilmenite.

Between these two extremes are at least two distinctly different phyllosilicates. Muscovite is the dark gray relatively equant phyllosilicate, forming the matrix, that has large amounts of aluminum and silicon, substantial amounts of potassium and only traces of iron. Because these crystals are generally greater than 4 µm long, they qualify as muscovite rather than illite on textural grounds (following Srodon and Eberl, 1984). Berthierine is the elongate light gray phyllosilicate with a large amount of iron, substantial amounts of aluminum and silicon, some magnesium and potassium, and traces of manganese.

Taken as a whole this rock with its "fine felty mixture of muscovite and chlorite or serpentinite and iron oxides" corresponds to the rock type pinite (Deer et al., 1966, p. 86). Such fine-grained rocks of sericite and quartz also have been called agalmatolite, although the original examples of that rock include microcline and are not so dark with iron minerals (Russell and Allison, 1985).

Reassessment of features of the paleosol

These samples show many features of soils at the rather coarse resolution of optical microscopy, but a distinctly more metamorphic appearance in backscattered electron photomicrographs. The following paragraphs deal with various features of the paleosol observed in the field and in petrographic thin sections (Retallack, 1986b), and evidence from backscattered electron micrographs of the extent to which they have been altered by metamorphism.

Depositional layering

A prominent feature of the dark surface horizon of the Waterval Onder clay paleosol is fine laminae of dark and light minerals and with occasional oversize claystone grains (Fig. 3). In soil terminology such a surface horizon formed by sedimentation of thin laminae is called cumulative (Birkeland, 1984) or cumulic (Soil Survey Staff, 1975). The thickness of this dark laminated horizon varies considerably in the field, and represents local depressions in the paleosol surface horizon deformed by cracking and expansion of the underlying soil (Fig. 2). This is similar to the mukkara structure of soils, which is a subsurface expression of gilgai microrelief (Paton, 1974). In modern soils such laminae and clay galls form by the washing into gilgai depressions of clay from the nearby cracked ridges of swelling clay.

Such a depositional explanation for this layering is not obvious from backscattered electron microscopy (Fig. 4) in which phyllosilicates often are recrystallized across what appeared to be layering under the optical microscope. Grains of neomorphic berthierine show no clear preferred orientation and cut across what appear to have been pre-existing sedimentary layers.

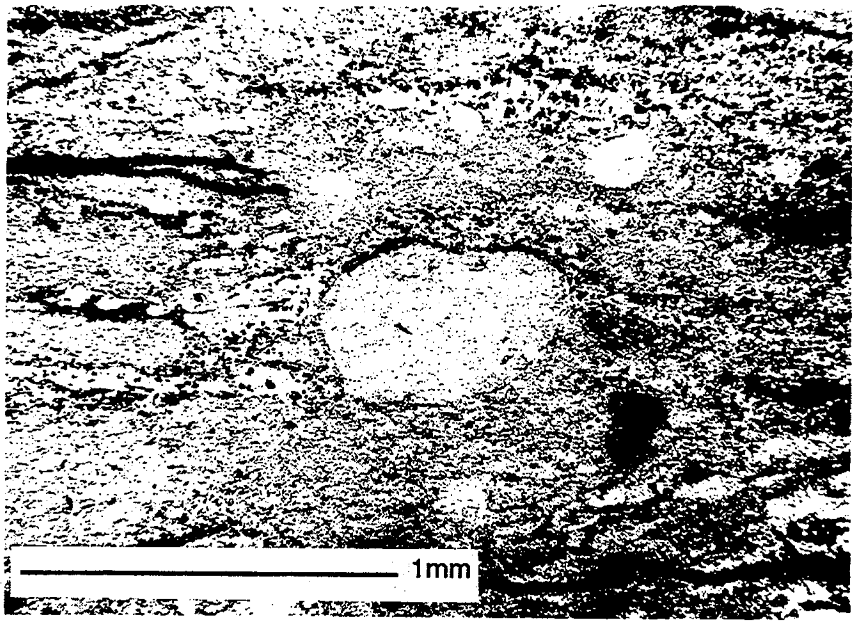

Fig. 3. Optical photomicrograph of lamination and clay clasts in the lower A horizon (level of Button's, 1979, sample 2) of the Waterval Onder clay paleosol.

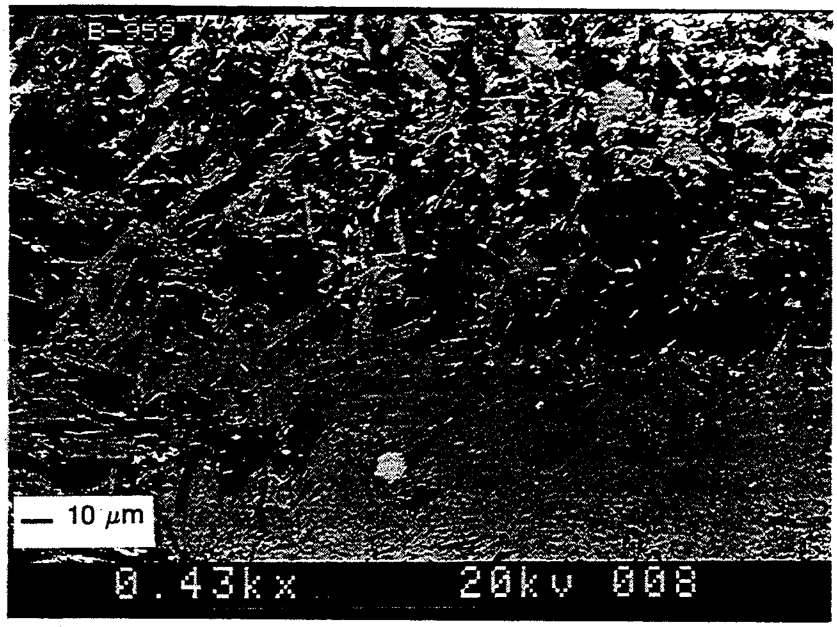

Fig. 4. Backscattered electron photomicrograph of laminae, showing recrystallized phyllosilicates disrupting primary lamination and grains: ilmenite (small white laths), berthierine (light grey elongate-tabular minerals) and muscovite (dark gray more equant phyllosilicate) (level of Button's sample 1).

Original grains

In optical thin sections the surface of the paleosol shows both grains of quartz and of what appears to have been claystone (Fig. 3). The quartz grains are relatively equant and entire-margined. The presumed "claystone grains" are in many cases well rounded, but occasionally angular. These oversized grains in a finer groundmass can be regarded as grains remaining from deep weathering (relict or skeleton grains in soil terminology of Brewer, 1976) and as resorted fragments of soil matrix (granular peds of Soil Survey Staff, 1975, or papules of Brewer, 1976).

Examined by backscattered electron microscopy, the grains apparent in thin section are not nearly so clearly defined (Fig. 5). Both quartz grains and "claystone" grains are extensively embayed by surrounding phyllosilicates, especially berthierine. In some cases, the boundary between quartz and muscovite matrix is so irregular that it is difficult to determine whether it was a grain or an area of quartz cement. In addition, the "claystone" grains are recrystallized internally to a felted aggregate of muscovite.

Other mineral grains observed with backscattered electron microscopy and energy-dispersive X-rays include large rounded grains of sphene, ilmenite and apatite with sharp edges (Fig. 4). These appear to have been original grains of the paleosol. Small magnetite grains vary from equant and rounded to sharp and acicular, the latter presumably recrystallized.

Grain coatings

The apparently sharp outlines of "claystone grains" in thin sections are due primarily to a coating of nearly opaque material (Fig. 3), that in places is thick and lumpy. These coatings can be labelled manganoferriargillans in the terminology of soil science (Brewer, 1976). They are commonly thicker on top of the grains, that is toward the ancient land surface of the paleosol. This, together with their irregular and lumpy appearance, is suggestive of ministromatolitic forms of rock varnish (Retallack, 1986b, 1990).

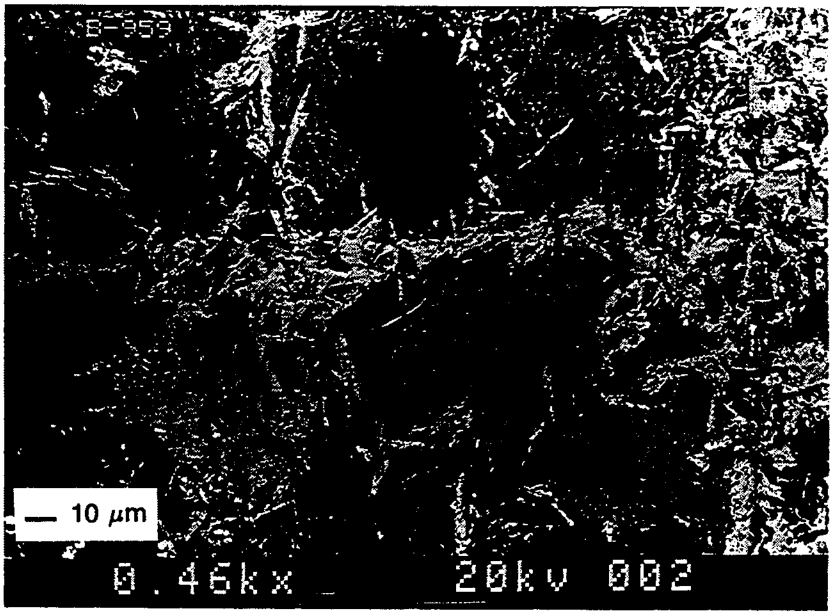

Fig. 5. Backscattered electron photomicrograph of grains of claystone (recrystallized to dark muscovite) and quartz (dark with diffuse rim) embayed by neomorphic berthierine (light gray phyllosilicates) (level of Button's sample 1).

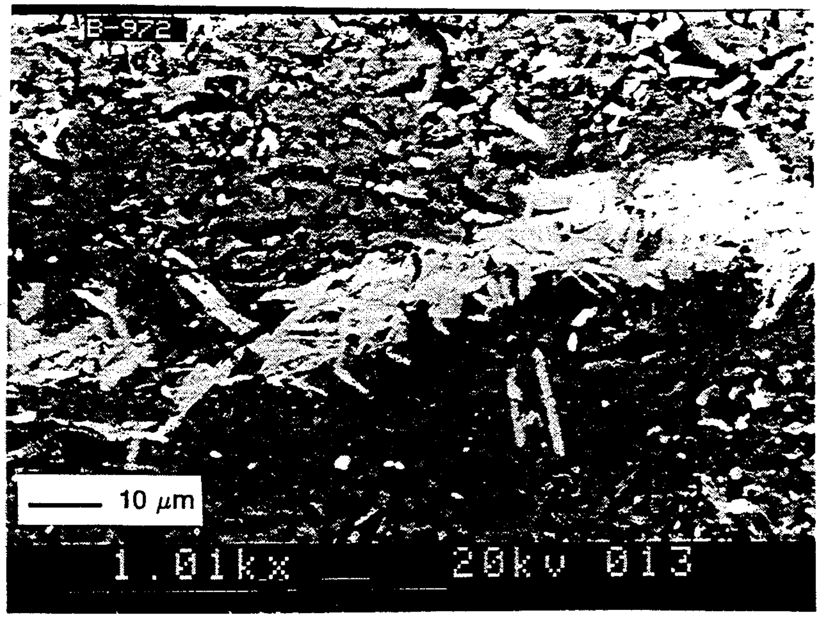

Fig. 6. Backscattered electron photomicrograph of a recrystallized clast of muscovite (dark phyllosilicates below) with coatings of crudely aligned berthierine (gray) (level of Button's sample 1).

Examination by backscattered electron microscopy does not confirm interpretation as rock varnish. The opaque coatings are extensively recrystallized to randomly arranged berthierine crystals (Fig. 6). Thus the coarse resolution furnished by optical microscopy of these features shows as much detail of the morphology of the coatings as can be obtained. There is little chance of being able to find ministromatolitic or other diagnostic ultrastructures which have been documented from modern rock varnish (Perry and Adams, 1978; Krinsley et al., 1990; Dorn, 1991). In addition, these recrystallized coatings are richer in silica and alumina and less rich in iron and manganese than expected for rock varnish. Presumably they were originally more clayey and less opaque than typical for rock varnish today. Similar recrystallized, presumably originally clayey, grain coats have been found in other Precambrian paleosols (Grandstaff et al., 1986). Although these Precambrian grain coatings may have been microbial laminates of some sort analogous to rock varnish, they are different from rock varnish of modern deserts.

Crack fillings

One of the most prominent features of the Waterval Onder clay paleosol in the field is the abundance and variety of cracking features (Fig. 2). Some of the largest are filled with quartz grains which have fallen down from the overlying Dwaal Heuvel Formation, and can be labelled clastic dikes in the terminology of sedimentary geology, or silans in soil terminology (Brewer, 1976). Most of the finer cracks, however, are filled with fine-grained material dark with magnetite and berthierine from the surface horizon. The larger cracks below the surface horizon contain aligned magnetite. This is suggestive of the kind of vertical alignment found in cracks within a soil filled successively in thin increments when the cracks were open and compacted when swelling clays closed the cracks. In soil terminology these are illuviation manganoferriargillans (Brewer, 1976).

Backscattered electron microscopy shows that these features also have been strongly recrystallized to berthierine, magnetite and muscovite (Fig. 7). The random growth of neo-

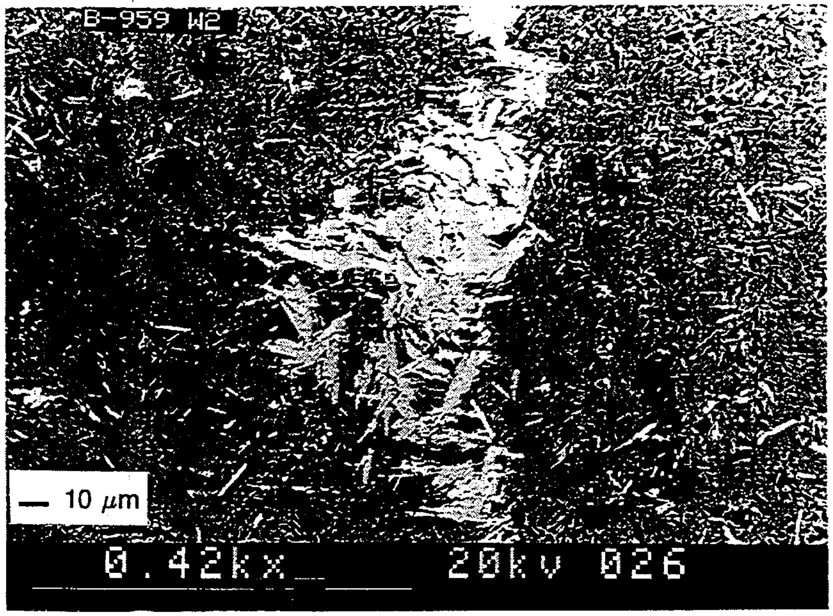

Fig. 7. Backscattered electron photomicrograph of a presumed former clastic dike (illuviation manganoferriargillan) now contorted and recrystallized to berthierine (light gray), in a matrix of muscovite (dark gray) (level of Button's sample 2).

morphic phyllosilicates has obscured fine lamination of these structures as well as the contacts with original clayey matrix.

Fine-grained matrix

The abundant cracks and swale-like form of the surface horizon of this paleosol are very like features of clayey modern soils, and such similarities extend also to the appearance of the fine grained matrix in thin section under crossed nicols. In clayey soils it is common to see striking local variations in the degree of birefringence of clays, with large areas of dark flecked clay surrounded by wispy streaks of high birefringent clay. This so-called "sepic plasmic fabric" is thought to be produced by the finer grain size and higher degree of orientation of clays along microscopic planes of weakness in the shrinking and swelling soil (Brewer, 1976). A similar microfabric can be seen in the Waterval Onder paleosol, except that the overall level of birefringence of the clayey matrix is already high and the more highly birefringent streaks are blue and purple with second-order colors (Fig. 8). Indeed, this could be called clinobimasepic plasmic fabric in the terminology of Brewer (1976).

Backscattered electron microscopy has shown that these more highly birefringent streaks are microfractures that include muscovite of more platy and elongate habit than the felted muscovite which comprises the bulk of the matrix (Fig. 9). These microfractures and unusually elongate grains also form curved to irregular, ptygmatically deformed zones in the felted muscovite matrix, more like compacted soil features than later purely metamorphic effects. Although clearly of coarser grain size than would be expected in a soil, the elongate grains may mimic the more highly oriented and finer-grained pedogenic clays of highly birefringent streaks characteristic of se-

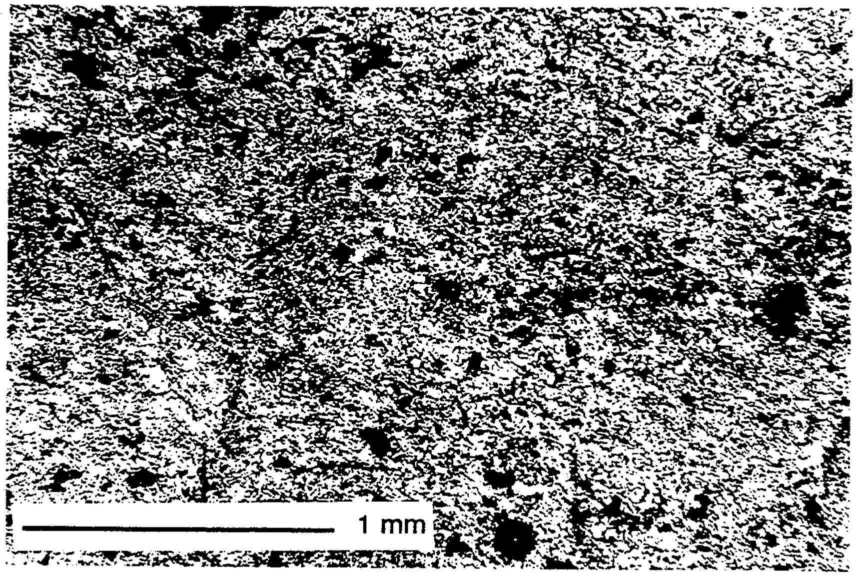

Fig. 8. Optical microphotograph under crossed nicols of streaks of highly birefringent muscovite (darker colors of second-order blue), which may represent a characteristic soil microfabric (plasma separations of clinobimasepic fabric: level of Button's sample 1).

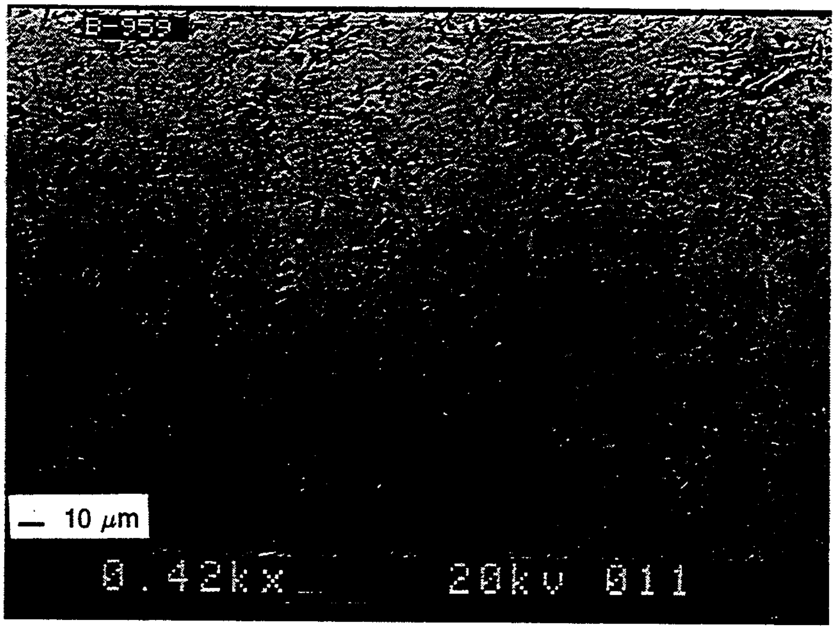

Fig. 9. Backscattered electron micrograph of muscovite matrix with irregular planes of grains of a more elongate habit that may have recrystallized from original clinobimasepic soil microfabric (level of Button's sample 1).

pic plasmic fabric (Retallack and Wright, 1990).

Degree of alteration

The Waterval Onder paleosol has little or none of the colloidal components found in soils and has been thoroughly recrystallized. Much of the matrix is of relatively even grain size as would be expected from the culmination of illitization of original clays by Ostwald ripening (Eberl et al., 1990; Lanson and Champion, 1991). The textures observed in this paleosol are comparable to those found near the anchizone–epizone boundary of metamorphism (Weaver et al., 1984). Sharpness of the muscovite 10 Å peak and its near total conversion from the monoclinic disordered (1Md) to two layer monoclinic ($2M_2$) polytype, also are compatible with alteration within the epizone and lower greenschist facies metamorphism (Frey, 1987). The persistence of berthierine, and the presence of stilpnomelane and chloritoid lower in the paleosol are also compatible with lower greenschist facies metamorphism (Button, 1979). In general, stilpnomelane and chloritoid are rare within the anchizone of transitional diagenesis–metamorphism, and although berthierine can persist into the anchizone and even the epizone, it is most common in less altered rocks (Frey, 1987). Alteration beyond the lower greenschist facies is unlikely considering the fine grain size of muscovite and the lack of such indicator minerals as biotite and andalusite in the paleosol.

Given burial of the paleosol by some 10–16 km of overlying sedimentary and intrusive rocks, pressures would have been about 2–4 kbar. With a typical geothermal gradient of 25°/km, this depth amounts to burial temperatures in the range of 250° to 400°C. Greenschist facies metamorphism and the epizone boundary is generally considered to begin at 350–375°C at about 10 km burial (Winkler, 1979). This result is supported by comparison with detailed studies of the Late Cambrian Conasauga Shale in the southeastern U.S., which is metamorphosed comparably to the Waterval Onder paleosol (Weaver et al., 1984). Experimental studies have shown that berthierine (a 7 Å chlorite) is converted to ferrous chamosite (a 14 Å chlorite) at temperatures in excess of 450°–550°C over the range of 1–3 kbar (Nelson and Roy, 1958; James et al., 1976). This is compatible with observations of small amounts of berthierine in slates altered to near the anchizone–epizone boundary in Pennsylvania and Louisiana (Frey, 1970; Lee et al., 1984; Ahn and Peacor, 1985). However, this transition also has been noted in Japanese coal measures at temperatures of as low as 160°C and burial as low as 3 km (Iijima and Matsumoto, 1982). In hydrothermally altered rocks near the Salton Sea of California, the transition begins at 150°C, with dominance of 14 Å chlorite from 260° to 310°C (Yau and Peacor, 1984). Even if one regards reactions in these Japanese and Californian rocks as hastened hydrothermally (following Weaver et al., 1984), the abundance of berthierine in the Waterval Onder paleosol is unusual for the lower greenschist facies. Nevertheless, there are so many inconsistencies in the distribution of berthierine in deeply buried rocks that Frey (1987) has noted "the 7 Å → 14 Å chlorite polymorph change cannot be used as a reliable metamorphic indicator at the present time".

Commonly proposed metamorphic reactions may explain the main minerals of the Waterval Onder paleosol. Muscovite and chlorite can form from illite and mixed layer illite–smectite (Weaver et al., 1984). Berthierine can form from kaolinite and siderite (Bhattacharyya, 1983). Some of these clay minerals are likely to have been common in the original soil (Retallack, 1986b). A closely comparable modern Vertisol developed on basaltic colluvium and alluvium in the Darling Downs of Queensland contains either illite (40–50%) or randomly interstratified clay (40–50%), with kaolinite (30–40%) and quartz (10–20%:

Stace et al., p. 98, profile G). Neither siderite nor glauconite would be expected in such a soil today, but a variety of other poorly crystalline iron and manganese hydroxides are present in this and comparable soils. Models for the metamorphic alteration of shaly rocks using such typically marine minerals as glauconite may not be appropriate for assessing metamorphic alteration of paleosols. The post-Hekpoort Geosol including the Waterval Onder profile varies considerably in metamorphic grade over its enormous area of outcrop (Button, 1979; Button and Tyler, 1981) and with further study could become a standard for low-grade metamorphism of paleosols.

Discussion

Enhanced understanding of the degree of metamorphic alteration of the Waterval Onder paleosol through study of our backscattered electron micrographs allows reassessment of some critical features of the paleosol and assists in interpretation of its paleoenvironment.

A fundamental difference of opinion has arisen as to whether the Waterval Onder paleosol was a strongly developed soil weathered from basalt (Button, 1979; Holland, 1984; Holland and Beukes, 1991) or a weakly developed soil weathered from sedimentary cover to basalt (Retallack, 1986b; Maynard, 1992). If developed on basalt then the prominent berthierine-rich bands, erratic subhorizontal banding, pronounced geochemical anomalies low in the paleosol and the sharp contact to underlying basalt must all be regarded as products of metamorphism, perhaps analogous to "chlorite pods" of regional metamorphism. Alternatively, these various features of the lower part of the profile can be regarded as original beds of basaltic alluvium and colluvium comparable with that in modern Vertisols (Stace et al., 1968; Paton, 1974), but in this case recrystallized during metamorphism.

Genuine chlorite pods of regionally metamorphosed slates are illustrated by scanning electron micrographs of Weaver et al. (1984) and are distinct from any structures seen during backscatter imaging of the Waterval Onder clay paleosol. Chlorite pods are relatively closely spaced and extend as lenses over only a few millimeters. The phyllosilicate grains within them are highly oriented, often at an oblique angle to the elongation of the pod. The boundaries of the pods are defined by a thin layer of elongate platy grains at a high angle both to the chlorite within the pods and the illitic and sericitic matrix outside the pod.

Berthierine laminae of the Waterval Onder clay paleosol in contrast are as thick as 3 mm, separated by several centimeters, and can be traced laterally for more than 30 cm. Near the base of the profile there is a berthierine–quartz bed 8 cm thick, and below that another berthierine–quartz bed 110 cm thick. Berthierine crystals within these beds are randomly arranged and also cut across the former bed boundary (Retallack, 1986b, figs. 7, 8). In all respects these berthierine beds low in the paleosol appear to be scaled-up versions of the thin berthierine-rich laminae revealed by this study (Figs. 4, 5). Origin as recrystallized sedimentary laminae and beds also explains a variety of other observations: cutting of berthierine-rich laminae by clastic dikes, greater lateral disruption of the laminae near the surface compared with deeper in the profile, textures within berthierine-rich rocks that look like ripple marks, alignment of berthierine-rich laminae with bedding rather than fracture cleavage, strong geochemical anomalies in resistate elements (Ti, Zr) in berthierine-rich beds, and the presence of berthierine-rich clasts in overlying sandstones (Retallack, 1986b; Maynard, 1992).

Although this paleosol probably developed on shale, this is not to say that paleosols formed directly on basalt do not also exist at about this stratigraphic level. Such a profile below the Waterval Onder clay paleosol was too weathered within the surface soil zone to be worth studying geochemically. The Daspoort Tunnel road cuts near Pretoria may be fresh exposures of a paleosol developed on basalt, but here too there is an overlying sericitic unit with sharp basal contact and distinct chemical composition surprisingly rich in soda (Hart, 1986). The post-Hekpoort Geosol is a remarkably widespread unit (Button, 1979) that includes a variety of different local paleosols on basalt, colluvium, alluvium and perhaps even estuarine sediments.

Reinterpretation of the Waterval Onder clay paleosol as a profile developed on sediments overlying basalt casts doubt on whether it indicates only 3×10^{-4} atmospheres (0.0015 PAL) of free O_2 some 2.2 Ga ago (Holland and Zbinden, 1988), and thus a dramatic rise to 3×10^{-2} atmospheres (0.15 PAL) by 1.9 Ga, as indicated by another paleosol developed on the Kuruman Iron Formation in Griqualand West (Holland and Beukes, 1991). As interpreted here, the Waterval Onder clay paleosol is enriched in iron, and its sedimentary parent material has a much lower compositional reducing power (Holland's R value of about 2.96×10^{-2}) compared with the Hekpoort Basalt (R about 4.5×10^{-2}: Retallack, 1986b). Because of the low compositional reducing power of its parent material and its gain in iron, the Waterval Onder paleosol does not indicate an especially low atmospheric oxygen level. Significant amounts of atmospheric oxygen during formation of the Waterval Onder paleosol are compatible with its abundant surficial opaque oxides (Retallack, 1986b), and very low levels of reduced carbon (R. Dorn, pers. commun., 1984; H. Strauss and A.J. Kaufman, pers. commun., 1988). Although the Waterval Onder profile is no longer especially critical as an indicator of atmospheric composition, other paleosols of the post-Hekpoort Geosol may prove more important when analyzed in detail.

An additional disappointing result of the present work is that metamorphism precludes study of the ultrastructure of possible microbial trace and body fossils in the Waterval Onder paleosol because of pervasive recrystallization. Light microphotographs of possible rock varnish structures (Fig. 3) provide all the detail available. Recrystallization does not allow higher resolution of such features as ministromatolites or compositional banding that would make interpretation as biologically mediated rock varnish convincing. Some tubular and club-shaped structures currently under investigation in this paleosol must also remain dubiofossils because convincing ultrastructural details cannot be obtained by backscattered electron microscopy or probably any presently available technique.

A residue of arguments remain that this paleosol supported life (Retallack, 1986b, 1990). What else could have mitigated gully erosion of this thick, clayey, well-drained paleosol and its cracked and brecciated zones of coated clasts (peds and cutans of soil terminology)? Why else would there be a surficial enrichment in trace elements (P, Ba, Cr, Cu, Ni) commonly enriched with organic matter in the surface of paleosols? Why else would it be so much lower in organic carbon than many Precambrian sedimentary rocks? These and other approaches remain for investigating how much and what kinds of life existed on land during Precambrian time, but ultrastructural studies of this and other paleosols metamorphosed to comparable degree are unlikely to be useful.

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