Morphology and Age Relationships of Antarctic Soils

I. B. Campbell and G. G. C. Claridge

Soil Bureau, Department of Scientific and Industrial Research,
Lower Hutt, New Zealand

Abstract

Glacial deposits in East Antarctica have been widely studied in recent times; with increasing knowledge of their ages, largely through potassium/argon dating of related rocks, it has become apparent that these deposits form sequences extending through the whole of the Quaternary period.

Soil studies in Antarctica have shown that weathering processes can be expressed in the soil profile by a number of distinctive morphological properties and that soil differences can be related to a number of factors, including topography, climate, and time. Using these characteristics it is possible to recognise up to six weathering stages in soils formed on moraine and regolith along the Trans-Antarctic Mountains. Accepting the current chronology for dated deposits in the McMurdo Sound region, apparent ages for these weathering stages are proposed: *Stage 1*—up to 50 000 years; *Stage 2*—50 000-500 000 years; *Stage 3*—0.5 to 2.1 m.y.; *Stage 4*—2.1 to 3.5 m.y.; *Stage 5*—>3.5 m.y.; *Stage 6*—>>3.5 m.y.

These weathering stages have been observed in a number of places along the Trans-Antarctic Mountains and suggest contiguity of glacial events throughout East Antarctica throughout the Quaternary and in the Pliocene.

Introduction

The nature and the age of glacial deposits in East Antarctica have been widely studied from the period of early exploration until the present. Recent studies, particularly in the vicinity of McMurdo Sound, but also in other scattered localities along the Trans-Antarctic Mountains, have shown that there have been several periods of glacial advance and retreat; chronologies have been established and a number of attempts have been made to correlate various glacial deposits (see, among others, Péwé 1960; Nichols 1961; Bull 1962; Mercer 1963; Calkin 1964; Ugolini and Bull 1965; Grindley 1967).

With increasing knowledge of the significance of the glacial deposits, it has become apparent that the glacial sequences, and the soils developed on them, span a far wider time than was previously thought. This largely resulted from the recent establishment of an absolute chronology for deposits in the McMurdo Oasis based on potassium/argon ages of basalts emplaced during and after some periods of ice advance and retreat (Calkin *et al.* 1970; Denton *et al.* 1970). Apart from this region, the only means of correlating glacial deposits at present is by the use of comparisons of soil development and weathering processes. When weathering and soil development on surfaces of unknown age are compared with those found in the McMurdo Sound region, an estimate of the ages of the glacial deposits throughout Antarctica can be made.

Previous Soil-Weathering Studies

Only in the last decade has it been shown that soil weathering processes in Antarctica are expressed in the soil profiles by a number of distinctive morphological properties. Ugolini (1963) suggested that the main features of the soils were due to salinisation and oxidation, and, from an examination of moraines in the Wright Valley, Tedrow and Ugolini (1966) considered that mechanical composition, depth to frozen ground, electrical conductivity, pH, and salt content were properties that could be used to indicate age differences in the soils. Claridge (1965) showed that clays in antarctic soils can be produced by slow hydration of mica and its expansion to vermiculite; and that montmorillonite was probably present as a result of aridity and high pH. Kelly and Zumberge (1961) examined exposed quartz-diorite rocks at Marble Point and found that no clays were being formed, and that chemical alteration was confined to the oxidation of ferrous iron to ferric hydroxides. In an examination of soils in the Taylor Valley, McCraw (1967) found soil development to be weak and the effects of time difficult to distinguish from other variables, although small differences attributable to age differences were noted.

The recognition of major weathering differences between antarctic soils was made by Campbell and Claridge (1967, 1968) and Claridge and Campbell (1966, 1968a, 1968b) when they examined soils in a number of places along the Trans-Antarctic mountains—Cape Hallett, Inexpressible Island, Victoria Valley, Darwin Glacier, and Shackleton Glacier. The soils examined covered a range of climatic conditions between coastal Antarctica and the edge of the interior antarctic plateau (Weyant 1966), under differing biological conditions, and at greatly differing altitudes, where surfaces and moraine deposits were obviously of greatly differing ages. These examinations showed that soil differences could be attributed to a number of factors.

1. Soil development and morphology were influenced by relatively small topographic differences. Soils in hollows and small depressions had greater concentrations of salts in their profiles than elsewhere, and soils on stable slopes where there was no cryoturbic movement were better developed than those on slopes where there was pronounced cryoturbic movement.

2. The influence of climate was expressed in the soil through the salts present in the profile and the manner in which they were distributed. Soils of the most arid regions had salts that included mainly nitrates concentrated in a thick band; soils of comparatively moist environments contained more chlorides, and the salts tended to be dispersed through the profile rather than concentrated in a single horizon. Also, where the water equivalent from summer snowfall and thaw was comparatively high, frozen ground was present at shallow depths, where as it was either deep or not observed in the most arid regions.

3. The influence of the biological factor on soil development processes was found to be restricted to the relatively few habitats where there are significant concentrations of plant and animal life.

4. Soil formation and degree of weathering could be clearly expressed by the development of a distinctive colour profile and by increasing oxidation; by the amount of rounding, staining, and polishing of surface rocks; by increase in amount of soluble salts present in the profiles; by small but significant increases in the amounts of clay present in the upper parts of the profiles; by the state of hydration and weathering of the clay minerals; and, in the case of soils formed on ablation moraines, by increases in the depth of soil underlying glacial ice. There was a clear relationship between the development of these soil properties and the age of glacial surfaces and deposits, as is outlined below.

Recent studies by Everett (1970) in the vicinity of the Meserve Glacier, Linkletter (1973) in the Taylor Valley, and others have confirmed the significance of the chemical and physical criteria noted above in the pedogenesis of Antarctic soils.

SOIL MORPHOLOGICAL CHARACTERISTICS DEVELOPED WITH INCREASING AGE

Because of the antiquity and stability of most of the geomorphic features of glacial deposits, many of the soils have remained virtually undisturbed since deposition of the parent material. This is shown in a number of ways, for example by perched boulders or by the shape and weathering relationships of many surface boulders. Deflation of surfaces to form stone pavements and fragmentation of boulders to form a superficial veneer of debris both undoubtedly occur, but they are often local rather than widespread occurrences. In many places the degree of profile development on moraines or other deposits reflects the amount of weathering since deposition.

Observations made over several field seasons and in many localities throughout the Trans-Antarctic Mountains suggest that weathering is progressive with increasing distance or elevation away from present ice levels. It is possible to recognise six weathering stages in the soils of the region on the basis of field criteria and laboratory examination. The characteristics of these weathering stages are given below and summarised in Table 1.

Stage 1

The first weathering stage consists of the least weathered soils, those in which the expression of soil weathering processes is almost negligible. The soil surface is commonly very bouldery, and rocks are fresh, unstained, and angular. Beneath the surface, the material is normally weakly consolidated or loose. The soil colours are influenced by the lithology of the material of which they are composed and are commonly pale olive to light grey (5Y 6/3 to 7/2) although they may be more strongly coloured if the detritus has been weathered prior to transport. Whatever the colour of the parent material however, profiles of the first weathering stage are monochromic and show no colour horizonation.

TABLE 1.—Morphological Development of Soils with Increasing Weathering

Weathering Stage	Surface Rock Characteristics	Soil Colour	Horizon Development	Soil Salts	Soil Depth	Other
1	fresh, unstained, coarse and angular	pale olive to light grey (5Y 6/3-7/2)	nil	absent	very shallow, underlain by ice	moderate patterned ground development
2	light staining, slight rounding, some disintegration	pale brown to light brownish grey (10YR 6/3-2.5Y 6/2)	weak	few flecks	shallow, underlain by ice	strong patterned ground development
3	distinct polish, staining and rounding, some cavernous weathering,, some ventifacts	light yellowish brown (10YR 5/3-2.5Y 6/4)	distinct	many salt flecks in upper part of profile and beneath stones	moderately deep	some disintegration of boulders in the soil, slight increase in fine fraction
4	boulders much reduced by rounding, crumbling and ventifaction, strongly developed cavernous weathering; staining and polish well developed; some desert varnish	yellowish brown (10YR 5/4) in upper horizons, paler in lower horizons	very distinct	in discontinuous or continuous horizon beneath surface	deep	(*as for Stage 3*)
5	few boulders, many pebbles forming pavement, extensive crumbling, staining, rounding, pitting and polish	dark yellowish brown to yellowish red (10YR 4/4-5YR 5/8)	very distinct	in horizon 20-30 cm from surface and scattered throughout profile	deep	(*as for Stage 3*)
6	weathered and crumbled bedrock, very strongly stained, mainly residual	strong brown to yellowish red and dark red (7.5YR 5/6-5YR 4/8 or 2.5YR 3/6)	very distinct	(*as for Stage 5*)	shallow to deep	bedrock sometimes crumbled to 50 cm depth

The textures of Stage 1 soils are variable and are inherited from the parent material. There are no accumulations of salts under stones or within the profile, although salt accumulations are occasionally found in undrained depressions where percolating waters carrying salts have evaporated. The soils are shallow and are formed on ice or on frozen ground.

These soils are found on the youngest glacial deposits of Antarctica, along the margins of the valley glaciers and around the alpine glaciers, on fans and other alluvial deposits and on coastal benches. In some places these deposits can be quite extensive but are usually limited to a narrow band around glacial margins. Near the edge of the ice, these deposits comprise little more than a few centimetres of coarse-textured ablation moraine, as the fine fractions have been blown away, but away from the ice edge (where the cover of moraine is thicker), the fine fraction ablating from the ice is trapped by the overlying coarse skeleton and the moraine deposits are fine-textured. A typical soil of this stage is shown in Figure 1.

Stage 2

Soils of the second weathering stage are still only weakly developed, even by Antarctic standards, but they do show some evidence of weathering processes and horizonation (Table 1). Surface boulders and pebbles may be lightly stained, while some rounding due to fragmentation and abrasion is noticeable. The main morphological developments in the profile include a small but perceptible increase in intensity of colour at or near the soil surface, an increase in profile thickness, and the occurrence of some salts, usually as small flecks within the upper part of the profile. In many places, even on steep valley sides, the soils overlie old glacial ice, although in moister locations near the coast they may overlie frozen ground.

Stage 2 soils are more extensive than those of the first stage and are found on older moraine deposits. In the major glacial valleys these soils are found on moraines up to 400 m above glacier levels, although in the middle and upper reaches of the valleys they are generally less than 200 m above glacier levels. In the Taylor and Wright Valleys, these soils are found mainly at lower elevations and on valley floor moraine, except where they are formed on alpine moraines at higher elevations, where they are again found usually in a narrow zone adjacent to the alpine glaciers.

Stage 3

Soils of the third weathering stage are distinctly more weathered than those of the second stage. Surface boulders and pebbles commonly show distinct rounding, and also some cavernous weathering and ventifaction; they are generally a little smaller and less numerous than those on the younger and less weathered surfaces. Oxidation and staining of the surface rocks and wind polish on the fine-textured rocks is also distinct while exfoliation and pitting are frequently found. Within the profiles, horizonation is distinctive; soil colours are light yellowish brown (10YR 6/4-2.5Y 6/4) in the upper part of the profile, decreasing in chroma and value downward to olive brown (2.5Y 4/4) or pale olive (5Y 6/3). The surface horizon is often found to be a little paler than the horizon immediately beneath as a result of the accumulation of fragmental material from surface boulders. Rock fragments in the profiles often show some oxidation and staining on their surfaces.

The profiles of this weathering stage also have a small although distinctive increase in the proportion of finer material within the top 20 - 30 cm. This gives the soil a more powdery appearance, a somewhat softer consistency underfoot, and a greater cohesion in profile pits. The higher proportions of clay and silt in the soils of this weathering stage probably result from the freeze and thaw of occasional surface snow melts.

Another significant morphological difference in the Stage 3 soils is the form and amount of salts present in their profiles. Salt accumulations occur beneath many of the surface boulders in flecks or in small lenses. They are most commonly found within the upper 30 cm of the profile although sometimes are found in small flecks through the whole profile.

These soils are formed at intermediate levels in valleys of major glaciers, in the dry valleys, and on the older deposits of the alpine moraine sequences (see Figure 2 for a typical Stage 3 soil). In some areas, including the valleys of the Scott and Shackleton Glaciers, small increases in the degree of profile development have been noted in soils formed on successions of moraines separated by only minor changes in physiography or relief. Locally it is possible to separate Stage 3 soils, but they have been difficult to trace regionally because of differences in local glacial control, parent material, and climate.

Stage 4

Soils of the fourth weathering stage are characterised by much more advanced weathering of the surface boulders and rocks. Large boulders are rare and may show very strong cavernous weathering or pitting, but most boulders are small, rounded, and well stained.

The degree of oxidation and horizon development is greater than that found in the soils of the third weathering stage. Below the well-stained layer of surface exfoliate, the soil colours are generally yellowish brown (10YR 5/4) to dark brown (10YR 4/3), decreasing in chroma and value with increasing soil depth to brownish yellow (10YR 6/8) or olive yellow (2.5Y 6/6).

In profiles of this stage, salts are often abundant beneath surface boulders and also through the profiles. In inland and high-altitude areas where the soils are very dry the salts are sometimes found in a concentrated and slightly consolidated horizon a few centimetres below the surface of the soil; nearer the coast and at lower altitudes where the soils are not so dry the salts are often found as abundant flecks throughout the profile.

Like the soils of the previous stage, these soils also appear to have increased amounts of silt and clay in the horizons within about 40 cm of the surface. The coarser-grained boulders in the profiles are often found to have disintegrated, and they crumble during excavation of the profile pits.

Stage 4 soils are found mainly on high benches and spurs and are formed on some of the oldest moraine deposits of the present glacial episode. For example, in Taylor and Wright Valleys, they occur on high moraine deposits between 400 and 900 m above the valley bottoms, although they are found at somewhat higher elevations in major glacial valleys such as those of the Scott and Shackleton Glaciers. Figure 3 shows a typical soil of this stage.

Stage 5

This weathering stage includes the most weathered soils formed on moraine deposits in Antarctica, and

FIG. 1 (left).—Soil of weathering stage 1, from recent moraines of the Rhone glacier, Taylor Valley.
FIG. 2 (right).—Soil of weathering stage 3, from moraines of the Meserve glacier, Wright Valley.

soil development is significantly more advanced than in previous stages. Soils have a very strongly developed desert pavement, with surface boulders reduced to small ventifacts or sometimes stained with a distinctive dark coating of desert varnish, extremely pitted. The colours of soils containing dolerite are dark reddish brown to yellowish red (5YR 3/3-5/8) while soils on granite are somewhat browner (dark yellowish brown to light yellowish brown, 10YR 4/4 - 5/4). The colour development often extends to below 50 cm. Beacon Group rocks in the profile are completely disintegrated to a powdery sand.

Soils of this weathering stage are formed on moraines which occur as small deposits in a few areas and are considered to be remnants of a glacial episode earlier than that which gave rise to the oldest Taylor

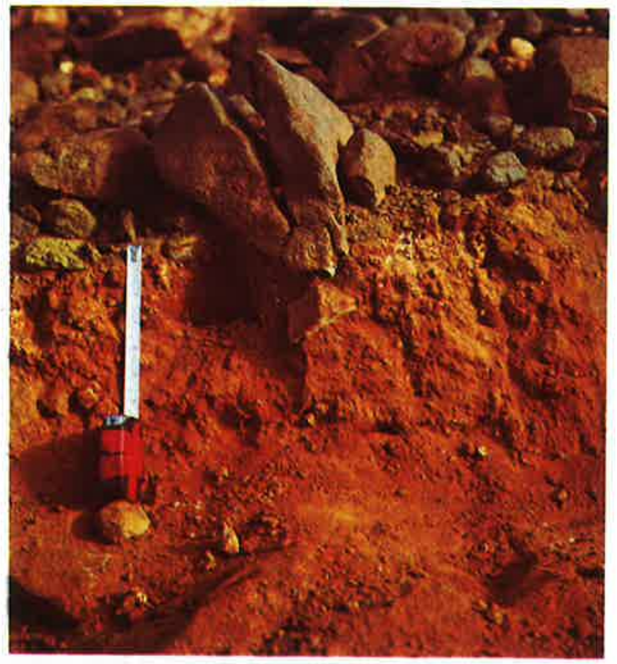

FIG. 3 (left).—Soil of weathering stage 4, from moraines of the Taylor glacier.
FIG. 4 (right).—Soil of weathering stage 5, from moraines in a dry cirque in the Asgard range, above the Wright Valley.

and Wright glaciation (Denton *et al.* 1970; Calkin *et al.* 1970) or their equivalents. They have been observed on very high benches in the Scott and Shackleton Glacier valleys, and also in the Wright Valley, in the dry hanging valleys near Mt. Thor (Fig. 4) and no doubt occur elsewhere where they have been preserved.

Stage 6

Soils of this stage are the most weathered soils found in Antarctica by the authors. Unlike soils of the previous weathering stages, which were formed on moraine deposits, these soils are residual, deriving from *in situ* weathering of the local rock. Their residual nature is illustrated by the almost complete absence of rock fragments with compositions differing from that in the parent rock below the profiles. These soils are the most striking yet seen by the authors in East Antarctica. Surface features associated with them include the deep etching and erosion, sometimes to a depth of several metres, of the surrounding rock to bizarre forms often reminiscent of modern sculpture.

The most characteristic feature of the profiles is their soil colour. On fine-grained quartz porphyritic meta-volcanic rocks in the Scott Glacier region, the soils have a strong brown (7.5YR 5/6) colour with only a slight decrease in chroma at a depth of 50 cm, while salts are very abundant and form a thick horizon. In a profile from dolerite at Roberts Massif the soil was even more strongly coloured (reddish brown and yellowish red, 5YR 5/3 and 5YR 5/8) and contained abundant salts. Similar soils with dark red (2.5YR 3/6) and yellowish red 5YR 4/8) horizons but without such distinctive salt horizons were observed on high surfaces in the Asgard Range. In the valley of the Scott Glacier, soils of this stage have been found on very high knolls about 500 m above glacier level on the Ackerman Ridge near the head of the glacier. Similarly weathered soils have also been observed about 400 m above the polar plateau at Roberts Massif in the Shackleton Glacier, and near Mt Thor on a high surface about 500 m above the Wright Glacier.

ANALYTICAL EVIDENCE FOR WEATHERING STAGES

The six weathering stages are also recognisable from analytical data obtained for the soils, but care is needed in the interpretation of the data. Although as a general principle the older stages are more weathered and contain more fine-particle sized material than the younger, it is necessary to take account of the nature of the original parent materials. Some young moraines may be coarse and bouldery, others may be initially very fine-textured, and these differences are often greater than the changes caused by long continued weathering. The lithology of the moraine is also significant, sedimentary rocks often breaking down rapidly to the size grading of the original sediment, yielding abundant, although unweathered clay size material, while igneous rocks reduce initially to the grain size of the crystals that they contain. Again, these textural differences persist.

Clay minerals and extractable iron are more sensitive indicators of weathering, provided that a suite of soils on one parent material is being considered. As weathering progresses the micaceous minerals, initially somewhat disordered and of low crystallinity due to damage during transport, become more ordered, and the proportion of the hydrated forms of mica increases. In many soils of the fifth and sixth weathering stages the micas may be completely converted to montmorillonite, although some of this mineral may be authigenic, derived from the weathering of ferromagnesian minerals and feldspars.

Extractable iron values increase from 0.2-0.3% in soils of Stage 1 to as high as 4-5% in some very strongly weathered soils of Stage 6, although for most sequences they do not rise above 1%. The amount depends on the quantity of iron contained in weatherable minerals in the parent material, so consequently soils from granite or granitic moraine are less strongly coloured than those from dolerite. The form of the iron depends on the amount present and whether the climate is dry enough to dehydrate goethite to haematite. This dehydration tends to take place slowly in nearly all antarctic environments, so older soils tend to be redder as well as more strongly coloured.

Salts accumulate in the soil as a result of weathering, or more commonly, from precipitation (Claridge and Campbell 1968c). In arid sites there is little or no leaching, but in moister conditions salts may be leached out. They are among the most mobile constituents of antarctic soils, and recent work indicates that salts may move along humidity gradients (H. Keys, pers. comm.). Nevertheless, greater accumulations of salts are found in the older soils, and in the oldest and driest the accumulations may be quite massive. Accumulations of salt range from less than 0.1 kg/m^3 in soils of Stage 1 to 1.00 kg/m^3 in the oldest and driest soils found.

TABLE 2.—Suggested Relationships of Soil Weathering Stages of Glacial Deposits in East Antarctica

Proposed Weathering Stage	Probable Age (yr BP)	Alpine Glaciations (Denton *et al.* 1970) (yr BP)	Taylor Glaciations (Denton *et al.* 1970) (yr BP)	Lower Wright Glaciations (Calkin *et al.* 1970)	Victoria Valley Glaciations (Calkin 1964)	Queen Maud Range (Mayewski & Goldthwait 1973)
Stage 1	0-50 000	Alpine 1 12 200	Taylor 1	Lower Wright	Packard	Swithinbank
Stage 2	50 000-500 000	Alpine 2 0.4×10^6	Taylor 2	Trilogy	Vida	Shackleton
Stage 3	$1.5 - 2.1 \times 10^6$	2.1×10^6 Alpine 3 3.5×10^6	Taylor 3 1.6×10^6 2.1×10^6	Loop	Bull	Scott
Stage 4	$2.1 - 3.5 \times 10^6$		Taylor 4 2.7×10^6 3.5×10^6	Pecten	Insel	
Stage 5	$>3.5 \times 10^6$		Taylor 5			
Stage 6	$>> 3.5 \times 10^6$					Queen Maud (probably older)

CORRELATION

Within the McMurdo Sound region a number of glacial chronologies based on geomorphological and soil evidence have been drawn up. These chronologies have been tied to radiometric ages from volcanic eruptions that took place 2-4 m.y. ago. Other chronologies have been erected for areas away from the McMurdo Sound region where radiometric control is not available. In all these areas the six weathering stages described in this paper have been recognised; this has permitted a correlation between the various chronologies to be drawn up (Table 2). It is also possible, using the assigned ages for some of these events, to assign approximate ages for the younger weathering stages, and then to extrapolate in order to estimate the ages of the older stages. Judging by the relative difference in weathering between Stage 4 (*ca.* 3.5 m.y.) and Stages 5 and 6, it is obvious that Stage 5 must be older than 3.5 m.y. and Stage 6 must be very much older again. The maximum age is given by the time of onset of glaciation in Antarctica, which is now thought to be mid-Miocene (approximately 15 m.y. ago) (Hayes *et al.* 1973).

It is thought that the onset of glacial conditions was associated with a period of intense glacial erosion which cut the basic features of the present topography and deposited the Sirius Formation (Mercer 1972), a widespread deposit of glacial till apparently deposited by wet-based glaciers. However, it is considered that the sixth weathering stage recognised here postdates the Sirius Formation.

CONCLUSIONS

Along the mountains of East Antarctica the widespread glacial deposits can be divided into a series of soil-weathering stages which can be correlated with glacial events of varying magnitude. Within some of the valley systems it has been possible to place absolute ages on some of the glacial events, and this has established that the history of glacial events in Antarctica extends over a much longer period of time than that covered by the Quaternary record of temperate regions.

The recognition that the six weathering stages described here are found, in whole or in part, throughout the Trans-Antarctic Mountains, implies that glacial events through East Antarctica took place in synchrony. It is therefore possible to draw up a regional correlation and extend the chronology established by radiometric dating in the Taylor and Wright Valleys to all the glaciated regions of east Antarctica. Establishment of the correlation on a soil-weathering basis makes it possible to extrapolate the time scale beyond that available from radiometric data and makes plausible the statement that some surfaces in Antarctica may have been exposed to weathering since at least the beginning of Pliocene times.

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