A COMPARISON OF THE WEATHERING OF IGNEOUS ROCKS AT LONG RIDGE AND BLACK HILL, WESTERN MURRAY BASIN, SOUTH AUSTRALIA.

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SUMMARY

In this study, microscopic, X-ray spectrometric and X-ray diffraction techniques have been used to investigate the weathering of a granodiorite and a norite exposed in the western Murray Basin, South Australia.

Weathering along joints and near-surface weathering profiles from both sites were analysed. Clay formation around individual crystals adjacent to joints appears to have initiated the physical disintegration of the rock at both sites.

Mineral stability and the mobility of elements follow the trends outlined by earlier workers, but different microenvironments produce on the one hand varied weathering products developed on the same parent rock, and, on the other, similar weathering products on both types of rock. Montmorillonite has formed in response to impeded drainage on both rocks, and nontronite has formed in joints at Black Hill. Illite, kaolin and randomly interstratified material are formed from both rock types. Weathering products inherited from a previous environment can be distinguished at Black Hill.

STATEMENT

This thesis is based on original research carried out in the Department of Geography, University of Adelaide. It contains no material previously submitted for a degree at any University, and to the best of my knowledge contains no material previously published or written by another author except when due reference is made in the text of the thesis.

Dianne S. Lindsay

February, 1980

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CHAPTER 1

INTRODUCTION

Weathering is the process whereby minerals formed under one set of conditions are altered to form minerals which are in equilibrium with the temperatures and pressures found at and near the earth's surface.

Rock types vary in their susceptibility to weathering, as do their constituent minerals. A broad measure of agreement has been reached concerning the relative stability of the rock forming minerals when exposed to the agents of weathering. The order of stability is generally the reverse of the Bowen reaction series given in Table 1 (Goldich, 1938; Brewer, 1964; Loughnan, 1969). However, although undoubtedly valid in general terms, this sequence is oversimplified for "the stability or resistance to weathering of a mineral species depends on a large number of factors, which include hardness, cleavage, coefficient of expansion, original cracks in the crystal and solubility under a specific environment." (Haseman & Marshall, 1945). Thus the degree of mineral alteration that takes place during weathering and the mineralogy of the weathering products depends on rock type, structure and composition as well as local environmental factors such as climate, relief and drainage.

TABLE 1.

MINERAL-STABILITY SERIES IN WEATHERING

(After Goldich, 1938, p.56.)

Olivine	Calcic plagioclase
Augite	Calcic-alkalic plagioclase
Hornblende	Alkali-calcic plagioclase
Biotite	Alkalic plagioclase

Potash feldspar
Muscovite
Quartz

Studies by Tiller (1962), Craig and Loughnan (1964), Nettleton, Flach and Nelson (1970), Dan and Singer (1973), Tardy, Bocquier, Paquet and Millot (1973), Gunn (1974), Adams, Campbell and Cutler (1975), illustrate the role which climate, relief, drainage and biological factors can play in the development of different weathering products on the same rock type. Barshad (1966) and Bjorlykke (1975) have shown that in the same climatic and topographic situation contrasted rock types can be weathered to produce different end products. On the other hand, Butler (1953) has recorded that different rock types weather to the same products under similar climatic conditions.

Thus, there is no simple formula for rock weathering. There are many variables which need to be taken into account when studying the complex of weathering processes and products.

The ideal site for study contains a weathering profile (regolith), and outcrop of fresh rock associated with it. Several of the outcrops of crystalline rock in the western Murray Basin lack the first of these requirements, but an outcrop of granodiorite known as Long Ridge and the norite of Black Hill both proved suitable. These sites have been quarried for facing stone, providing good exposures of joints and associated weathering. Regolith and fresh rock are well exposed so that their relations are clear and weathering profiles are readily sampled (Figure 1).

The western Murray Basin is hot and semi-arid. Most of the studies cited above have been carried out in humid or temperate areas of the earth's surface, so that the study area offers an opportunity to investigate causes and products of the weathering of two different rock types but in a climatic environment that has not previously received much attention.

AIM

The aim of this study is to investigate the physical and chemical weathering of two petrologically contrasted crystalline rock types from the western Murray Basin, South Australia.

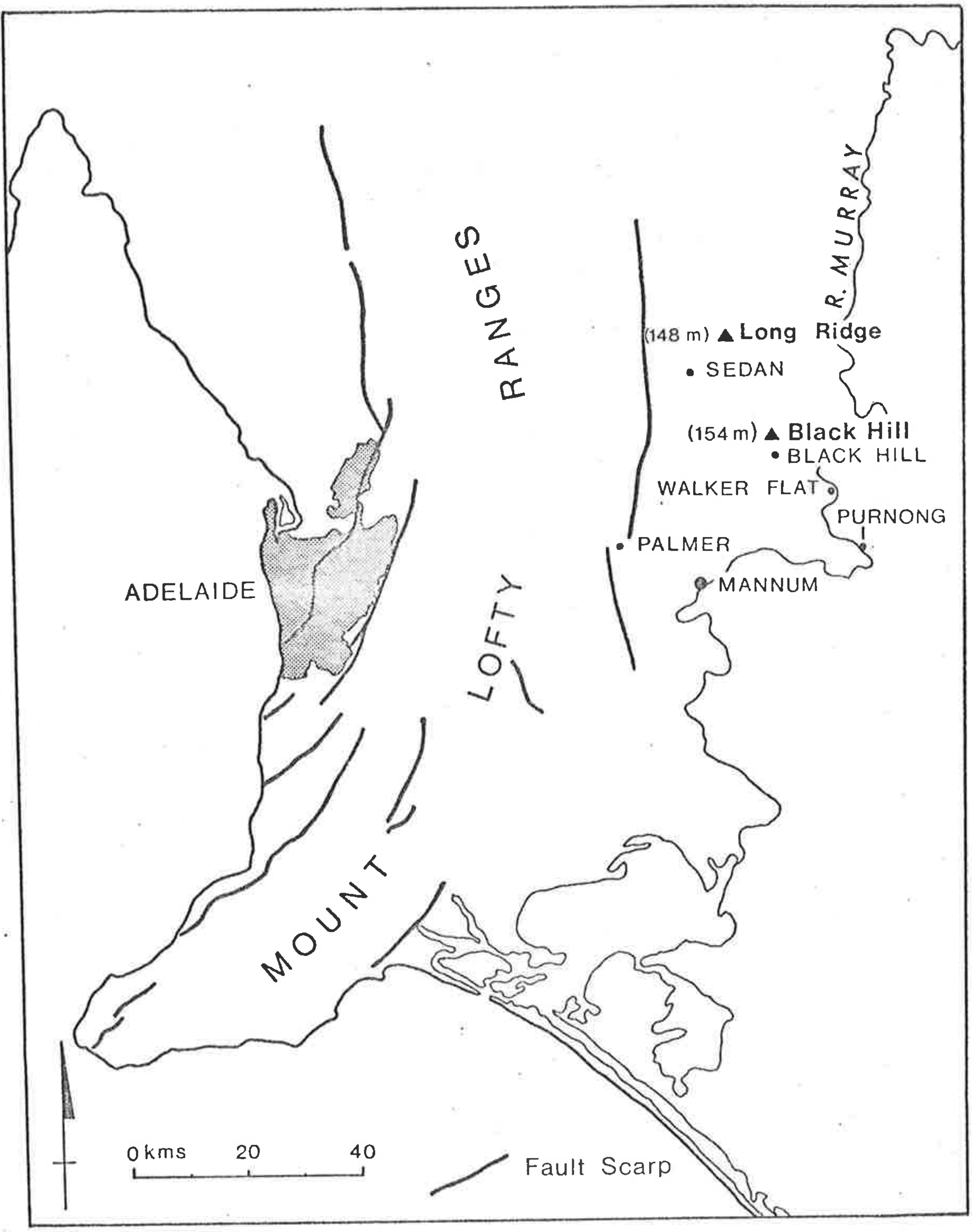

Fig. 1. Location of study area.

In detail this includes determining:

1. the mineralogy and chemistry of the fresh rock using thin section microscopy and X-ray spectrometric analysis.
2. the relative stability of the rock forming minerals.
3. the processes causing the physical and chemical weathering of the rock, utilising field observations, thin section analysis, X-ray diffraction and X-ray spectrometric analysis.
4. the mobility of the rock forming elements during weathering using X-ray spectrometric analysis and comparing it with work carried out on other rock types in various climates.
5. the mineralogy of the weathering products formed along joints and in weathering profiles at various sites on both rocks, using X-ray diffraction techniques.

In the light of these findings and those of other workers, explanations are offered for the changes demonstrated. These explanations involve consideration of the following:

(a) the influence of the semi-arid climate on the mineralogy of the weathering products.

(b) the influence of the rock chemistry on the mineralogy of the weathering products.

THE GENERAL STUDY AREA

The undulating surface of the western Murray Plain is underlain by the Kanmantoo Group of sedimentary rocks of early Palaeozoic age, into which granites, granodiorites and some norite were intruded during the Ordovician (Milnes, Compston & Daily, 1977). Limestone laid down during a Miocene marine transgression overlies the Kanmantoo rocks and is exposed in the cliffs of the modern River Murray Gorge, and encountered in bores and road cuttings.

On the plain itself the Tertiary strata are largely masked by the riverine-lacustrine Blanchetown Clay of early Pleistocene age and by later Quaternary dune sand and calcrete. The inliers of granodiorite and norite now form topographic highs standing above the general level of the surrounding plain (Figures 2 and 3).

The western Murray Basin has a semi-arid climate. Most of the rainfall occurs in the winter months, from May to September. An average annual rainfall of 302 mm has been recorded at Sedan over the last 90 years (Figure 1).

LONG RIDGE

The outcrop of granodiorite known as Long Ridge lies 10 km north of Sedan, on the Sedan-Blanchetown road, 75 km north-east of Adelaide (Figure 1). It stands 148 m above sea level and 55-59 m above the surrounding plain.

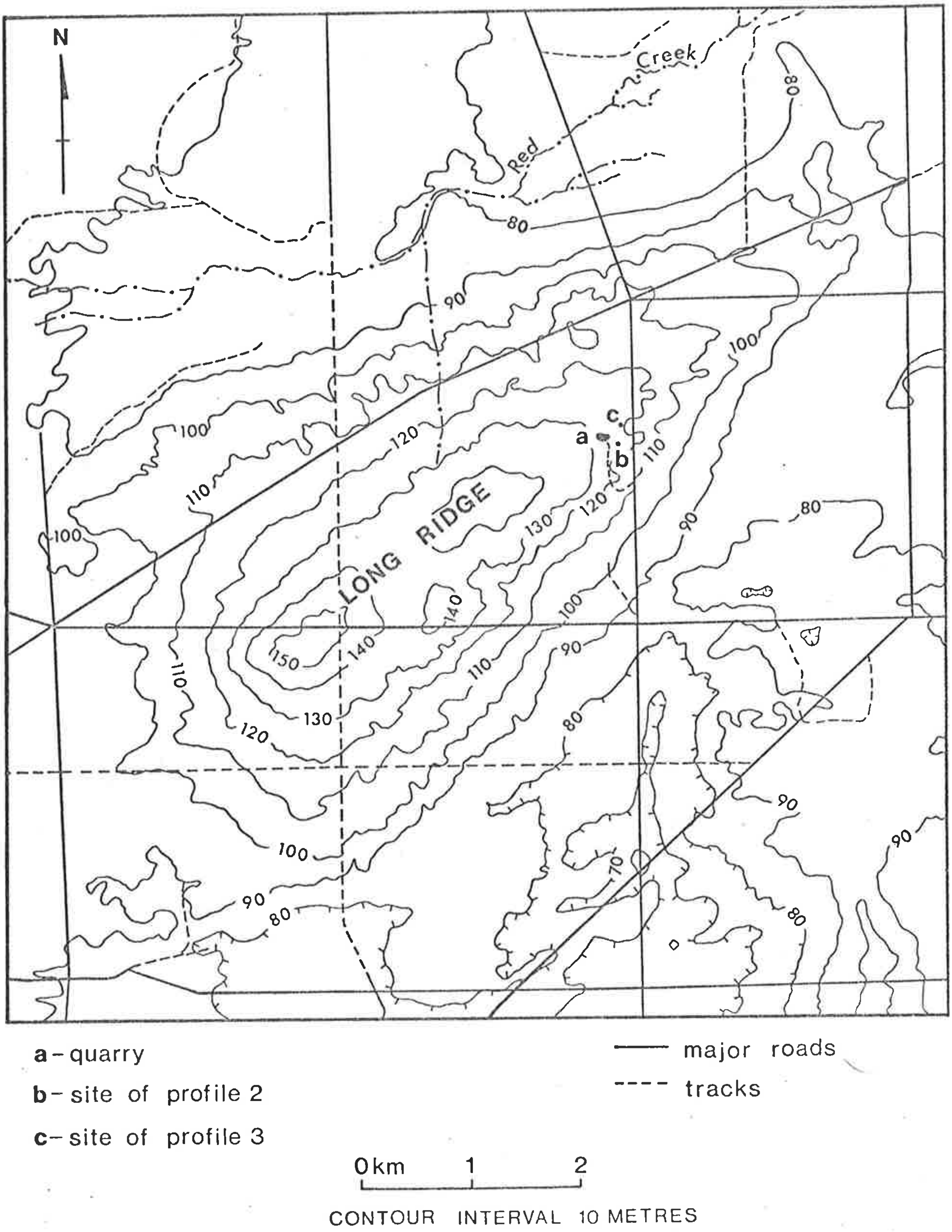

Fig. 2. Long Ridge. - Topography

Source: Sandleton (Draft).
1:50,000 Topographic Series
South Australian Dept. of Lands

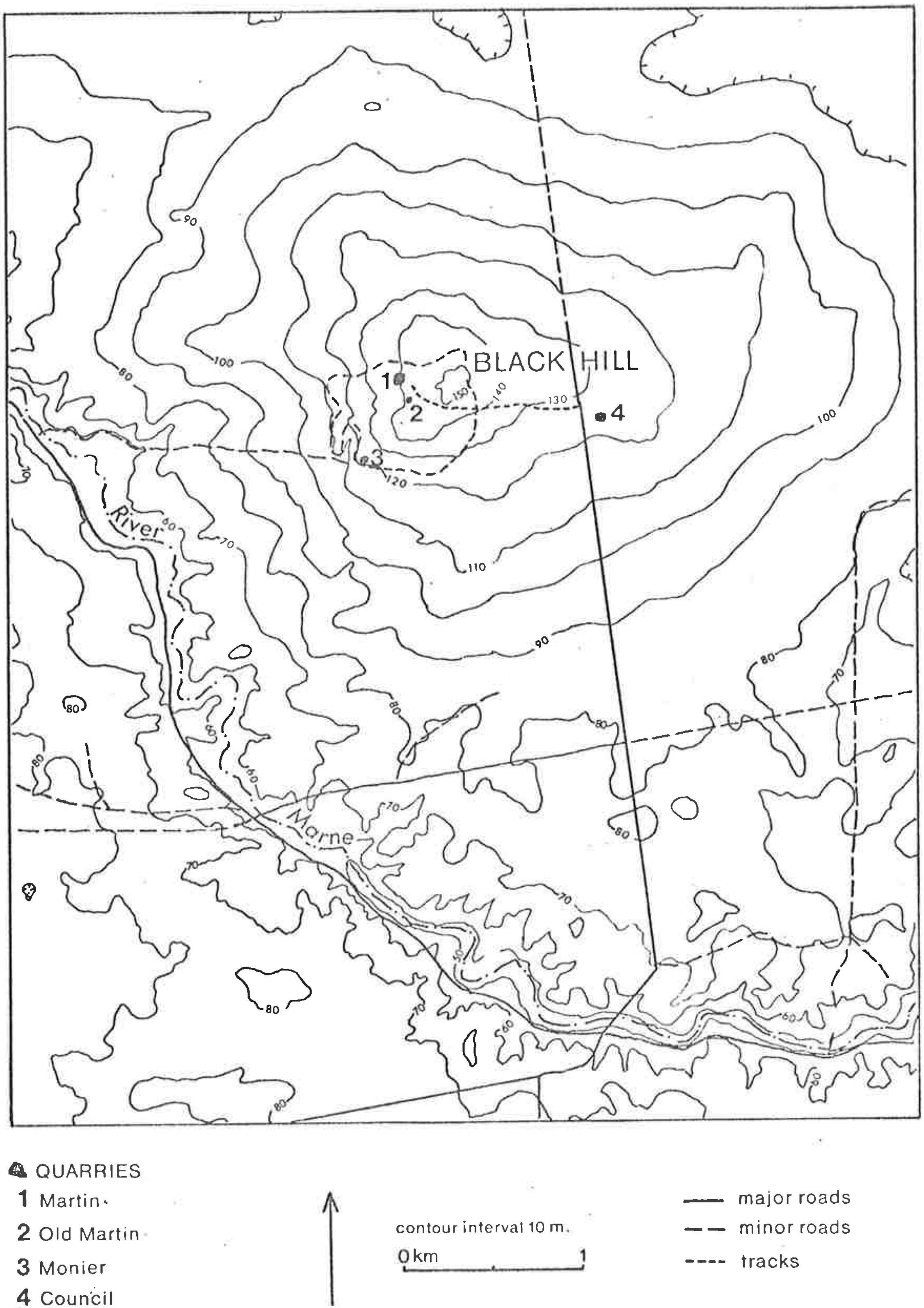

Fig. 3. Black Hill. - Topography

Source: Cambrai 1:50,000
Topographic Series, 1973.
South Australian Dept. of Lands

(i) Petrology

The granodiorite contains plagioclase, potash feldspar, quartz and biotite. The outcrop is the site of a small quarry which has exposed the joint system and weathering patterns. Near the surface in the quarry, the rock is predominantly pink in colour and medium grained, with pink potash feldspar, white plagioclase and grey quartz. Xenoliths of a pale grey fine grained rock, occur in the pink granodiorite. The fine grained rock occurs more frequently at depth in the quarry walls.

The quarry was a source of pink facing stone and the xenoliths of white rock were regarded as flaws in the stone. As the white rock is more prevalent with depth the quarry became no longer viable and quarrying ceased (Mr. R. Rowley, pers. comm.).

(ii) Geomorphology

The landform assemblage developed on the Long Ridge granodiorite is limited in variety. The South-western slopes are boulder strewn (Plate 1). One boulder displays a flared slope (Plate 2), which indicates that stripping of the regolith has occurred, as flares are usually developed in the sub-surface (Twidale, 1962). A rock pavement occupies most of the crest of the ridge. It is a weathering front or etch surface exposed on removal of the regolith (Plates 3 and 4).

Plate 1. Groups of boulders on the South western slopes of Long Ridge.

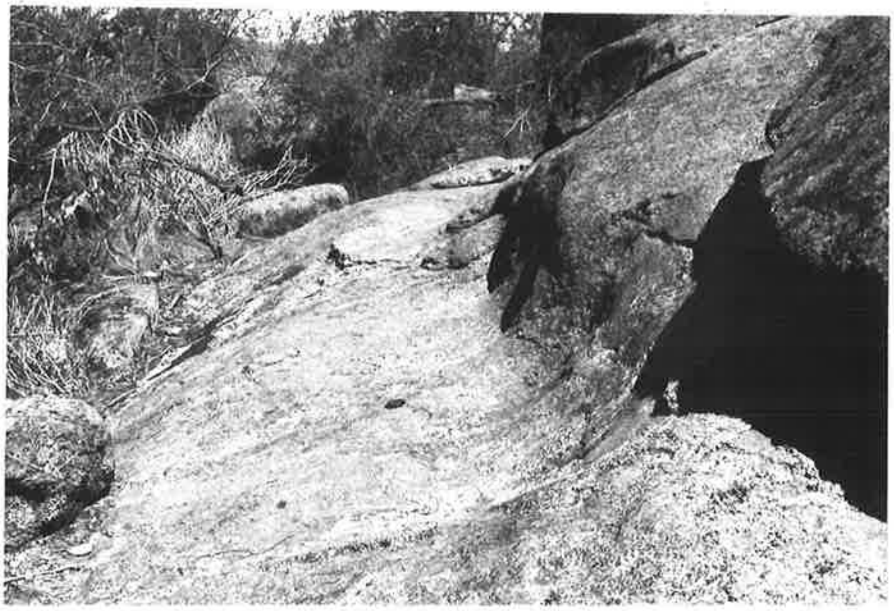

Plate 2. Flared slope on boulder, Long Ridge.

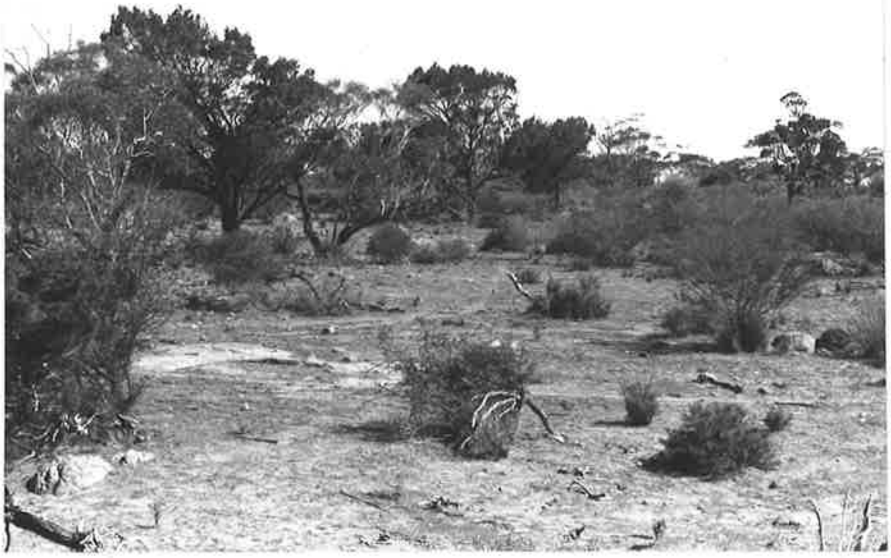

Plate 3. Part of the rock pavement, Long Ridge.

Plate 4. Rock pavement at the top of the ridge looking towards quarry, Long Ridge.

The jointing in the quarry faces is widely spaced and vertical or near-vertical with no evidence of horizontal fractures. There is no evident corestone development, although weathering has taken place along two near-vertical joints. There were insufficient joints exposed to enable jointing trends to be accurately determined.

(iii) Description of Samples

Samples of (a), the weathering along joints and (b), weathering profiles extending from the surface to fresh rock, were collected for analysis.

(a) *Joint Weathering*

The joint on the western face of the quarry was sampled in five cross-sections C, D, E, F, G (Plates 5 and 6).

Fresh Rock:	Varied in colour from pink to pale grey. There was some iron staining on crystal faces.
Fractured Rock:	Often present on one side of the cross-section only in a zone 2-5 cm wide. Iron staining was evident. The rock was quite friable, having a blocky structure in some places and disintegrating to a gritty sand elsewhere.

Plate 5. Weathering along joint on western face of quarry, Long Ridge.

Plate 6. Close up of joint weathering, Long Ridge.

Highly weathered rock: There was a sharp boundary between the fractured rock and the highly weathered rock, which was mottled red-brown and white, and finely divided. The red-brown samples appeared to have a moderate clay content, while the white samples appeared to have a high lime content.

There was distinct separation of the red-brown and the white material which facilitated their collection.

The vertical joint in the southern face of the quarry was filled with a hard material. There was no fractured rock between the white material and the fresh rock. Samples of the white material and the adjacent rock were collected (Plate 7).

(b) Weathering Profiles

To ensure that all mineralogical and chemical changes in each of the profiles could be detailed, the profiles were sampled where changes in colour, consistency or calcium carbonate content were detected.

On the eastern face of the quarry weathering profile 1, extending from the surface to fresh rock, was sampled (Figure 2). It appeared to be *in situ*. To avoid contamination the area of the profile to be sampled was first scraped clean.

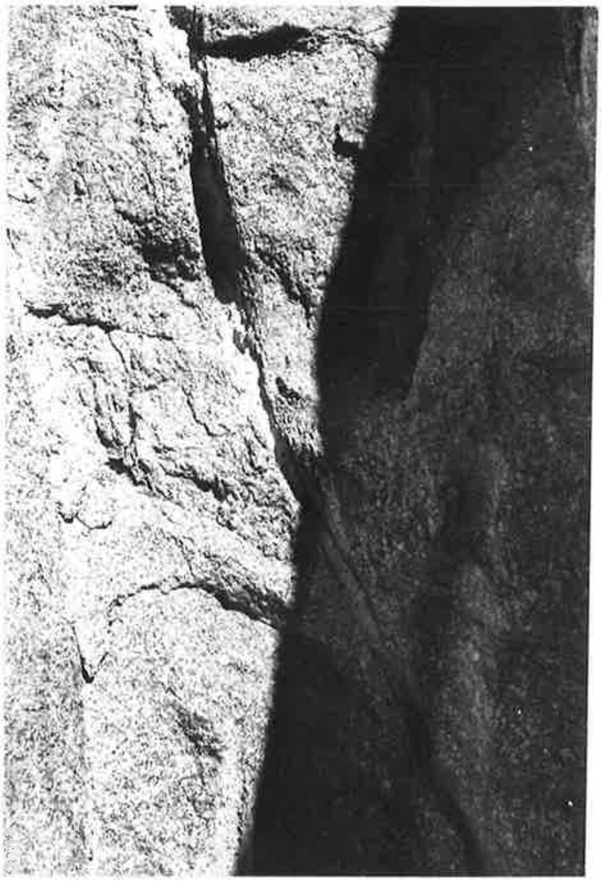

Plate 7. Joint filled with white material, southern face of quarry, Long Ridge.

Plate 8. Weathering profile 1; eastern face of quarry, Long Ridge.

Description*

W.P. 1.

1. 0 - 40 cm : Red-brown and white mottled gritty clay.

2. 40 - 60 cm : Red-brown clay with fragments of partially weathered rock 5-10 mm in size.

3. 60 - 80 cm : Fractured rock, iron stained, friable.

4,5. below 80 cm : Pink fresh rock, with pale grey rock below 100 cm.

Samples from each of these horizons and of the fresh rock were collected for analysis (Plate 8).

Weathering profile 2 to the south of the quarry was sampled using a hand auger (Figure 2).

Description*

W.P. 2.

A,B. 0 - 30 cm : Red-brown sandy loam containing 1-2 mm grains of granodiorite and 1-2 mm nodules of calcium carbonate.

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*Notes:

1. The symbol W.P.1 (etc.) is used in the tables as shorthand for weathering profile 1 (etc.).
2. The different sample numbers, i.e., 1, or letters, i.e. A, are those used in field collection and laboratory analysis and are retained in the text for consistency.
3. D,E. 45-60 cm, or 4,5. below 80 cm, indicates that two samples were taken.

W.P. 2 (continued)

C. 30 - 45 cm : Red-brown sandy loam with 15 - 30 mm calcium carbonate nodules.

D,E. 45 - 60 cm : Pink sandy loam due to increase in finely divided calcium carbonate. The concentration of calcium carbonate in nodular form, 15-30 mm diameter, increased.

F,G. 60 - 90 cm : Pink loam with finely divided calcium carbonate, no calcium carbonate in nodular form.

H. 90 - 105 cm : Pink loam, containing 2-5 mm grains of granodiorite.

I. 105 - 115 cm : Band of brown-green sticky clay, containing fragments of unweathered rock 5-10 mm in size.

J,K. 115 - 120 cm : Pink loam containing nodules of calcium carbonate 5-15 mm in diameter.

L,M. 120 - 150 cm : Partially altered rock, iron stained, friable.

Below 150 cm : Hard rock. Not sampled.

Samples from each of these horizons were collected for analysis.

Another weathering profile was collected down slope, to the east of the quarry (Figure 2).

Description*

W.P. 3.

1,2. 0 - 25 cm : Red-brown sandy loam with some calcium carbonate 1-2 mm in diameter.

3,4, 5. 25 - 50 cm : Red-brown sandy loam containing calcium carbonate nodules 5-20 mm in diameter.

6,7. 50 - 70 cm : Red-brown loam with some nodular calcium carbonate, 5-10 mm in diameter.

8,9. 70 - 85 cm : Red-brown loam with some calcium carbonate and fragments of granodiorite 5-10 mm in size.

10. 85 - 100 cm : Disaggregated granodiorite, friable and iron stained.

Below 100 cm: Hard rock. Not sampled.

Samples from each of these horizons were collected for analysis.

Six samples of the fresh rock, which had been exposed and broken up during quarrying were also collected for analysis, to determine the mineralogical and chemical composition of the rock, and compare it with that of the weathered material.

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*See Notes, p.13.

A profile sampled at Long Ridge by Potter, Wetherby and Chittleborough (1973) is very similar in the horizons encountered, to all of those described here.

BLACK HILL

The outcrop of norite at Black Hill* stands 154 m above sea level and 45 m above the surrounding Murray plains, 80 km east of Adelaide (Figure 1).

(i) Petrology

The norite is a dark grey medium grained gabbro containing plagioclase, pyroxene, biotite and quartz.

Though the rock appears uniform, there are thin, green, planar zones which consist of chlorite, with some amphibole, transecting the present joint blocks. They possibly represent an older set of joints which has been fused by hydrothermal alteration long before the rock was affected by meteoric waters. These zones are not planes of weakness.

A weak compositional zonation due to primary igneous processes also runs through the rock in the vicinity of the Monier Quarry. It is manifested in an increase in the percentage of feldspars and a corresponding decrease in the percentage of mafic minerals. It is grey-white in colour.

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*See also Hutton, Lindsay and Twidale (1977).

The norite polishes beautifully and was until recently in demand as a monumental and facing stone, both locally and overseas. Consequently, the small outcrop has been extensively quarried, providing excellent exposures of the joint systems and the related patterns of weathering.

(ii) Geomorphology

Black Hill takes the form of several low, boulder strewn hills (Plate 9), delineated by a N-S, E-W joint pattern. There are two actively worked and three abandoned quarries on the hill, which provide exposures of sub-surface jointing and weathering. The most common trends of the vertical or near-vertical joint sets are 60° and 150° with a 10° group also present. Essentially horizontal fractures are also well defined and this divides the rock into cubic or quadrangular joint blocks. This system has been exploited by the agents of weathering to give rounded corestones in some quarry faces (Plate 10). The corestones vary in size from 1 to 16 m in diameter. There is no apparent systematic increase in the size of the corestones with depth. The best example of sub-surface corestone development is in the western face of an abandoned quarry (Plate 10). This spectacular sub-surface development of corestones suggests that the boulders at the surface were developed in the two stage process of

Plate 9. Low boulder-strewn hills - Black Hill.

Plate 10. Corestones exposed in quarry face, Black Hill.

exploitation of a joint pattern by ground water and subsequent removal of the weathered material (Linton, 1955; Twidale, 1971; but see also Twidale, 1978).

The boulders at the surface display two distinct features: lenses of rock which are peeling off the boulders (Plate 11), and splitting of the boulders (Plate 12). Neither of these features is prominent in the corestones and appear to be due to the exploitation of the rock by sub-aerial processes.

In contrast to the boulder development in the massive, jointed rock at the top of Black Hill, the Council Quarry to the east (Figure 3), is in norite which has suffered granular disintegration of the whole rock mass, with relatively few corestones of fresh rock present. The council has placed the corestones in a heap at the edge of the quarry (Plate 13) and some can be seen *in situ* in the south facing quarry wall (Plate 14). The granular norite has been used for road metal. Joints are evident in the quarry faces as red bands in a rectangular pattern (Plate 15), which contrasts with the grey-black norite which they subdivide.

(ii) Description of Samples

Samples of (a) the weathering along joints, (b) surface to fresh rock weathering profile, and (c) the granular disintegration of the norite were collected for analysis.

Plate 11. Lenses of rock peeling off of boulders at Black Hill.

Plate 12. Split boulder, Black Hill.

Plate 13. Corestones removed during quarrying.

Plate 14. Granular disintegration of norite exposed in Council quarry, with corestones.

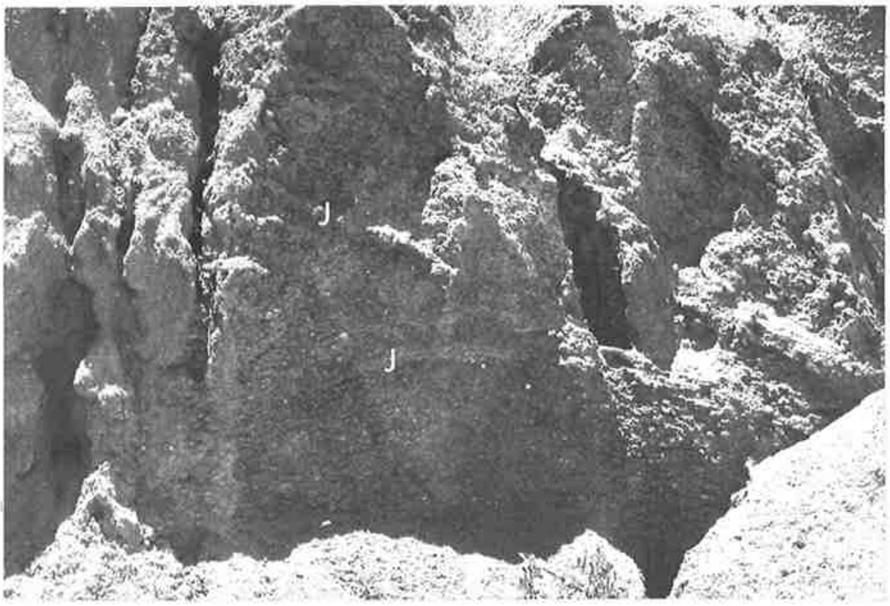

Plate 15. Red Bands of norite (J) in Council Quarry.

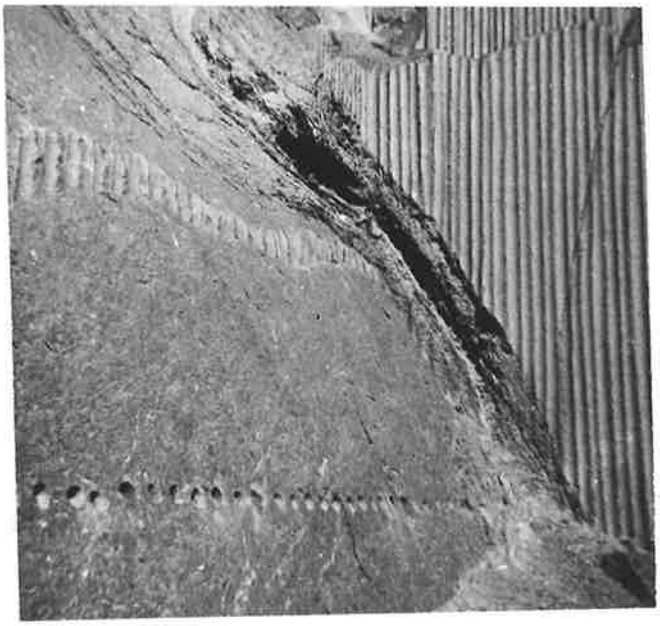

Plate 16. Joint Weathering, Black Hill.

(a) Joint Weathering

The most accessible site for collection of samples was the joint on the southern face of the Monier Quarry. The zone of weathered material was sampled in six cross-sections (Plates 16 and 17).

Corestone :- The rock was essentially fresh and very hard. Some iron staining was present on crystal faces.

Fractured Rock :- Closest to the corestone was a 5 cm-wide zone of extensively fractured rock. The main fractures parallel to the joint separated long thin sheets of rock, between 0.3 and 0.8 cm in width. There were commonly three or four sheets of rock of approximately the same thickness in this part of the joint zone, giving it a laminated appearance. In detail each sheet was made up of friable thin flakes of varying size.

There was an accumulation of a fine clay-like material on the outside of all flakes and along the fractures. Between the thickly laminated rock and the highly weathered rock was a

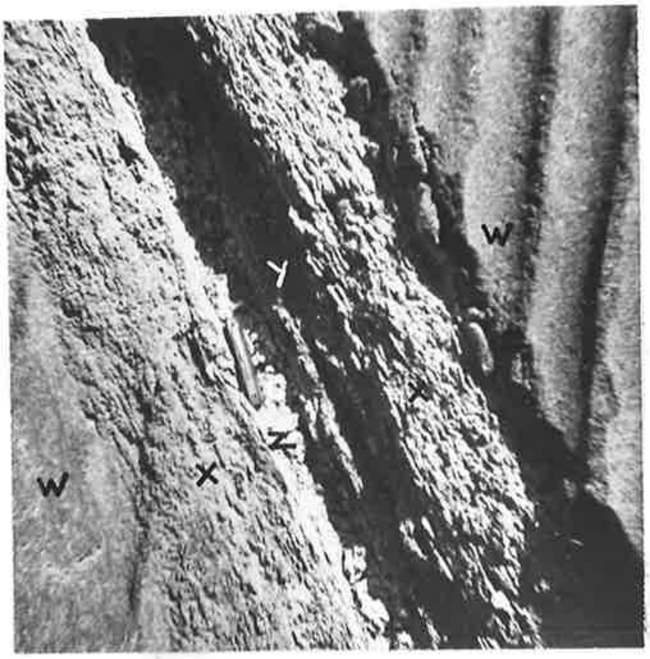

Plate 17 Close up of Joint Weathering in Plate 16.
(w) Corestone, (x) Laminated
(y) Thinly laminated rock
(z) Highly weathered material

Plate 18 Soil formed at Black Hill.

2-5 cm zone of rock which had been altered to finer laminations, 0.1-0.3 cm in thickness. It had the same structure and features as the thickly laminated rock.

Highly weathered rock:- The boundary between the laminated rock and the highly weathered rock was quite sharp. The highly weathered rock formed a band 1-2 cm wide, and was yellow-brown in colour. It appeared to have a high clay content.

The outer layer of fractured rock and weathered material were cleaned off to expose an uncontaminated surface. Samples of all stages of weathering described were collected for analysis. The quarrying has exposed very fresh rock. Samples were collected to determine the mineralogical and chemical composition of the rock and compare it with mineralogy of the weathered material.

In the joint zone sampled in the Old Martin Quarry an off-white, chert-like material was encountered between the laminated rock and the highly weathered norite as a vein 0.5-1 cm wide. Samples of this material were collected for analysis. In addition, pieces of the off-white material were collected on the surface near the Martin Quarry. Most of the surface material was very porous, and some was distinctly banded with occasional opaline lenses. The colours ranged from light red through pink to off-white.

(b) Soil Formation

On the edge of the Old Martin Quarry, a dark-brown soil has developed.

Where sampled, the soil was about 1 m deep and there is no reason to suggest that it has not developed *in situ* (Plate 18).

Description

0 - 20 cm : A dense friable loam with weak pedality and no carbonate.

20 - 30 cm : Many carbonate nodules. The profile displayed increasing differentiation.

30 - 60 cm : Moderately high in calcium carbonate, with increased size of nodules, to 2.5 cm. Some clay present, with mineral fragments.

60 - 100 cm : Consisted of granular, partly weathered norite, with carbonate coatings.

The profile was sampled completely to ensure all weathering changes would be detected.

(c) Granular Disintegration

At this site the surface has been disturbed by the quarrying operations. The sandy overburden has been bulldozed to the eastern side of the quarry, and this was not included in the sample from the quarry face (Plate 19).

Description

0 - 20 cm	Highly calcareous with lime nodules.
20 - 40 cm	White-pink finely divided carbonate with some granular norite.
40 - 60 cm	Highly calcareous, large nodules up to 3 cm diameter.
60 - 75 cm	Calcareous with granular norite and some red clay.
75 - 100 cm	A red band with granular norite, gritty, less than 1 mm in size.
100 - 135 cm	Norite gravel, black to yellow-grey in colour. Size of fragments increased to 2-4 mm.
135 - 160 cm	A mixture of red and grey-black granular norite.
160 - 200 cm	Red granular norite, 4-10 mm in size.
200 - 280 cm	Grey-black norite, 10-20 mm in size. Below this fresh rock was encountered.

The area to be sampled was scraped clean to avoid contamination and the profile was sampled in a vertical strip, 20 cm wide.

Plate 19. Mound of material removed from Council Quarry site.

CHAPTER 2

METHODOLOGY

THIN SECTIONS

In order to investigate the mineralogical changes that have taken place during weathering of the grandiorite and the norite, thin sections were made of the fresh rock and the fractured and highly weathered samples collected from the joints. Satisfactory thin sections of the fractured and highly weathered material were made by vacuum impregnating the dried samples with a slow-setting low-viscosity epoxy resin.

X-RAY SPECTROMETRIC ANALYSIS

A representative sub-sample of all samples collected was weighed and loss on heating to 105°C was determined. Twenty grams of the oven dried sample was then finely milled in a Sieb-technik ring and puck mill. The hard rock samples were milled for three minutes and the weathered samples for one minute. Part of the milled sample was used to determine loss on ignition at 1000°C.

The techniques used have been developed for analysing soils and have not been widely used for hard rock analysis. This applies particularly to the use of milled material for clay-size analysis. However, for sampling consistency and comparison of X-ray spectrometric and X-ray diffraction results, it was decided that each sample should be treated identically during the preparation for analysis. This meant that the milled sample was used for all analyses, as it is preferable to use it for the fusion buttons in the X-ray spectrometric analysis. X-ray spectrometric analysis of the samples was carried out using unignited milled sample for Long Ridge, and ignited sample for Black Hill. The fusion technique of Norrish and Hutton (1969) was used. The percentage of the oxides of iron, titanium, calcium, potassium, phosphorus, silicon, aluminium, magnesium and sodium present in each sample was determined. A new crystal was used to determine the amount of sodium present in the Long Ridge samples, while pressed powder buttons were used to determine the amount of sodium present in the Black Hill samples. The oxide percentages were converted to elemental percentages calculated on an ignited, carbonate-free basis for Black Hill.

X-RAY DIFFRACTION

Using the results of the X-ray spectrometric analysis as a guide, samples of differing chemistry in each joint and profile were selected for detailed X-ray diffraction analysis. The selected samples were placed in centrifuge tubes and treated with 1N HCl to remove all carbonate. The samples were then treated with 1N NaOH and tested, using universal litmus paper, until neutralised or alkaline. They were then centrifuged and excess water was decanted.

The samples were dried over night at 105°C.

The dried samples were scraped into shaker containers, and 7.5 ml of distilled water, 2.5 ml of 10% calgon and 0.25 ml 1N NaOH was added. Each container was shaken for 20 minutes to disperse the ground sample. Each sample was then washed into a 400 ml glass cylinder with distilled water. The volume in each cylinder was made up to 400 ml with distilled water at 5.00 pm and the sample was stirred vigorously for more than a minute to create a suspension. The following day at 9.00 am, 35 ml of each suspension was collected at a depth of 20 cm using a pipette. This technique utilises Stokes Law to collect the less than 2 µ*m*-size particles from the suspension.

The percentage of clay-size particles in each sample was determined by stirring the suspension again and collecting a 10 ml volume at 10 cm depth after 8 hours settling. These samples were placed in weighed containers and dried in the oven at 105°C over night. The weight of clay-size particles in the 10 ml suspension was then calculated and from this the percentage of these particles could be determined.

From the weight of clay in 10 ml of sample suspension the weight of clay in 35 ml of suspension was determined. This enabled approximately 100 mg of clay-size material to be pipetted into plastic centrifuge tubes. The samples were then centrifuged and excess water was decanted. The volume of liquid was made up to 5 ml and used for plating.

Square plates were made using 1.5 ml (30 mg) of sample. The plates were washed with distilled water twice, and 1N $MgCl_2$ solution three times. Two drops of glycerol were then added to the water-free plates to prevent the clay on the plate cracking or peeling. These plates were used to obtain diffractometer traces.

Round plates were made using 3 ml (60 mg) of sample to which 2 drops of P.V.A. solution had been added. The plates were washed twice with water, and three times with 1N $BaCl_2$ solution, then washed with distilled water three times. These plates were used to determine the cation exchange capacity of the clay-size particles in each sample.

The remainder of each sample in the solution was dried at 105°C and the clay was used for X-ray diffraction powder photographs for Long Ridge samples. For Black Hill X-ray diffraction powder photographs were taken using whole samples.

The photographs were taken using a 5.73 cm diameter Debye Scherrer camera, and Co k α radiation.*

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*This method of preparation was devised by Mr. J. Pickering for use in the mineralogy section of C.S.I.R.O. Division of Soils, Glen Osmond, S.A.

CALCIUM CARBONATE DETERMINATION

Five grams of each sample from the joints and the weathering profiles was treated with 10 ml of NaCl solution and allowed to stand for 15 minutes after stirring. Between 20 and 40 ml of 1N HCl was added gradually with stirring, depending on the amount of calcium carbonate present in each sample. When the effervescence ceased, signifying the neutralising of the calcium carbonate, the solution was left to stand for an hour. The amount of acid added to each sample was recorded. A fresh solution of 1N NaOH, was prepared and the Fisher titrimeter used to back titre the excess acid with the 1N NaOH solution. The percentage of calcium carbonate present in each sample was then determined using the following formula:

$$\%\ CaCO_3 = (\text{Blank} - \text{titre}) \times \text{normality}$$

The normality of the NaOH solution used was determined by dissolving 2.5 gm of potassium bithalate in 50 ml of water. It was then titrated to pH7 with 0.5N NaOH. The actual normality of the NaOH solution used was calculated thus:

$$\text{Normality} = \frac{\text{weight potassium bithalate}}{\text{volume sodium hydroxide used}} \times \frac{1}{0.2041}$$

The actual normality was 0.48 N.

The blank titre was determined by titrating 10 ml of 1N HCl with the made-up NaOH solution until the pH was 7.

These figures were used to recalculate the spectrometric data on a carbonate-free basis.

DENSITY DETERMINATION

Cores of known length and diameter were taken from the clay in the joint zone weathering sites at Black Hill and their weights as collected and after drying at 105°C were recorded. From these data the density of each sample was calculated. The densities of the harder samples were obtained by finding the volume of water displaced by fragments of known weight.

CHAPTER 3

RESULTS - LONG RIDGE

MINERALOGY - THIN SECTION

The mineralogy of the fresh rock is:

Potash feldspar	20 - 30 %
Plagioclase	45 - 55 %
Quartz	20 - 30 %
Biotite	4 - 8 %
Muscovite/Sericite	2 - 4 %
Opaques	1 - 2 %
Accessories	trace

Source: Mines Department of S.A.
Report on building stones of South Australia, 1975.

(i) Joint Weathering

Thin section examination of samples of the corestone showed that the quartz, potash feldspar and plagioclase were fresh but there was some iron staining along crystal boundaries. The placioclase was frequently zoned, with a perthitic texture. The biotite had undergone alteration, as indicated by its paler colour (Plates 20 and 21).

In the fractured rock, iron staining had increased along crystal interfaces and along cracks in the crystals of all minerals.

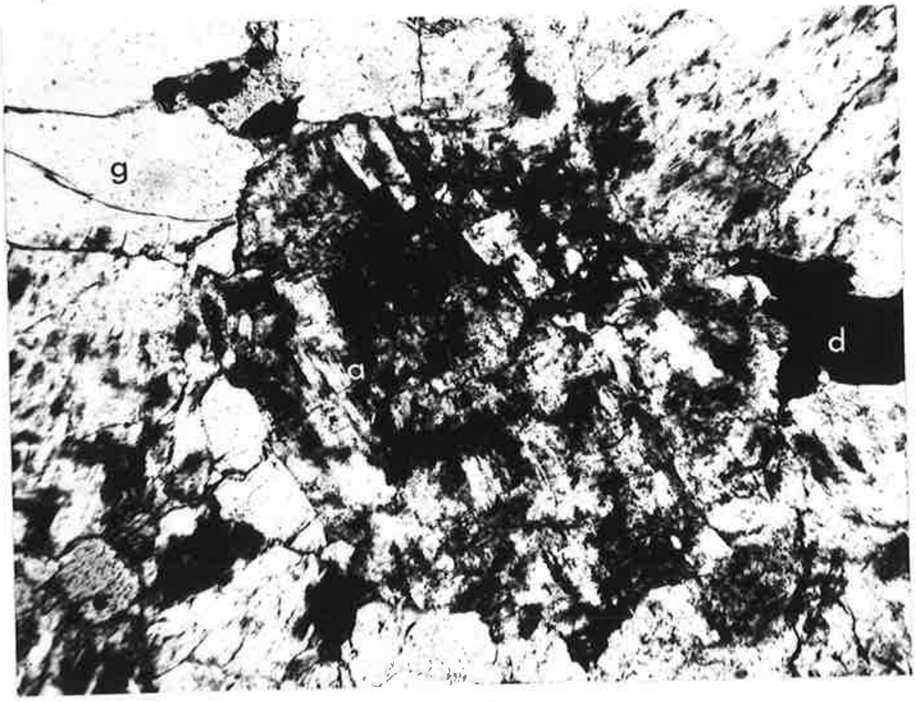

Plate 20. Granodiorite in the corestone under transmitted plane polarised light. Showing plagioclase(a) biotite (d) and quartz (g). (2.5 times objective).

Plate 21. Granodiorite in the corestone under crossed nicols. (2.5 times objective).

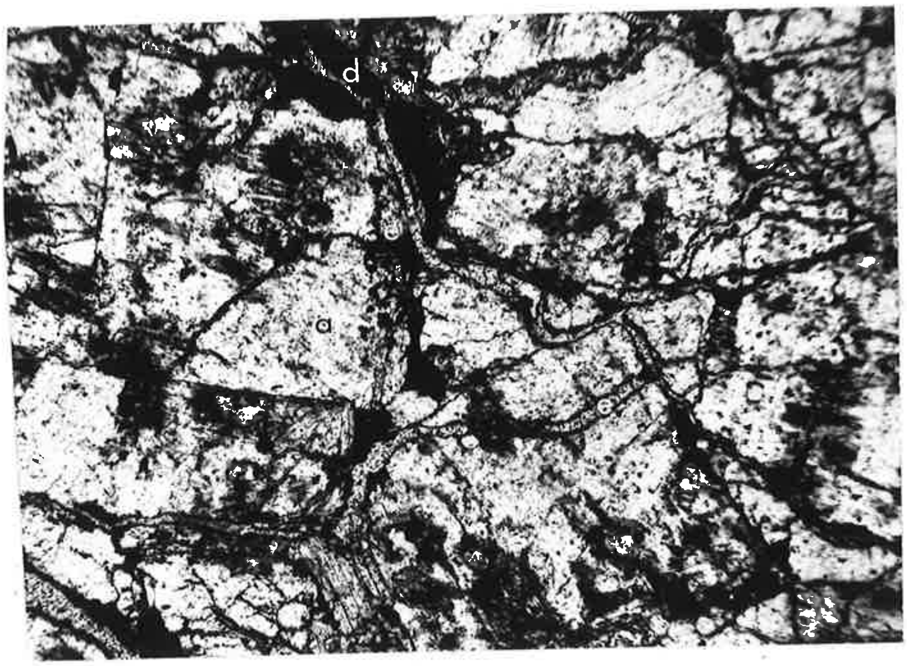

Plate 22. Plagioclase (a) and biotite crystal (d) from the laminated rock showing clay (e) accumulation in and around the crystals, under transmitted plane polarised light. (2.5 times objective).

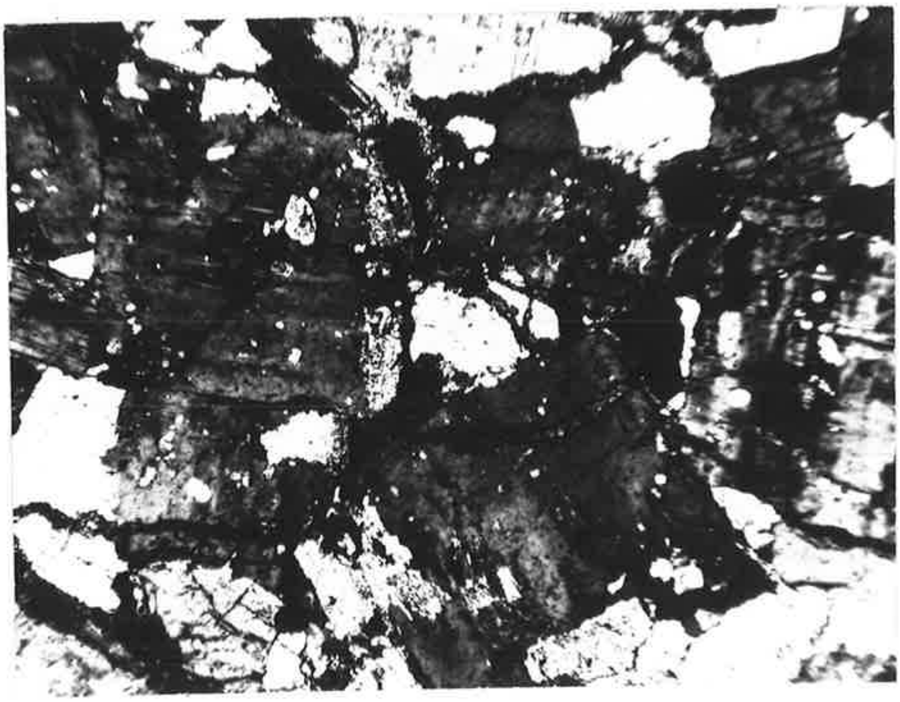

Plate 23. Plagioclase, biotite and clay in Plate 22 under crossed nicols. (2.5 times objective).

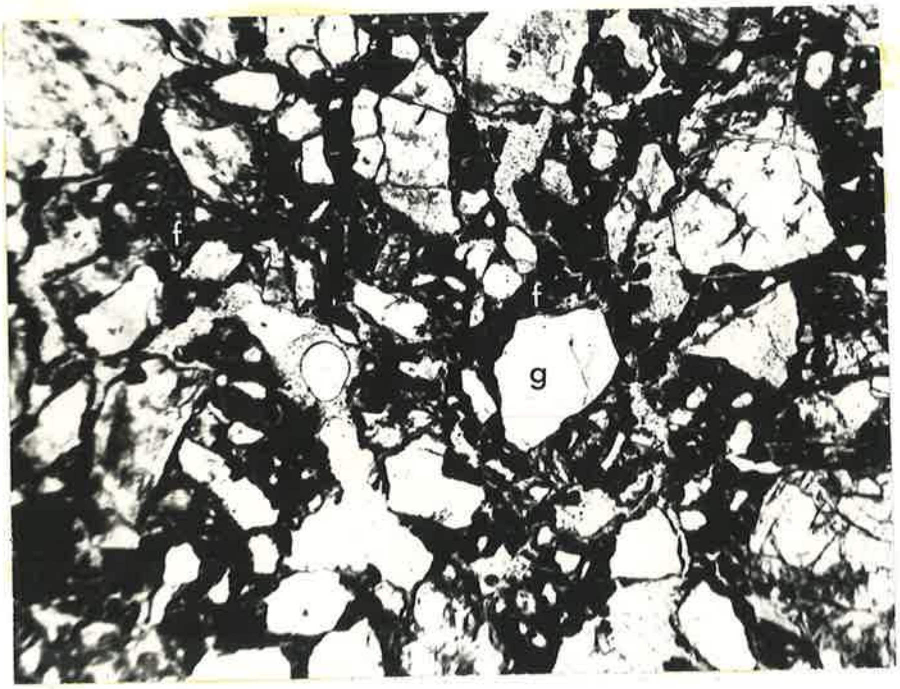

Plate 24. View of highly weathered material showing iron oxide accumulation (f) and quartz crystals (g), under transmitted plane polarised light. (2.5 times objective).

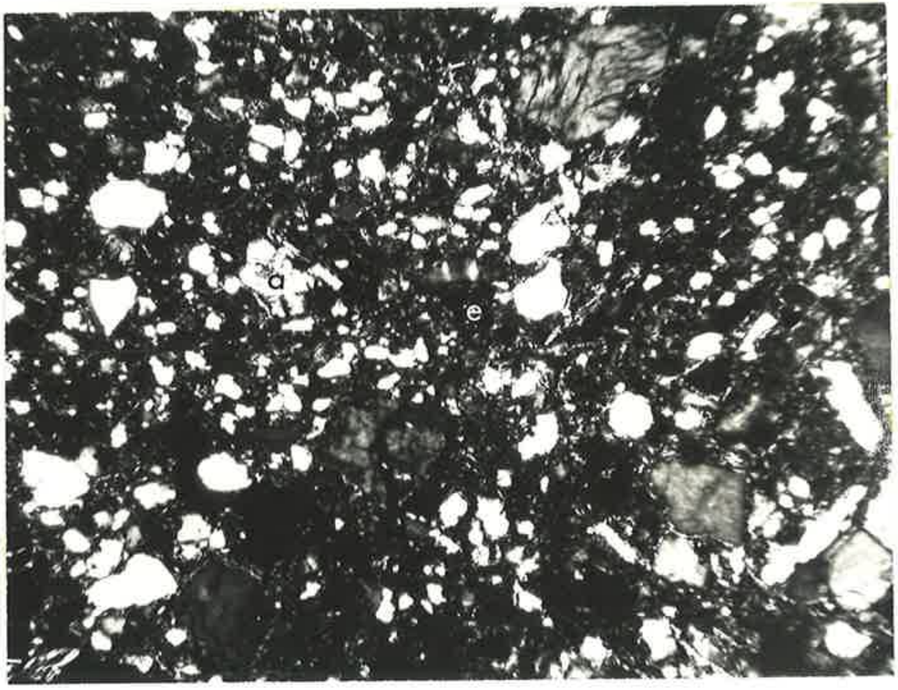

Plate 25. View of highly weathered material showing plagioclase crystals (a) and clay (e), under crossed nicols. (2.5 times objective).

Accumulations of finely divided clay along cracks in plagioclase crystals indicates that some weathering has taken place (Plates 22 and 23). The biotite was paler in colour but the quartz and potash feldspar appeared to be unaltered.

The highly weathered material consisted of crystals of plagioclase, quartz and potash feldspar in an iron stained matrix of finely divided clay and crystal fragments. Biotite was absent as large crystals and rare in the smaller crystal fraction (Plates 24 and 25). Dispersal and sedimentation showed the damp material to be 23% clay-size material.

X-RAY SPECTROMETRIC ANALYSIS

(i) Fresh Rock

The fresh rock collected from the quarry at Long Ridge has two markedly different chemical analyses. The samples grouped in Table 2a have significantly lower iron and aluminium, and higher silicon content than the samples grouped in Table 2b. The Si/Al, Al/Ti and Fe/Si ratios in Table 3 highlight the differences in the chemistry of the two rocks.

Joint weathering samples F and H and weathering profiles 2 and 3 appear, on the whole, to have chemistries related to that of the fresh rock chemistry in Table 2a, having similar aluminium and titanium content.

TABLE 2.

LONG RIDGE-FRESH ROCK CHEMISTRY

TABLE 2a

Sample No.	Fe_2O_3	TiO_2	CaO	K_2O	P_2O_5	SiO_2	Al_2O_3	MgO	Na_2O	Loss	Total
1 5	1.97	0.20	1.16	5.16	0.01	73.709	14.40	0.62	2.50	0.71	100.47
F1	1.86	0.23	1.12	4.39	0.03	73.924	12.30	0.36	4.23	0.58	99.06
H1	1.04	0.21	1.02	4.58	0.02	73.948	12.25	0.27	3.45	0.72	97.54
2	2.09	0.24	1.30	4.52	0.05	73.678	12.93	0.52	3.94	0.48	99.78
3	2.15	0.25	1.11	4.32	0.02	73.022	13.21	0.40	3.88	0.57	98.97
4	2.09	0.24	1.11	4.17	0.02	72.476	12.32	0.49	3.66	0.61	97.24
5	1.98	0.21	1.08	4.27	0.04	72.402	12.74	0.33	3.77	0.65	97.51
6	2.33	0.30	1.36	3.97	0.07	73.508	12.27	0.46	3.66	0.30	98.26
m/9(s.d.)	2.03	0.24	1.14	4.42		73.36	12.81	0.43	3.62		
	(.45)	(.03)	(.12)	(.33)		(0.59)	(0.69)	(.11)	(.48)		

TABLE 2b

Sample No.	Fe_2O_3	TiO_2	CaO	K_2O	P_2O_5	SiO_2	Al_2O_3	MgO	Na_2O	Loss	Total
1 , 4	3.59	0.60	1.97	3.55	0.02	65.96	17.01	0.76	5.17	1.08	96.66
C1	3.22	0.48	1.70	3.78	0.03	66.977	16.14	0.62	4.77	0.83	98.58
D1	3.60	0.59	1.95	3.53	0.03	65.916	16.50	0.78	5.20	1.32	99.44
E1	4.33	0.66	1.70	3.77	0.06	64.235	15.62	0.93	4.83	1.20	97.38
G1	3.50	0.55	1.72	3.94	0.03	65.366	15.30	0.65	4.83	1.08	97.02
m/5 (s.d.)	3.65	0.56	1.81	3.71		65.69	16.11	0.75	4.16		
	(.41)	(.07)	(.14)	(.17)		(1.0)	(.68)	(.13)	(.20)		
TABLE 1c	MURRAY BRIDGE GRANITE *										
	0.74		1.04	5.13	0.09	73.83	12.45	0.24	4.29		

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*Source: Joplin, G.A., 1963: *Chemical Analyses of Australian Rocks. part 1. Igneous and Metamorphic.* Department of National Development. Bureau of Mineral Resources, Geology and geaphysics. Bulletin No. 65.

TABLE 3.

LONG RIDGE RATIOS

	Si : Al	Al : TI	Fe : Si
Fresh Rock			
1	5.70	53.42	0.028
2	5.70	54.63	0.037
3	5.53	52.02	0.029
4	5.88	50.92	0.029
5	5.68	59.55	0.027
6	5.99	40.63	0.032
Joint Weathering			
C1	4.15	33.62	0.048
C2	4.17	29.01	0.059
C3	4.76	28.79	0.087
D1	3.99	28.11	0.055
D2	3.87	28.36	0.054
D3	3.93	25.03	0.043
D4	4.23	24.52	0.062
E1	4.11	23.49	0.067
E2	4.92	35.56	0.055
E3	4.71	26.59	0.083
E4	5.32	34.40	0.045
F1	6.01	53.93	0.025
F2	5.98	60.76	0.027
F3	5.64	21.02	0.056
G1	4.27	27.62	0.054
G2	3.98	27.47	0.064
G3	4.39	30.31	0.054
H1	6.04	59.47	0.014
H2	6.84	36.50	0.019
Weathering Profiles 1.			
1	5.25	20.80	0.075
2	4.13	27.00	0.048
3	3.93	32.38	0.054
4	3.88	34.02	0.054
5	5.12	72.00	0.027

TABLE 3. (Cont.)

LONG RIDGE RATIOS

	Si : Al	Al : Ti	Fe : Si
Weathering Profiles 2.			
A	7.02	27.13	0.037
B	6.78	28.43	0.036
C	6.37	28.59	0.054
D	5.92	26.22	0.064
E	5.52	26.92	0.067
F	5.55	25.43	0.058
G	5.38	26.42	0.062
H	5.34	27.88	0.061
I	6.11	30.84	0.039
J	5.71	22.75	0.067
K	5.71	21.19	0.071
L	5.88	21.61	0.080
M	5.31	24.39	0.064
Weathering Profile 3.			
1	5.57	26.44	0.061
2	5.71	29.05	0.060
3	3.93	29.38	0.052
4	5.94	28.31	0.052
5	6.00	28.60	0.054
6	5.08	35.08	0.052
7	5.25	34.08	0.052
8	5.16	34.89	0.053
9	5.24	34.40	0.055
10	5.78	31.52	0.056

TABLE 4.

LONG RIDGE - JOINT WEATHERING

Whole Sample Chemistry of Calcium Carbonate Rich Samples

Sample No.	Fe_2O_3	TiO_2	CaO	K_2O	$CaCO_3$	P_2O_5	SiO_2	Al_2O_3	MgO	Na_2O	Loss	Total	CO_2
D3	2.78	0.66	3.23	2.99	1.8	0.022	64.23	16.35	0.96	4.96	3.16	99.37	0.79
D4	3.04	0.48	14.76	2.48	21.5	0.038	49.31	11.65	1.10	3.49	13.80	100.17	9.46
E4	2.64	0.28	14.46	3.38	23.7	0.03	51.92	9.76	0.72	1.87	14.43	99.54	10.43
F3	2.61	0.39	16.99	1.71	27.1	0.04	46.79	8.30	1.07	1.67	19.70	99.30	11.02
H2	0.95	0.20	19.23	2.66	32.2	0.04	49.11	7.18	1.05	1.59	17.91	99.95	14.17

Joint weathering samples C, D, E and G and weathering profile 1 (excluding sample 5) have chemistries related to the fresh rock chemistry given in Table 2b, with similar aluminium and titanium content.

(ii) Joint Weathering

The results are shown in Tables 4 and 6 and are expressed on unignited sample weight. Table 4 gives the chemistry of calcite-rich sample before calcium carbonate was removed, to indicate the amounts of free calcium carbonate present. Table 6 is expressed on a carbonate-free basis for comparison. The samples high in carbonate correspond to the white material collected from the joints.

The fresh rock samples from the joints include the two differing chemistries detected by X-ray spectrometric analysis. In each case the fractured rock has a similar chemistry to the associated fresh rock. There has been a relative loss of silicon, sodium, phosphorus and potassium while aluminium has remained constant and magnesium and iron have increased in concentration in most of the highly weathered samples (Table 6).

TABLE 5.

WEATHERING PROFILES - WHOLE SAMPLE CHEMISTRY

Sample No.		Fe_2O_3	TiO_2	CaO	K_2O	P_2O_5	SiO_2	Al_2O_3	MgO	Na_2O	Loss	Total	CO_2	$CaCO_3$
W.P.$_1$	1	4.75	0.57	3.18	2.67	0.02	63.31	12.19	3.36	3.07	7.34	100.48	3.33	7.6
	2	3.15	0.59	2.15	3.41	0.02	65.73	15.92	2.08	4.65	2.99	100.75	1.36	3.1
	3	3.57	0.52	2.00	3.74	0.02	66.11	16.84	1.10	5.16	1.28	100.39	-	-
	4	3.59	0.50	1.97	3.55	0.02	65.96	17.01	0.76	5.17	1.08	99.66	-	-
	5	1.97	0.20	1.16	5.16	0.01	73.71	14.40	0.62	2.50	0.71	100.47	-	-
W.P.$_2$	A	2.54	0.36	3.81	2.84	0.05	69.29	9.87	0.65	2.56	9.41	101.42	2.80	6.4
	B	2.28	0.33	7.98	2.77	0.06	62.53	9.22	0.73	2.21	12.10	100.23	5.76	13.1
	C	2.61	0.27	18.38	2.38	0.07	48.27	7.58	0.82	1.80	19.66	101.87	13.40	30.6
	D	2.51	0.25	24.73	1.85	0.06	39.23	6.62	1.02	1.60	23.76	101.66	16.60	37.7
	E	3.14	0.32	16.74	2.21	0.04	46.60	8.44	2.13	1.76	18.64	100.04	13.70	31.2
	F	3.22	0.39	10.35	2.66	0.04	55.68	10.04	1.87	2.94	13.59	100.81	8.00	18.3
	G	3.72	0.41	7.23	2.90	0.03	59.61	11.07	1.75	2.87	10.83	100.46	5.50	12.4
	H	3.69	0.41	5.05	3.17	0.02	60.94	11.40	1.42	2.72	8.32	99.20	3.80	8.7
	I	2.85	0.39	0.81	3.40	0.02	73.49	12.03	0.37	2.70	2.48	98.59	-	-
	J	4.54	0.52	2.31	2.93	0.03	67.66	11.86	1.43	2.56	4.59	98.48	1.32	3.0
	K	4.79	0.56	1.70	5.87	0.02	67.18	11.77	1.40	2.55	4.18	100.05	0.75	1.7
	L	5.45	0.54	1.54	3.09	0.03	68.11	11.58	1.33	2.32	4.25	98.28	0.62	1.4
	M	4.27	0.51	2.24	3.08	0.02	66.28	12.47	1.34	2.73	4.05	97.03	0.88	2.0
W.P.$_3$	1	4.22	0.47	0.95	2.65	0.04	69.29	12.43	0.90	1.61	7.77	100.36	-	-
	2	4.02	0.41	2.60	2.82	0.04	66.90	11.71	1.06	1.49	8.44	99.51	1.32	3.0
	3	3.20	0.30	7.65	2.71	0.05	61.29	10.67	1.36	1.46	11.81	100.58	5.50	12.4
	4	3.14	0.36	8.18	2.62	0.04	60.08	10.11	1.46	1.47	12.08	99.56	5.90	13.4
	5	3.33	0.36	7.17	2.40	0.04	61.20	10.19	1.92	1.37	12.12	100.15	4.88	11.1
	6	3.19	0.34	5.25	2.75	0.04	61.28	12.05	1.57	1.36	11.71	99.59	3.60	8.2
	7	3.43	0.37	3.22	2.30	0.03	66.09	12.57	1.66	1.35	9.22	100.25	2.35	5.3
	8	3.53	0.38	2.53	2.37	0.03	66.85	12.95	1.43	1.38	8.91	100.41	1.85	4.2
	9	3.58	0.36	3.08	2.28	0.03	64.88	12.37	1.33	1.31	8.92	98.18	2.24	5.1
	10	3.73	0.37	3.48	2.04	0.03	66.99	11.59	1.32	1.11	9.23	99.92	2.55	5.8

TABLE 6.

LONG RIDGE - JOINT WEATHERING - CALCIUM CARBONATE FREE

Sample No.	Fe_2O_3	TiO_2	CaO	K_2O	P_2O_5	SiO_2	Al_2O_3	MgO	Na_2O	Loss	Total
C1 (F.R.)	3.22	0.48	1.70	3.78	0.03	66.98	16.14	0.62	4.77	0.83	98.58
C2 (Fr.R.)	3.93	0.55	1.50	4.19	0.03	66.03	15.84	0.74	4.05	2.25	99.15
C3 (H.W.M.)	5.62	0.47	1.16	3.60	0.02	64.71	13.59	0.86	2.44	5.67	98.19
D1 (F.R.)	3.60	0.59	1.95	3.53	0.03	65.92	16.50	0.78	5.20	1.32	99.44
D2 (Fr.R.)	3.54	0.60	2.15	3.60	0.02	65.59	16.96	0.69	5.47	1.36	100.01
D3 (H.W.M.)	2.83	0.67	2.26	3.05	0.02	65.51	16.66	0.98	5.06	2.42	99.49
D4 (White)	3.86	0.61	3.45	3.15	0.04	62.62	14.79	1.39	4.43	5.51	99.89
E1 (F.R.)	4.33	0.66	1.70	3.77	0.06	64.23	15.62	0.93	4.83	1.20	97.38
E2 (Fr.R)	3.70	0.38	1.19	4.38	0.02	66.86	13.58	0.67	2.85	3.80	97.47
E3 (H.W.M.)	5.30	0.51	1.42	3.36	0.03	63.77	13.54	0.86	2.81	5.71	97.34
E4 (White)	3.45	0.37	1.56	4.43	0.05	68.02	12.78	0.95	2.45	5.24	99.33
F1 (F.R.)	1.86	0.23	1.12	4.39	0.03	73.92	12.30	0.36	4.23	0.58	99.06
F2 (Fr.R)	2.00	0.20	1.19	4.42	0.04	73.06	12.21	0.29	3.60	0.69	97.75
F3 (White)	3.58	0.54	2.49	2.34	0.05	64.10	11.36	1.46	2.28	10.65	98.88
G1 (F.R.)	3.50	0.55	1.72	3.94	0.03	65.36	15.30	0.65	4.83	1.08	97.01
G2 (Fr.R.)	4.12	0.60	1.92	3.56	0.04	64.24	16.12	0.75	5.14	1.41	97.93
G3 (H.W.M.)	3.51	0.49	1.49	3.52	0.03	64.83	14.76	0.69	3.47	4.29	97.13
H1 (F.R.)	1.04	0.21	1.02	4.58	0.02	73.95	12.25	0.27	3.45	0.72	97.54
H2 (White)	1.39	0.29	1.76	3.90	0.05	72.19	10.56	1.55	2.34	5.49	97.56

F.R.: Fresh Rock
Fr.R: Fractured Rock

H.W.M. : Highly Weathered Material
White : Calcite rich

TABLE 7.

LONG RIDGE - WEATHERING PROFILES - CALCIUM CARBONATE FREE

Sample	No.	Fe_2O_3	TiO_2	CaO	K_2O	P_2O_5	SiO_2	Al_2O_3	MgO	Na_2O	Loss	Total
W.P. 1,	1	5.13	0.61	-1.17	2.88	0.03	68.37	13.16	3.63	2.84	4.32	101.12
	2	3.24	0.61	0.42	3.52	0.02	67.70	16.40	2.15	4.99	1.68	101.74
	3	3.57	0.52	2.00	3.74	0.02	66.14	16.84	1.10	5.16	1.28	100.39
	4	3.59	0.50	1.97	3.55	0.02	65.96	17.01	0.76	5.17	1.08	99.66
	5	1.97	0.20	1.16	5.16	0.01	73.71	14.40	0.62	2.53	0.71	100.47
W.P. 2,	A	2.72	0.39	0.25	3.04	0.06	74.14	10.55	0.70	2.74	7.05	101.63
	B	2.62	0.38	0.74	3.18	0.07	71.91	10.60	0.88	2.54	7.29	100.23
	C	3.75	0.39	1.78	3.42	0.10	69.51	10.91	1.18	2.59	8.93	100.89
	D	4.04	0.41	5.82	2.97	0.10	63.16	10.66	1.64	2.57	11.54	102.94
	E	4.55	0.46	-1.05	3.21	0.06	67.57	12.24	3.08	2.54	7.14	100.70
	F	3.92	0.48	0.12	3.24	0.05	67.93	12.25	2.28	3.59	6.76	100.66
	G	4.24	0.47	0.32	3.30	0.04	67.95	12.62	2.00	3.27	6.14	100.39
	H	4.02	0.45	0.20	3.46	0.02	66.43	12.43	1.55	2.97	4.91	96.48
	I	2.85	0.39	0.81	3.40	0.02	73.49	12.03	0.37	2.69	2.48	98.59
	J	4.68	0.54	0.65	3.02	0.03	69.69	12.22	1.48	2.64	3.27	98.25
	K	4.88	0.57	0.76	5.99	0.02	68.52	11.99	1.43	2.60	3.52	100.31
	L	5.50	0.54	0.77	3.12	0.03	68.79	11.70	1.34	2.35	3.28	97.45
	M	4.36	0.52	1.14	3.14	0.02	67.60	12.72	1.36	2.78	3.23	96.90
W.P. 3,	1	4.22	0.47	0.95	2.65	0.04	69.29	12.43	0.89	1.61	7.77	100.36
	2	4.14	0.42	0.94	2.90	0.04	68.90	12.06	1.09	1.53	7.33	99.39
	3	3.64	0.34	0.80	3.09	0.05	69.87	12.16	1.54	1.66	7.24	100.43
	4	3.60	0.41	0.77	3.01	0.05	69.09	11.62	1.67	1.69	6.18	98.13
	5	3.73	0.40	1.06	2.69	0.05	68.55	11.41	2.15	1.54	8.10	99.71
	6	3.48	0.37	0.72	3.00	0.05	66.79	13.13	1.71	1.48	8.83	99.59
	7	3.61	0.39	0.27	2.42	0.03	69.39	13.20	1.74	1.31	7.23	99.63
	8	3.67	0.39	0.19	2.46	0.03	69.53	13.47	1.49	1.43	7.35	100.05
	9	3.75	0.38	0.24	2.40	0.03	68.12	12.99	1.39	1.38	7.01	97.72
	10	3.96	0.39	0.24	2.16	0.03	71.01	12.29	1.40	1.17	7.08	99.77

(iii) Weathering Profiles

The results are given in Tables 5 and 7 and are expressed on unignited sample weight. The chemistry before and after removal of carbonate is given to indicate where concentrations of carbonate occurred.

In weathering profile 1 the chemistries of the samples from 20 - 60 cm are similar to that of the fractured rock and the fresh rock below it, with a relative increase in magnesium and iron and a decrease in sodium, calcium and potassium near the surface (Table 7). The fresh rock sample collected below 100 cm differs greatly from the fresh rock and the weathering profile above it. It appears to be the pale grey granodiorite (Table 2a), while the fresh rock above it is predominantly the pink granodiorite (Table 2b).

Weathering profile 2, displays a marked change in chemistry at 105 - 115 cm, with an increase in silicon and a decrease in iron, calcium and magnesium relative to the samples above and below it in the profile (Table 7). There has been an increase in magnesium between 30 and 105 cm relative to the chemistry of the fractured rock at 120 - 150 cm. The concentrations of the other elements vary down the profile with a general increase in the concentration of phosphorus and iron and a decrease in silicon, sodium and potassium relative to the fresh rock chemistry given in Table 2a, while aluminium is almost constant.

The chemistry of weathering profile 3 is similar to that of the fresh rock chemistry given in Table 2a, with a slight increase in magnesium, potassium and iron in the weathered samples. There is a decrease in silicon and sodium and varying aluminium content down the profile.

X-RAY DIFFRACTION

These results were obtained by diffractometer trace analysis and powder photograph interpretation carried out by Mr. J. Pickering, C.S.I.R.O. Division of Soils, Adelaide, and are given in Table 8.

(i) Joint Weathering

The highly weathered material in the joint zone contained kaolin and montmorillonite in the less than 2μm fraction, while the same fraction from the fractured rock contained illite, feldspar and quartz.

(ii) Weathering Profiles

The clay minerals illite and montmorillonite were present in the less than 2μm fraction separated from selected samples in profile 1. Profile 2 contained illite, kaolin and randomly interstratified material in varying proportions in the upper 90 cm, with

TABLE 8.

LONG RIDGE - CLAY MINERALOGY

Sample No.		* Clay Minerals	K_2O %	C.E.C.	Clay %
J.W.	C1	I	5.22	11.24	13.04 (m.s.) 6.00 (um.s.)
	D2	I K	4.83	12.33	19.28 (m.s.) 6.00 (um.s.)
	C3	M I K	2.75	45.58	25.36 (m.s.)
W.P. 1,	2	I M	3.85	29.64	14.56 (m.s.)
	4	I M	4.54	13.27	23.12 (m.s.)
2,	B	R.I.S. I K	2.69	60.60	11.32 (m.s.)
	D	I K R.I.S.	2.34	50.56	9.16 (m.s.)
	H	M I K	2.38	70.48	12.52 (m.s.)
	I	I R.I.S.	3.82	21.60	15.00 (m.s.)
	M	I M K	2.55	47.30	21.16 (m.s.)
3,	2	I K	3.01	42.70	22.76 (m.s.)
	5	I K R.I.S.	2.60	58.96	19.92 (m.s.)
	10	I K R.I.S.	2.15	44.62	23.56 (m.s.)

* In order of dominance

I : Illite
K : Kaolin
M : Montmorillonite

R.I.S. : Randomly Interstratified Material
m.s. : Milled Sample
um.s. : Unmilled Sample

montmorillonite, illite and some kaolin between 90 and 105 cm, and 115 and 150 cm. A band of weathered material at 105 - 115 cm contained illite, randomly interstratified material and kaolin. Illite, and kaolin were present in the less than 2μm fraction from near-surface samples in profile 3, while illite, kaolin and randomly interstratified material were present at depth.

PERCENTAGE OF CLAY SIZE PARTICLES

The results of the determination of the percentage of clay-size particles on selected samples are given in Table 8, where it can be seen that the percentage of these particles is very low.

(i) Joint Weathering

A sample of fractured rock, D_2, contained 19% clay-size particles while the highly weathered material contained up to 25% clay-size particles (Table 8).

(ii) Weathering Profiles

Content of clay-size particles ranged from 9% near the surface in profile 2, to 23% at depth in profile 3. In profile 1 23% clay was found in a sample of what appears to be slightly fractured rock (Table 8). This relatively high figure may be the result of the release of clay-size material from around individual minerals in the rock or the creation of clay-size particles during milling.

In order to attempt to determine the effect of using milled sample for clay-size percentage determinations, unmilled sample of fresh rock C_1 and fractured rock D_2 were made up into suspensions following the procedure outlined previously, and the less than 2μm fraction collected. Density determination of clay-size percentage was made. The results are in Table 8. Both samples contained 6% clay-size particles, which is less than half that detected using milled sample. This indicates that some clay-size material was released during milling which would not otherwise have been measured quantitatively.

It is, however, evident from the loss on ignition figures for these samples (0.83% and 1.32%), that not all the clay-size particles present in the milled sample were clay minerals, as a clay mineral content of 20-25% would result in a loss on ignition of 13%. It can be concluded that some clay-size particles were created during the milling process.

CATION EXCHANGE CAPACITY

The results of the cation exchange capacity determinations are given in Table 8. There are some anomalies for the samples containing montmorillonite.

Montmorillonite should give a high reading of between 50 and 70, but in the samples from profile 1 and the joint weathering which contain montmorillonite the values range from 13 to 45. Sample I from weathering profile 2 has a very low cation exchange capacity when compared with other samples containing illite and kaolin. It also has a high percentage of potassium oxide, which may be due to the presence of finely divided mica.

Fresh and fractured rock samples from the joint and from weathering profile 1 have a low cation exchange capacity and high potassium oxide percentages. This is characteristic for fresh rock.

CALCIUM CARBONATE DETERMINATION

The results are given in Tables 4 and 5. Samples of highly weathered material from the joints contain up to 27% calcium carbonate. The samples high in calcium carbonate correspond to the white material described previously.

The white material which filled the joint on the southern face of the quarry contained 32% calcium carbonate.

Weathering profile 1 has 7.6% calcium carbonate in the near surface sample, while there is a high concentration of calcium carbonate in the upper and middle levels of weathering profiles 2 and 3. These high concentrations correspond to the samples containing nodular and finely divided calcium carbonate. The highest concentration is 37%, between 45 and 60 cm in profile 2.

CHAPTER 4

RESULTS - BLACK HILL

MINERALOGY - THIN SECTION

The mineralogy of the fresh rock is:

Plagioclase feldspar (labradorite)	50 %
Potash feldspar	5 %
Pyroxene (Hypersthene and augite in almost equal amounts)	30 %
Biotite	8 %
Opaques	5 %
Apatite	2 %
Quartz	trace

Source: Russ and Mason (1968).

The band of feldspar-rich norite consists of 55-65% labradorite, 10-15% potash feldspar, 10-15% pyroxenes, 5% biotite and a trace of quartz.

(i) Joint Weathering

Thin section examination of samples of the corestone showed the feldspars, pyroxene and biotite to be quite fresh, though in some places there was iron staining along crystal interfaces (Plates 26 and 27). In the thickly laminated norite from the zone close to the corestone, the plagioclase and pyroxene were slightly weathered.

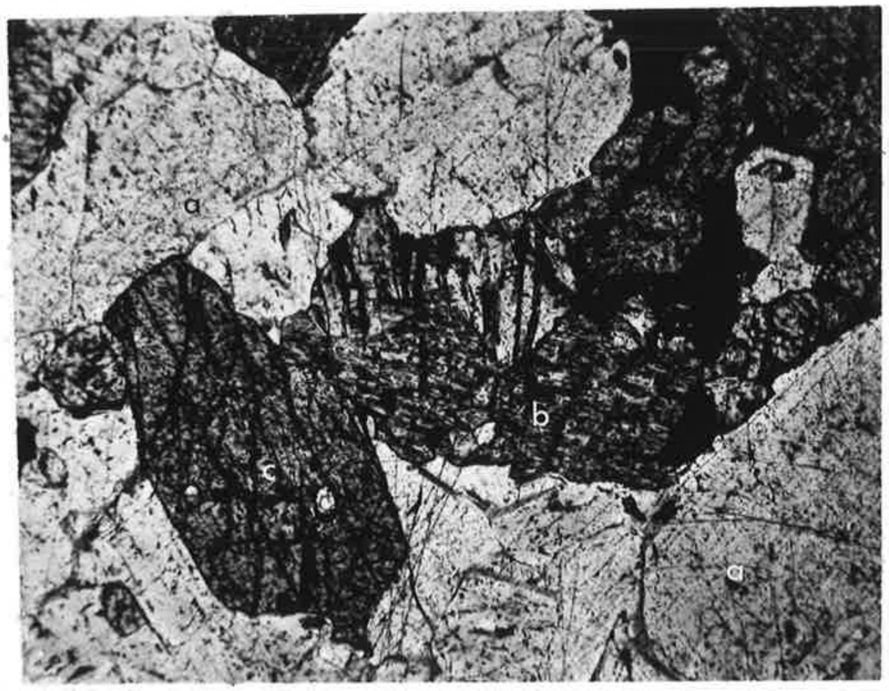

Plate 26. Norite in the corestone under transmitted plane polarised light. Showing plagioclase (a) ortho (b) and clino-pyroxene (c). (2.5 times objective).

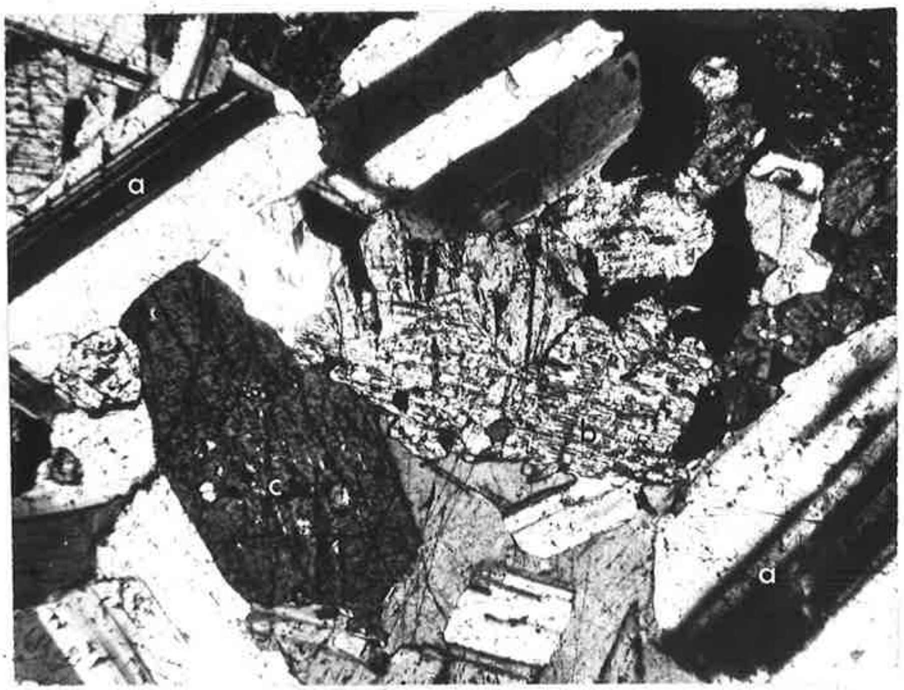

Plate 27. Norite in the corestone under crossed nicols. (2.5 times objective).

Plate 28. Plagioclase crystal (a) from the laminated rock showing clay (e) and iron oxide (f) accumulation along cracks in and around the edge of the crystal, under transmitted plane polarised light. (10 times objective).

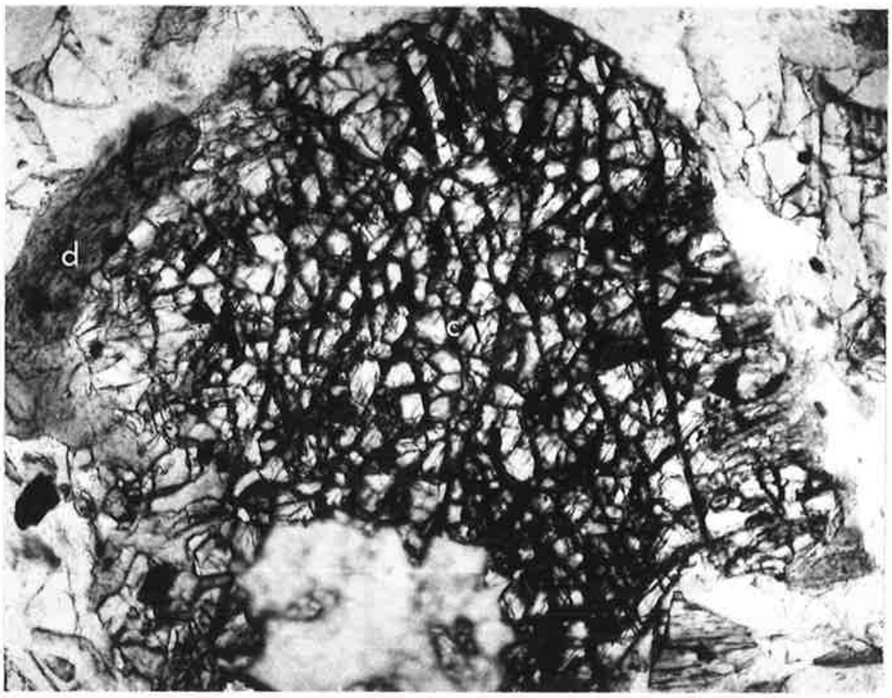

Plate 29. Cracked clino-pyroxene crystals (c) and altered biotite crystal (d) from the laminated rock, under transmitted plane polarised light. (10 times objective).

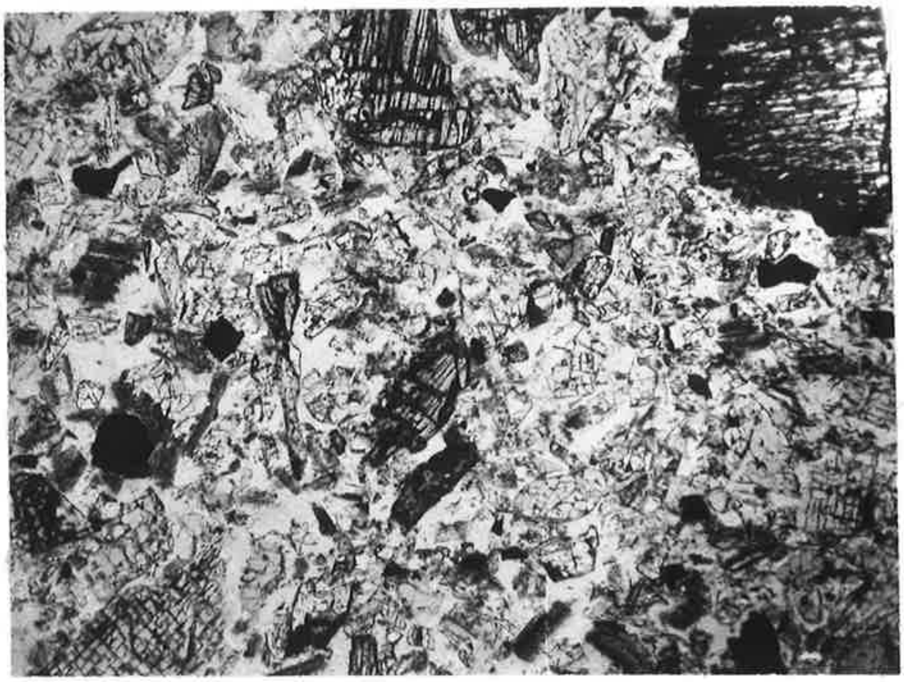

Plate 30. General view of the minerals in the thinly laminated rock, under transmitted plane polarised light. (2.5 times objective).

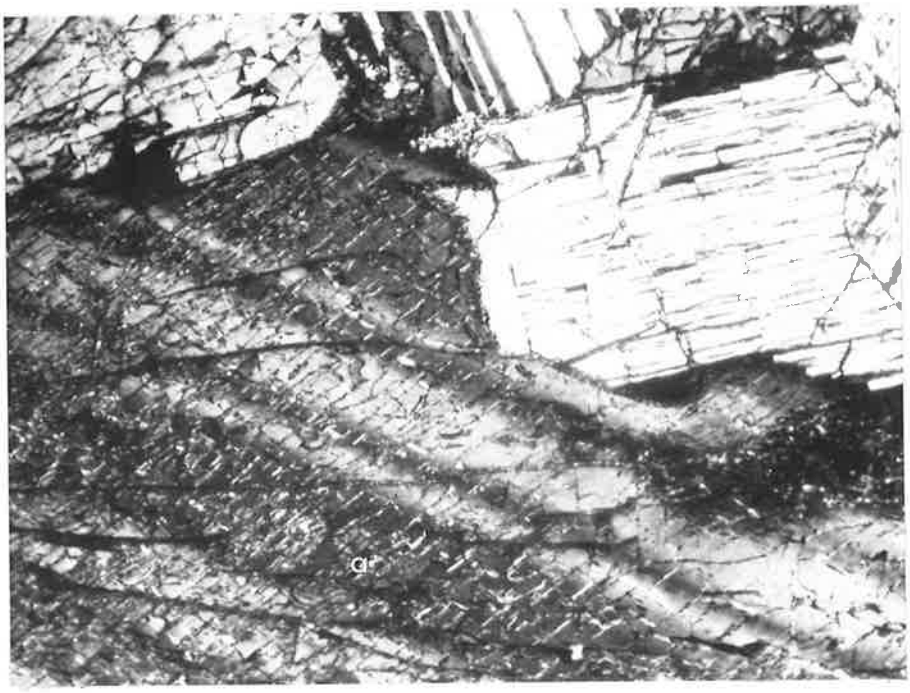

Plate 31. Fine cracks in plagioclase crystals (a) in the thinly laminated rock, under crossed nicols. (10 times objective).

Plate 32. Altered biotite crystal (d) and iron oxide (f) in the finely laminated rock, under transmitted plane polarised light. (10 times objective).

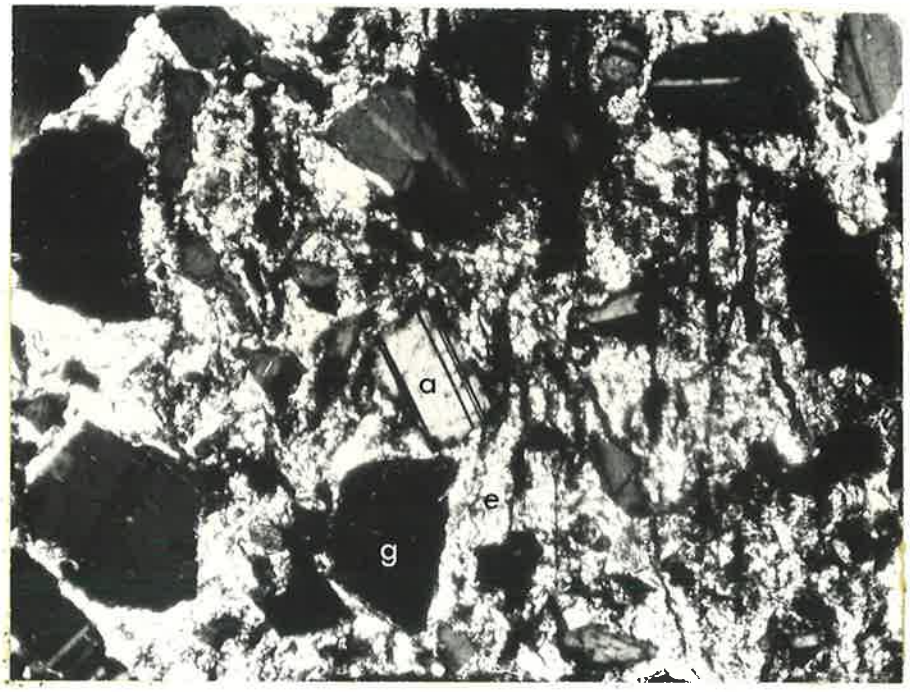

Plate 33. The finely divided clay (e), fractured plagioclase crystals (a) and quartz crystals (g) in the highly weathered material, under crossed nicols. (10 times objective).

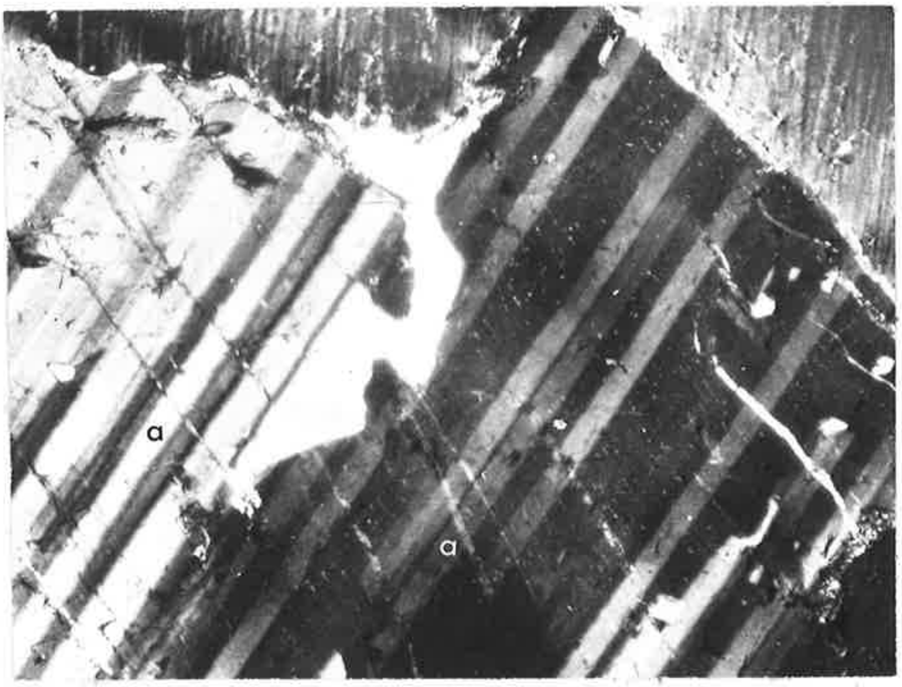

Plate 34. Plagioclase crystals (a) from the highly weathered material, under crossed nicols. (10 times objective).

This was indicated by an accumulation of finely divided clay along crystal interfaces, and in the cracks in the plagioclase, potash feldspar, and the pyroxene crystals. The cracks occurred both parallel and obliquely to the cleavage in the plagioclase and pyroxene crystals. Iron staining was present along cracks in the crystals, and the biotite has undergone partial change (Plates 28 and 29). Samples from the finely laminated material showed still greater alteration with more clay apparent and iron staining along cracks in the crystals. The corners of some of the labradorite crystals were altered to clay (Plates 30 and 31), but no wholly weathered crystals were detected. Further change in the biotite in these samples was indicated by its paler colour (Plate 32).

The highly weathered material consisted of a matrix of clay with feldspar and traces of pyroxene and biotite. The primary grains appeared to be smaller than those in the fresh rock, no doubt due to weathering. The plagioclase was fractured considerably and quartz was more evident (Plates 33 and 34). Dispersal and sedimentation showed the damp material to be 35% clay.

X-RAY SPECTROMETRIC ANALYSIS

The results are given in Tables 9, 10, 11, and 12* and are expressed on the ignited sample weight. In order

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*Tables 9, 10, 11, 12 After Hutton, Lindsay, and Twidale (1977).

to facilitate comparison with the analysis of the fresh norite, the data have been calculated on a calcite-free basis for the joint weathering and the soil profile. As the samples from the Council Quarry were high in carbonate minerals the results were recalculated on a calcite- and dolomite-free basis, using the following reasoning.

The non-carbonate fraction in the surface samples has been shown by X-ray diffraction to be partially weathered norite as is found in the samples from below 1 m. Hence, from comparison of the elemental composition of the surface samples with the material below 1 m, it should be possible to calculate the chemical composition of the carbonate fraction. The ratio of the amount of the elements iron, titanium, potassium and aluminium, in the surface samples to the average amount of these elements in the six samples between 1 m and 2.5 m is fairly constant for each sample (Table 11). Using the average of at least three ratios, the amount of calcium and magnesium in the surface samples that can be assigned to the partially weathered norite has been calculated. This calculated magnesium is subtracted from the total magnesium and, as dolomite is present in all samples, the remaining magnesium is calculated to dolomite. Any calcium remaining after taking the calcium present in the norite and the calcium present in the dolomite from the total calcium in the sample, is calculated to calcite. The amount of carbon dioxide associated with these minerals was also calculated and compared with that found on analysis (Table 13)*.

(i) Joint Weathering

Data for the joint weathering samples have been grouped into three sets on the basis of significantly different chemical analysis (Table 9). Of the samples from the Monier Quarry, Group I is considered to be the normal composition for this quarry and the standard deviation about the mean value for the number of samples indicated is given in parentheses after each value. Group II, particularly the six samples of laminated rock, is significantly different in many values and must represent a feldspar-rich variation of the norite. The rock sampled in the Old Martin Quarry appears to be sufficiently different in silicon, potassium and titanium (which may be due to a higher concentration of potash feldspar), to warrant a separate grouping.

The analysis of the off-white material collected from the vein along joints showed that it was composed of 90% SiO_2, with some Al_2O_3 and some K_2O, and a trace of Fe_2O_3 (Table 9).

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*Table 13 After Hutton, Lindsay, and Twidale (1977).

TABLE 9.

COMPOSITION OF THE JOINT WEATHERING SAMPLES (s.d. OF MEAN IN PARENTHESES.)

	Fe	Ti	Ca	K	P	Si	Al	Mg	Loss
Monier Quarry									
Group I									
Hard Rock	7.70	0.81	6.74	1.58	0.21	23.9	8.67	3.30	nil
(7 samples)	(0.09)	(0.03	(0.09)	(0.07)	(0.01)	(0.13)	(0.11)	(0.08)	
Laminated Rock	7.67	0.69	6.49	1.53	0.20	24.1	8.74	3.03	1.0
(13 samples)	(0.17)	(0.04)	(0.14)	(0.14)	(0.01)	(0.08)	(0.09)	(0.10)	(0.5)
Clay Material	9.45	0.52	2.15	1.23	0.024	25.3	7.67	1.88	8.5
(3 samples)	(1.1)	(0.06)	(0.17)	(0.33)	(0.004)	(0.31)	(0.43)	(0.14)	(0.1)
<0.5µm from clay material Ca saturated (1 sample)	12.5	0.19	2.3	0.21		28.3	7.3	2.0	n.d.
Group II									
Hard Rock	7.0	0.72	6.6	1.6	0.20	24.0	9.2	2.8	nil
(1 sample)									
Laminated Rock	4.38	0.44	6.78	1.5	0.14	24.8	11.3	1.68	0.7
(6 samples)	(0.38)	(0.06)	(0.15)	(0.26)		(0.19)	(0.37)	(0.20)	(0.6)
Clay Material	7.3	0.38	3.8	1.7	0.03	24.5	9.8	0.9	8.4
(1 sample)									

TABLE 9. (CONT.)

	Fe	Ti	Ca	K	P	Si	Al	Mg	Loss
Old Martin Quarry									
Hard and laminated rock (3 samples)	7.39 (0.06)	0.67 (0.03)	6.31 (0.06)	1.99 (0.08)	0.15 (0.02)	24.9 (0.04)	8.76 (0.07)	3.34 (0.04)	nil
Clay Material (1 sample)	7.2	0.7	4.2	1.6	0.1	28.0	8.0	2.0	3.0
	Fe_2O_3	TiO_2	CaO	K_2O	P_2O_5	SiO_2	Al_2O_3	MgO	
Amorphous silica	0.44	0.03	1.85	0.05	0.04	90.37	0.71	0.20	

TABLE 10.

COMPOSITION OF THE DARK-BROWN SOIL

Depth, cm.	Fe	Ti	Ca	K	P	Si	Al	Mg	Loss
0 - 8	6.28	0.77	3.01	1.73	0.052	30.0	7.14	1.74	4.4
8 - 20	6.08	0.78	2.12	1.78	0.053	30.6	7.57	1.61	4.1
20 - 30	6.20	0.73	4.55	1.63	0.054	28.3	7.52	1.94	5.3
30 - 50	6.52	0.70	13.3	1.53	0.061	22.5	7.23	2.76	12.0
50 - 60	5.96	0.63	21.1	1.34	0.076	19.2	6.56	3.13	20.0
60 -100	8.10	0.78	5.90	1.66	0.047	25.8	7.74	3.34	3.3

TABLE 11.

COMPOSITION OF THE GRANULAR MATERIAL (s.d. OF MEAN IN PARENTHESES.)

Depth, cm.	Fe	Ti	Ca	K	P	Si	Al	Mg	Loss
0 - 40 (2 samples)	1.75 (0.01)	0.30 (0.01)	24.3 (1.3)	0.52 (0.05)	0.037 (0.002)	19.8 (0.38)	2.68 (0.12)	8.06 (1.6)	42
60 - 85 (2 samples)	4.75 (0.65)	0.52 (0.06)	9.08 (2.4)	1.54 (0.20)	0.032 (0.01)	24.3 (1.4)	7.74 (1.2)	5.18 (1.4)	17
100 - 260 (3 samples lt.r. brown)	5.27 (0.25)	0.59 (0.02)	5.07 (0.49)	2.01 (0.08)	0.025 (0.008)	26.4 (0.30)	9.38 (0.15)	2.01 (0.19)	1
100 - 260 (3 samples y. grey)	8.30 (0.25)	0.83 (0.05)	5.61 (0.20)	1.76 (0.04)	0.079 (0.014)	24.4 (0.14)	8.88 (0.15)	2.89 (0.03)	1
below 260 (1 sample)	8.06	0.81	6.12	1.88	0.14	24.3	8.92	2.92	
Rock (4 samples)	8.30 (0.12)	0.78 (0.01)	6.78 (0.05)	1.81 (0.03)	0.16 (0.01)	23.2 (0.16)	8.26 (0.24)	3.40 (0.06)	

TABLE 12.

COMPOSITION OF SOIL AND GRANULAR MATERIAL, ON CALCITE/DOLOMITE FREE BASIS. (MEAN VALUES (%) WITH s.d. OF MEAN IN PARENTHESES.)

Depth, cm.	Fe	Ti	Ca	K	P	Si	Al	Mg
Dark-brown soil								
0 - 30 (3 samples)	6.23 (0.06)	0.76 (0.02)	3.07 (0.06)	1.72 (0.03)	0.053 (0.001)	29.6 (0.68)	7.43 (0.12)	1.77 (0.10)
30 - 100 (3 samples)	7.62 (0.28)	0.78 (0.002)	6.01 (0.72)	1.69 (0.01)	0.073 (0.014)	25.0 (0.63)	8.01 (0.10)	3.45 (0.24)
Rock (3 samples)	7.39 (0.06)	0.67 (0.03)	6.31 (0.06)	1.99 (0.08)	0.15 (0.02)	24.9 (0.04)	8.76 (0.07)	3.34 (0.04)
Granular Material								
0 - 40 (2 samples)	3.02 (0.06)	0.51 (0.01)	2.32 (0.06)	0.94 (0.06)	0.06 (0.003)	34.2 (0.05)	4.77 (0.14)	1.11 (0.01)
60 - 85 (2 samples)	5.10 (0.24)	0.56 (0.01)	4.14 (0.18)	1.66 (0.06)	0.04 (0.015)	26.4 (0.95)	8.34 (0.48)	1.95 (0.15)
Rock (4 samples)	8.30 (0.12)	0.78 (0.01)	6.78 (0.05)	1.81 (0.03)	0.16 (0.01)	23.2 (0.16)	8.26 (0.24)	3.40 (0.06)

TABLE 13.

CALCULATED COMPOSITION OF CARBONATES OF COUNCIL QUARRY GRANULAR MATERIAL.

Depth, cm.	Ratio of elements in sample to elements in 100-260 cm. samples					Weathered Norite (calculated)		Actual Analyses of whole sample			Carbonate fraction (calculated)				
	Fe	Ti	K	Al	Aver.	Ca	Mg	Ca	Mg	CO_2	Ca	Mg	CO_2	Dolomite	Calcite
0 - 20	0.18	0.30*	0.22	0.21	0.20	1.0	0.47	18.2	4.6	29	17.2	4.1	27	32	26
20 - 40	0.18	0.27*	0.18	0.19	0.18	0.9	0.43	16.1	6.8	30	15.2	6.4	29	49	11
40 - 60	0.32	0.42*	0.35	0.32	0.33	1.6	0.54	12.3	6.9	25	10.7	6.4	24	49	0
60 - 75	0.48	0.51	0.58	0.57	0.53	2.7	1.25	9.3	5.4	18	6.6	4.2	15	32	0
75 - 85	0.67	0.70	0.79	0.83	0.76	3.8	1.8	5.8	3.3	8	2.0	1.5	6	12	0
85 -100	0.75	0.73	0.84	0.87	0.80	4.0	1.9	6.0	3.4	n.d.	2.0	1.5	6	12	0

* excluded from average

(ii) Soil Formation

From Table 10 it can be seen that the upper horizons (0-30 cm) of the dark brown soil have lost 50% or more of the magnesium, phosphorus and calcium and about 15% of the aluminium, potassium and iron relative to the fresh rock. The ratio of the latter three elements in this layer to the amount present in the fresh rock is constant at 0.85. According to Ruxton (1968), these are the elements usually retained during weathering. The dilution suggests that the excess silicon in the surface has come from an external source. It has probably been carried as sand grains by the wind from the surrounding sandy soils of the Murray Plains. If the constant ratio of 0.85 is applied to the silicon, the excess silica is about 18%. Normally titanium can be expected to behave in the same way as the elements aluminium, potassium and iron but in the dark brown soil profile the titanium in the surface is 1.13 times that in the fresh rock. If the excess wind-blown sand contained 1% titanium, this would contribute 0.18% titanium and thus, the titanium from the weathering would be 0.58% i.e. 0.87 of that in the rock (J.T. Hutton, pers. comm.). The non-carbonate fraction of the lower part of the profile is essentially similar to the unaltered rock.

(iii) Granular Disintegration

The carbonate-free calculations given in Table 12, indicate that there has been an increase in the amount of silicon and a decrease in the amount of magnesium, aluminium, phosphorus, potassium, calcium and iron in the near-surface samples, relative to the chemistry of the fresh rock. The unusual nature of the weathering at the Council Quarry site necessitated detailed chemical analyses of the samples to determine what factors have led to the granular disintegration of the rock. The results are detailed below.

Of the excess silicon detected 10% can be ascribed to the weathered norite, another 10% to quartz detected by X-ray diffraction. This leaves about 10% possibly present in an amorphous form. To confirm that this was in an amorphous form similar to that detected along the joint and elsewhere at the surface, the residue after removal of the carbonates by acid treatment, was treated with dilute caustic soda by Jackson's method (1956). This test showed that the residue contained 5% amorphous silica.

In this profile, from 75 - 280 cm, two distinct materials were sampled. One was dominated by fine red-brown particles and containing some grey gritty fragments; the other was free of fine material and consisted predominantly of yellow-grey, gritty weathered rock. These materials alternated in the profile.

Three samples of each of these two materials were collected. Chemically they are different, the red-brown material having lower (0.7) iron, titanium and magnesium and higher (1.1) aluminium, silicon and potassium than the yellow-grey grit (Table 11). These differences probably reflect variations in the composition of the norite for they are not attributable to weathering,as potassium and silicon have been lost during weathering at other sites,while titanium content has usually increased.

The bands of red-brown norite which have a near-vertical and near-horizontal configuration are present in all faces of the quarry. This gives them the appearance of a joint pattern. If these bands are weathered joints, the jointing is more dense in this part of the rock mass than at the Martin and Monier Quarry sites (Plate 15).

Neither the red-brown material nor the yellow-grey material has weathered to form much clay (the loss on ignition figures of about one percent suggests 5% clay). The lower phosphorus and calcium content and the colour of the red-brown material suggests it is the more weathered of the two materials.

To determine whether the norite at this site contained significantly more biotite than the norite at other sites which have not suffered granular disintegration, the chemistry of the fresh rock at each site was examined in detail.

The amounts of iron, titanium and magnesium are similar for all rock samples, with the exception of that in the Old Martins Quarry (Tables 9 and 11). This indicates that the mafic minerals, including biotite, are present in the same amounts at all sites.

X-RAY DIFFRACTION

(i) Joint Weathering

The clay associated with the laminated rock collected from the joint in the Monier Quarry was montmorillonitic. The chemical analysis of the less than 0.5μm fraction from this material, 12.5% Fe and 7.3% Al, indicates that it approaches nontronite in composition (J.T. Hutton, pers.comm.). The X-ray results for the finely milled corestone and laminated samples confirm the mineralogy noted by Alderman (1927).

Several samples of the off-white material found as a vein in the joint zones gave diffuse X-ray diffraction patterns indicative of amorphous material. The chemical analysis has shown that this material is amorphous silica.

(ii) Soil Formation

The minerals present in the less than 2μ*m* fraction separated from the surface (0-20 cm) of the dark brown soil were identified as kaolin, illite, haematite and a randomly interstratified material. However, with depth the interstratified material is replaced by a montmorillonite mineral. The carbonate in the profile was calcite.

(iii) Granular Disintegration

No clay minerals were detected in the unfractionated samples of the granular norite collected from the Council Quarry. The carbonate in the upper part of the profile (0-40 cm) was identified as a mixture of calcite and dolomite, while dolomite alone was detected in the samples between 40 and 75 cm.

The material sampled between 100 and 280 cm was shown to have the mineralogy of essentially unweathered norite. After acid treatment the surface samples had a mineralogical composition of unweathered norite, with an increase in the amount of free quartz to 10%.

DENSITY DETERMINATION

The average density of the norite was 3.04 gm/cm^3, which compares favourably with the value of 3.13 reported by Alderman in 1927. The average density of the damp plastic clay material of the joints was 1.8 gm/cm^3.

CHAPTER 5

DISCUSSION AND CONCLUSIONS

GENERAL COMMENTS

The chemical and mineralogical analyses of the weathering of the Long Ridge granodiorite and the Black Hill norite show that:

1. there are chemical and mineralogical variations in the fresh granodiorite and norite which have influenced the chemistry of the weathering products.
2. the stability of the rock forming minerals in the granodiorite and the norite is similar to that predicted by Goldich (1938), and supported by other workers.
3. the physical disintegration of the rock during weathering is due to clay formation along cracks in the crystals in essentially fresh rock.
4. chemical changes which occurred during the weathering of both rocks are similar to those observed by other workers.
5. the mineralogical changes detected are complex. Moreover, a distinction must be drawn between those changes which are attributable to the influence of the semi-arid climate and those which are attributable to the micro-environment in which the minerals are weathering.

6. some of the weathering products found on the norite are inconsistent with genesis in the present environment.

Each of the above will now be discussed in detail.

FRESH ROCK VARIATIONS AND EFFECTS

Neither the Long Ridge granodiorite nor the Black Hill norite is homogeneous. Mineralogical and chemical variations occur in both rocks.

At Long Ridge two chemically different rocks were detected (Table 2). Thin section examination of the two rocks revealed that the rock with a high silicon and lower aluminium content is composed of poorly shaped crystals. The feldspars are zoned and strongly perthitic. In contrast the other rock, with lower silicon and higher aluminium content, has blocky, well shaped feldspars which are only weakly perthitic and appears to contain more biotite. The two rocks have mineralogical characteristics which suggest that they crystallised under different conditions and are therefore different both mineralogically and chemically (Plates 35, 36, 37 and 38). The chemistry of the rock given in Table 2a is very similar to that of other granitic outcrops in the area, such as the Murray Bridge granite (see also Table 2). Thus, the chemistry at the rock given in Table 2b is anomalous. Such variations within a granitic rock have been encountered by other workers (Milnes, Kleeman & Compston, in prep.).

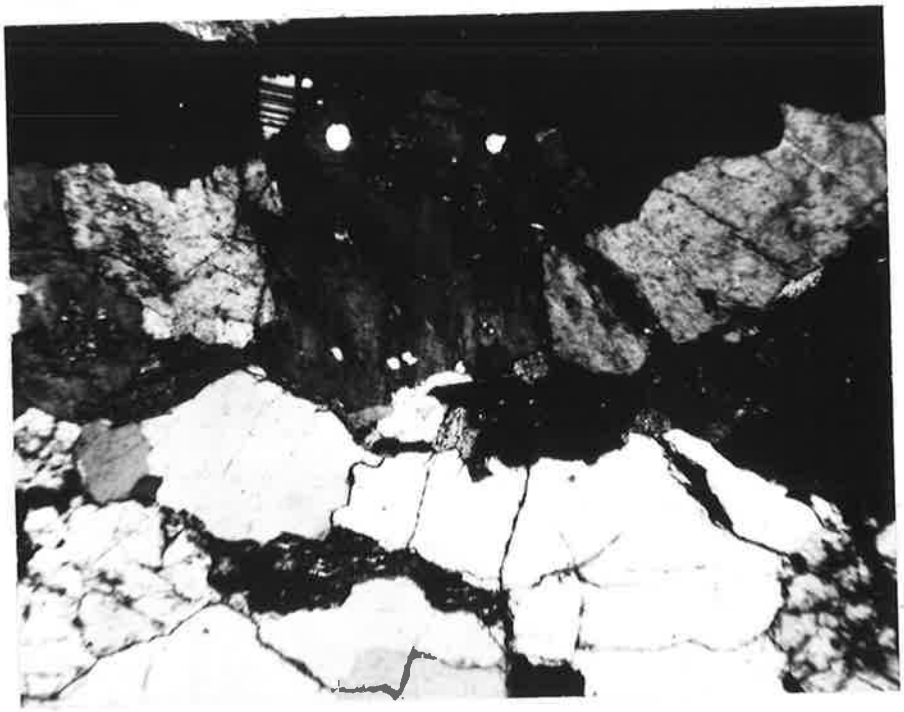


Plate 35. General view of rock high in silicon, showing poorly shaped crystals, under crossed nicols. (2.5 times objective).

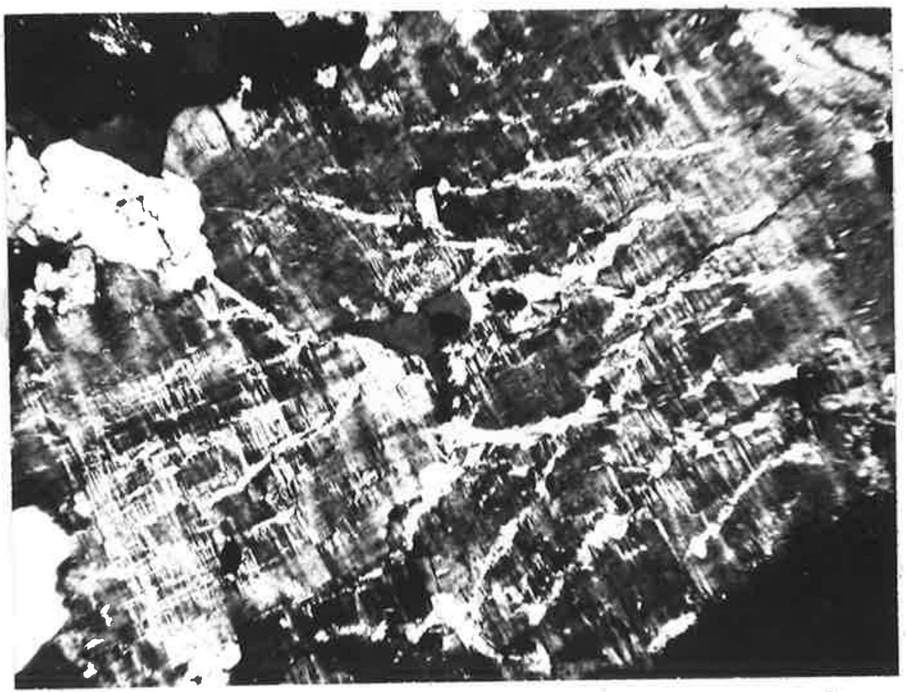


Plate 36. Strongly perthitic feldspar with poor crystal boundaries in rock high in silicon, under crossed nicols. (2.5 times objective).

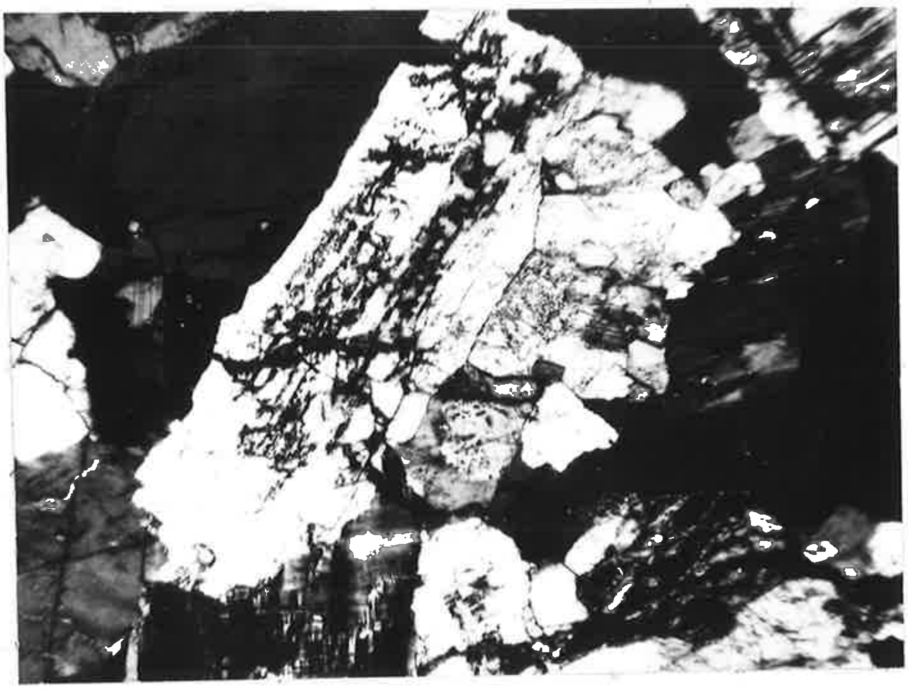


Plate 37. General view of rock low in silicon showing sharp crystal boundaries of feldspar crystals, under crossed nicols. (2.5 times objective).

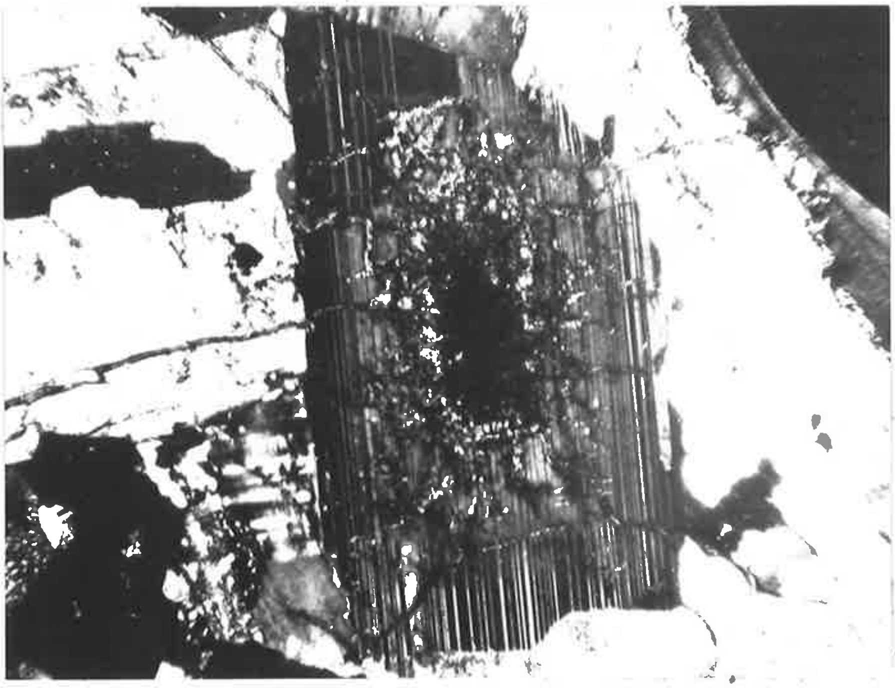


Plate 38. Well shaped, zoned plagioclase crystal in the rock low in silicon, under crossed nicols. (2.5 times objective).

The norite at Black Hill also varies in its fresh rock chemistry (Table 9). There is a colour change associated with the change in chemistry, which is due to variations in the feldspar and hypersthene content in the rock.

This study shows that the variations in rock chemistry are inherited by the weathered material (Tables 5, 7 and 9). This indicates that not all variations in the chemistry of a weathering profile are produced during the weathering process. Some reflect the heterogeneity of the parent rock.

The influence of parent rock chemistry is probably most significant in immature profiles and in low rainfall regimes where removal of soluble elements is limited (Brewer, 1964). Variations in the heavy mineral chemistry of igneous rocks may also be detected in weathering profiles in high rainfall regimes (Worden, 1970).

Thus, the importance of sampling parent material carefully in order to detect all possible variations in chemistry and mineralogy which may influence the interpretation of results of weathering studies has been highlighted by this study. This has also been noted by Evans and Adams (1975), and Hutton (1977, p.682).

MINERAL STABILITY

In this study thin section analysis of the weathering of the granodiorite and the norite along joints has enabled some light to be shed on the relative stability of the constituent minerals during weathering.

The relative stability of the rock-forming minerals has been under study and debate for over 100 years. Investigations have been based on the hypothesis that the least stable minerals under conditions at or near the earth's surface would be those that crystallise at the higher temperatures. This gives an order of stability which is the reverse of the Bowen reaction series (Goldich, 1938) (Table 1).

Microscopic and chemical analysis has been used to determine the relative stability of the rock forming minerals under varying conditions. The persistence of a mineral through the weathering sequence is used as a measure of its stability under the prevailing conditions. Brewer (1964, Ch.5) reviews the work done in this area and concludes that relative mineral stability is close to that derived by Goldich (1938). Workers have differing ideas on the order of stability in detail and Brewer (1964, Ch.5) stresses that this is due largely to the influence of the micro-environment in which the minerals are weathering.

The major minerals in the granodiorite and the norite samples examined in this study are plagioclase, potash feldspar, hypersthene, augite, biotite and quartz. Thin section examination shows that the biotite and the plagioclase are the first minerals to undergo slight chemical alteration. The biotite becomes paler in colour and clays form in and around the plagioclase crystals. Hypersthene and augite also display iron staining and clay formation around the minerals and along cleavage planes in corestone and laminated rock samples (Plates 28 and 29). The potash feldspar and the quartz appear to be unaltered in the corestone and laminated rock samples.

In samples of highly weathered rock, sharp crystal faces are no longer present on any of the minerals and there has been a reduction in crystal size (Plates 25 and 33). In the highly weathered granodiorite, the biotite and the plagioclase have weathered to a greater extent than potash feldspar and the quartz, though all the minerals are still present. By comparison, in the highly weathered norite the augite is no longer present and hypersthene is present only in small quantities. Large crystals of plagioclase and potash feldspar are present and the concentration of quartz appears to have increased.

There is only 10 - 30% clay size particles in the analysed samples which suggests that mineral breakdown and alteration has not gone to completion. Thus, an attempt to assign a relative order of stability to the minerals, based on persistence of the minerals through a weathering sequence would be tentative. There is, however, evidence to suggest that the minerals do display a relative stability similar to that derived by Goldich (1938) (Table 1), as illustrated in Table 14 below. Some differences can be attributed to variations in micro-environment highlighted by Brewer (1964).

TABLE 14

RELATIVE MINERAL STABILITY OF CONSTITUENT MINERALS IN GRANODIORITE AND NORITE AT LONG RIDGE AND BLACK HILL.

Biotite		Plagioclase
Augite		
Hypersthene		Potash feldspar
	Quartz	

PHYSICAL CHANGES

At both sites the rock has suffered considerable physical disintegration: blocky and granular disintegration of rock adjacent to joints at Long Ridge, lamination of rock adjacent to joints and granular disintegration in the Council Quarry at Black Hill.

There is no evidence to suggest that the contemporary sets of joints in each rock, now open to the atmosphere, have been invaded by hydrothermal waters and gases (as was suggested, for example, with respect to the Dartmoor granite by Palmer and Nielson, 1962), though, as mentioned, an earlier set has been sealed by such activity at Black Hill. The regional metamorphism which has affected the Long Ridge granodiorite (Mines Department of South Australia, 1975), has not affected the mineralogy of the rock adjacent to joints. At Black Hill the mineralogy of the joint planes is similar to the rest of the rock mass and stands in marked contrast to the mineralogy of the sealed set of joints.

Insolation has not caused the disintegration of the rock along the joints because it extends to depths of 8 m, far beyond the range of either diurnal or annual temperature changes.

The disintegration must be related to the infiltration of water down joints and into the slightly permeable rock. Thin sections of the granular granodiorite and the laminated norite reveal that there is clay around individual crystals. Thus, some chemical change has accompanied the physical disintegration of the rock, but it must be so slight as to be undetected by X-ray diffraction or X-ray spectrometric analysis.

Such physical disintegration immediately adjacent to unweathered corestones and joint blocks is characteristic of many weathering sequences (Larsen, 1948, p.118; Twidale, 1962, and 1971, p.30). Thin section of the disintegrated rock samples examined in these studies has shown that clay formation has occurred around individual crystals, similar to that observed in this study.

The presence of clay minerals in small amounts is significant as they have comparatively high water absorbing properties and would allow the penetrating water to react with fresh minerals in contact with the clays. This allows the whole process to continue. Clay minerals occupy a considerably greater volume than the primary minerals from which they are formed.

Clay percentage determinations of the blocky and granular samples of granodiorite indicate that they contain up to 13% clay (Table 8), while some quantitative measure of the clay content seen optically in the laminated samples of norite can be obtained from the figures for loss on ignition (Table 9). The norite itself lost less than 0.5% while most of the weathered material with 40% clay (on oven dried basis) lost 8.5% on heating from 105°C to 1000°C. The laminated samples lost up to 1.6% suggesting that they may contain up to 8% clay. Such amounts of clay in thin layers around hard mineral grains could produce sufficient pressure to cause the observed fracturing.

This production of clay, which offers an explanation of the physical features observed in the field, poses a space problem, for the density of the clay is 1.8 gm/cm^3 compared to 3 gm/cm^3 for the rock. How could this low density material be accommodated in the space available?

If the joints were of normal dimensions, some of the clay produced by weathering must have been evacuated. It may have swelled upwards but there is no sign either of shearing in the clay or bulges where the joint traces meet the land surface. Ruxton (1958) has adduced evidence to suggest that clays can be lost from weathered rock by flushing during strong through-flow of water following heavy rains. Evidence at Long Ridge and Black Hill does not support the suggestion that clay has been lost during such through-flow. In the laminated rock the clay appears to form around the individual crystals and so is not accessible to flowing water. The presence of the clay mineral montmorillonite and the iron-rich montmorillonite, nontronite, suggest stagnant conditions, with no leaching of cations or loss of fine clay particles. Thus, while the formation of clays offers a satisfactory solution for the production of granular, blocky or laminated structures in the weathering rock along joints by the increase in volume, it is difficult to accommodate this increased volume in the joints.

CHEMICAL CHANGES

Anderson and Hawkes (1958) established an order for the loss of elements during weathering: magnesium → calcium → sodium → potassium → silicon → aluminium = iron, from studies in New England, U.S.A. Dennen and Anderson (1962), assuming aluminium to be constant, derived a pattern of element behaviour during weathering. Their conclusions state that silicon is concentrated in the weathered material as residual quartz or in clay, while iron is concentrated as an insoluble iron oxide. Potassium may be concentrated by absorption and calcium, magnesium and sodium should be depleted by leaching. Harris and Adams (1966), regard calcium and sodium in plagioclase as the most mobile elements during weathering with potassium, silicon and magnesium next and aluminium and iron are the least mobile. Loughnan (1969, p.52) summarises the results of a number of studies in a table which gives an order of mobility similar to that of Anderson and Hawkes (1958).

Chemical changes that have occurred along joints and in the profiles during the weathering of the granodiorite at Long Ridge and the norite at Black Hill are summarised in Table 15. Increases or decreases in the concentrations of the elements in the weathered material relative to that of the related fresh rock are indicated. For most elements the calcium carbonate-free calculations (Tables 6, 7, 9, and 12), were used for the comparison, as the presence of

TABLE 15.

SUMMARY OF WEATHERING CHANGES ALONG JOINTS AND IN PROFILES AT LONG RIDGE & BLACK HILL.

	Fe	Ti	Ca	K	P	Si	Al	Mg	Na
Joint Weathering									
Long Ridge Av. % change	+36	± 50	+ 600 (calcite rich) - 29	-10	-20	- 2.5	-10	+ 23	-34
Black Hill Av.% change	+22	-35	- 68	-22	-88	+ 6	-12	+ 43	-
Weathering Profiles									
Long Ridge 1. Av. % change	+59	+ 8	+ 18 (calcite rich) - 76	-20	-66	+ 3	+ 1.8	+186	-31
Long Ridge 2. Av. % change	+84	+60	+1500 (calcite rich) - 80	-22	-	- 5	-14	+174	-28
Long Ridge 3. Av. % change	+79	+39	+ 441 (calcite rich) - 43	-30	-	- 5	- 5	+258	-54
Black Hill Soil Av. % change	-21	- 3	+ 213 (calcite rich) - 53	+12	-76	+17 surface -20 depth	-13	- 41	-
Black Hill Granular Av. % change	-33	-37	+ 260 (calcite rich) - 38	-40	-17	+43 surface + 2 depth	-44	+144 surface dolomite - 40 depth	

calcium carbonate dilutes the concentrations of the other elements. An indication of the retention of calcium and magnesium as calcite or dolomite is given in Tables 4, 5, 11 and 12.

(i) Joint Weathering

In general, there has been a loss of potassium, calcium and phosphorus from the weathered rock adjacent to the joints in both systems. Sodium has been lost from the granodiorite, but was not present in the norite. Although there has been an overall loss of calcium in both joint systems, some has been retained as calcium carbonate along joints on Long Ridge. Aluminium concentrations show little change, while silicon has been lost from the joints at Long Ridge and has increased in concentration in the joints at Black Hill.

On the granodiorite, magnesium has been retained in the montmorillonite and iron has been incorporated in insoluble iron oxide, which has resulted in a relative increase in the concentration of the two elements. There has been a similar increase in the concentrations of iron and magnesium along joints in the norite. However, in this case both of these elements have been incorporated in the montmorillonite.

(ii) Weathering Profiles and Soil Formation

There has been an overall loss of silicon, sodium, phosphorus, aluminium, potassium and titanium in all profiles. There has been an increase of silicon in the near-surface samples of the dark brown soil on the norite as a result of contamination of wind-blown sand or amorphous silica formation. However, silicon has been lost from samples lower in the profile.

In the near-surface samples of all profiles calcium has been retained due to the formation of a calcite layer, or a calcite and dolomite layer, in the case of the Council Quarry profile.

Magnesium has been retained in all profiles, apart from the dark brown soil developed on the norite. On the granodiorite it has been incorporated in the montmorillonite in profiles 1 and 2 and in the randomly interstratified material in profile 3. On the norite in the Council Quarry, the magnesium is present near the surface as dolomite. The lower parts of that profile have been depleted of both calcium and magnesium.

Iron has been retained in the near-surface samples of profiles 1, 2 and 3 on the granodiorite due to the formation of insoluble iron oxides, but lost from the dark brown soil on the norite.

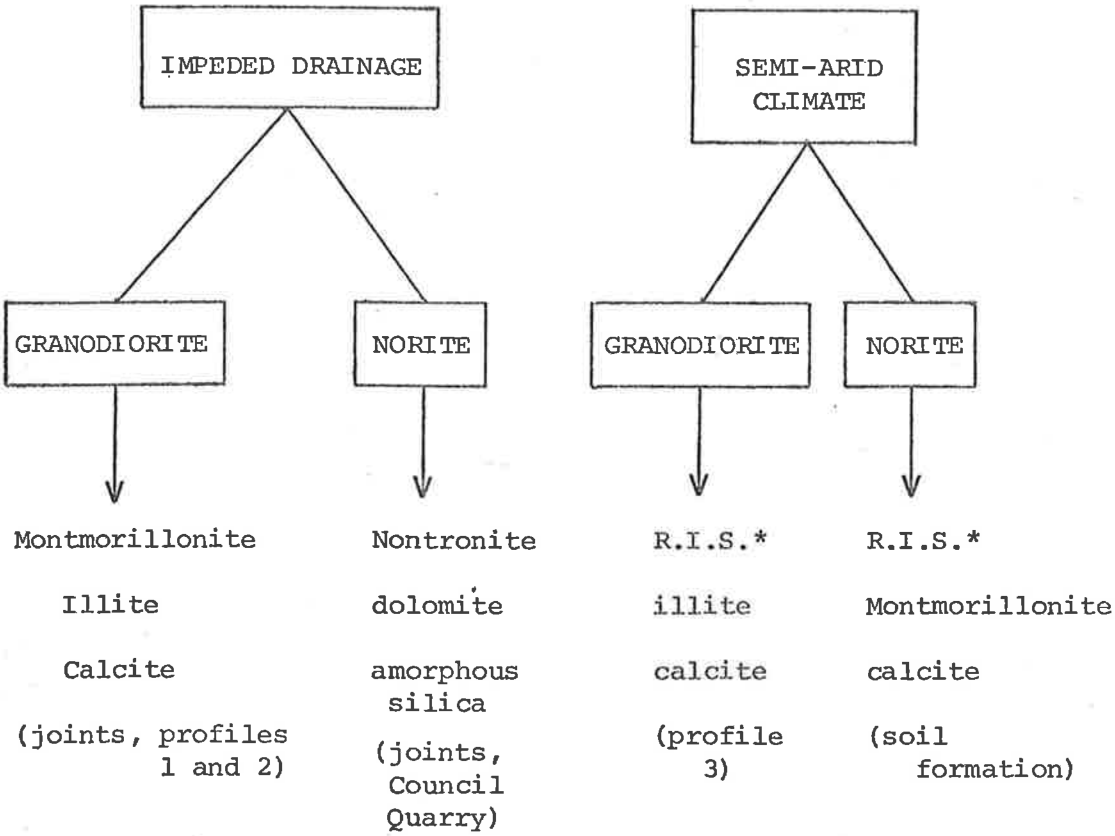
In summary, the weathering of the granodiorite and the norite has involved a loss of sodium, phosphorus and some potassium from the systems at an early stage. Calcium and magnesium have also been released from crystal lattices but are, on the whole, retained in clay minerals, calcite and dolomite. Iron has been released and retained as iron oxides or in clay minerals. Silicon and aluminium have been retained to a large degree in clay mineral formation (although there has been an overall loss of silicon during weathering at Long Ridge). Silicon is present as amorphous silica, or free quartz, at Black Hill.

Thus, in general, the loss or retention of elements during the weathering of the granodiorite and norite is a similar pattern to that described by other workers. However, the retention of calcium and magnesium during weathering of both the granodiorite and the norite is not in keeping with the findings of others. This is probably due to the influence of either the semi-arid climate, or the micro-environment under which the rock is weathering.

The role that the semi-arid climate and the micro-environment play in influencing the loss or retention of elements, and thus the mineralogy of the weathering products is discussed in detail under the heading "Mineralogical Changes and their implications" in this Chapter.

FIGURE 4

SUMMARY OF MINERALOGICAL CHANGES DURING WEATHERING ON THE GRANODIORITE AND THE NORITE.



*R.I.S. = Randomly Interstratified Material

MINERALOGICAL CHANGES AND THEIR IMPLICATIONS

The minerals produced by the weathering of the granodiorite and the norite are summarised in Figure 4. The complex clay mineral montmorillonite occurs:

(a) along the joints in the granodiorite and the norite,

(b) in weathering profiles 1 and 2 on the granodiorite,

(c) and at depth in the dark brown soil on the norite.

The conditions under which montmorillonite forms are variable, depending on rock type, topography, climate and drainage conditions.

Stace *et al* (1968, pp.113-114, and pp.334-335) records that montmorillonite develops under impeded drainage conditions on basalt in the high rainfall regions of eastern Australia. Gunn (1974) also records montmorillonite forming at depth in a profile on basalt as a result of impeded drainage. Nettleton *et al* (1970) found montmorillonite forming on a tonalite associated with impeded drainage conditions, while Tardy *et al* (1973) record it developing on the lower slopes of a granite where drainage was impeded. J.T. Hutton (pers. comm.) has found montmorillonite at depth in a profile developed on granite, in an arid climate in Central Australia, under conditions of impeded drainage.

Craig and Loughnan (1964), Singer (1966), Dan and Singer (1973), and Singer (1973) found montmorillonite in soils derived from the weathering of basalt in a semi-arid climate under freely drained conditions.

In these studies montmorillonite has formed on basic, intermediate and acidic crystalline rocks, usually under impeded drainage conditions. The exception has been the development of montmorillonite on basalt (a basic igneous rock) in a freely drained situation, in a semi-arid climate.

Jackson (1954), Keller (1956), Loughnan (1969), and Millot (1970) have also drawn this conclusion from an analysis of a large number of studies. Both of these situations (impeded drainage and semi-arid climate) provide a micro-environment that contains a high concentration of active ions due to a lack of through-leaching, favouring montmorillonite formation.

Brewer (1964, pp.100-101) emphasises the importance of the balance between the rate of weathering and the rate of leaching, which can account for a wide range of secondary minerals forming from primary minerals. Freely drained conditions usually lead to the formation of simple secondary minerals, whereas impeded drainage conditions favour the formation of complex layer silicates, such as montmorillonite.

The above evidence suggests that montmorillonite formation on the granodiorite (an acidic igneous rock) at Long Ridge may be due to impeded drainage. While the semi-arid climate may be influencing the formation of montmorillonite on the norite (a basic, igneous rock). However, other mineralogical changes and field evidence at both sites need to be considered before the environment under which montmorillonite is forming can be determined.

Illite is coexistent with montmorillonite along the joints and in profiles 1 and 2 on the granodiorite. Most workers acknowledge that, in high rainfall regimes, illite is formed in freely drained conditions on varying rock types. Montmorillonite only forms where drainage is impeded (Brewer, 1964; Millot, 1970).

However, Keller (1956) states that the conditions for illite formation can often be similar to those for montmorillonite. Both can form under the influence of moderate rainfall with wetting and drying in the presence of calcium carbonate, or under marine conditions (that is, standing water where there is no through-leaching). Supporting this view, Todd (1968, p.835), emphasises the importance of the micro-environment and states that a slower weathering rate, such as likely obtains in arid or semi-arid climates, or a high weathering rate and retarded leaching conditions, can result in high potassium ion soil concentrations and the development of secondary mica or illite on weathered orthoclase. These conditions also favour montmorillonite formation (see discussion, pp. 92-93).

Loughnan (1969, p.52), summarising the results of a number of workers, states that illite forms by fixation of potassium in the illite lattice when leaching is limited. These conditions may be present in arid or semi-arid climates or where through-drainage is impeded. Deer, Howie and Zussman (1966, p.253) concur with these workers, stating that both montmorillonite and illite do form under alkaline conditions.

Thus,there is some evidence to suggest that montmorillonite and illite can coexist in a semi-arid environment, or under impeded drainage conditions.

In this study, weathering is at present taking place in a semi-arid climate, but field evidence at Long Ridge suggests that drainage in the area where the two clays occur is in fact impeded. During this investigation it was noted that the quarry, which is sited in a depression near the top of the rise (Figure 2), was half full of water (Plates 39 and 40) from August 1974 till December 1977. This is an indication that the drainage through the rock in the vicinity of the quarry is very slow. The water accumulated during the unusually wet winter of 1974 (Mr. J. Rowley, pers. comm.), and was still present in December 1977 although the level had been reduced by

Plate 39. Long Ridge Quarry 1974, half full of water.

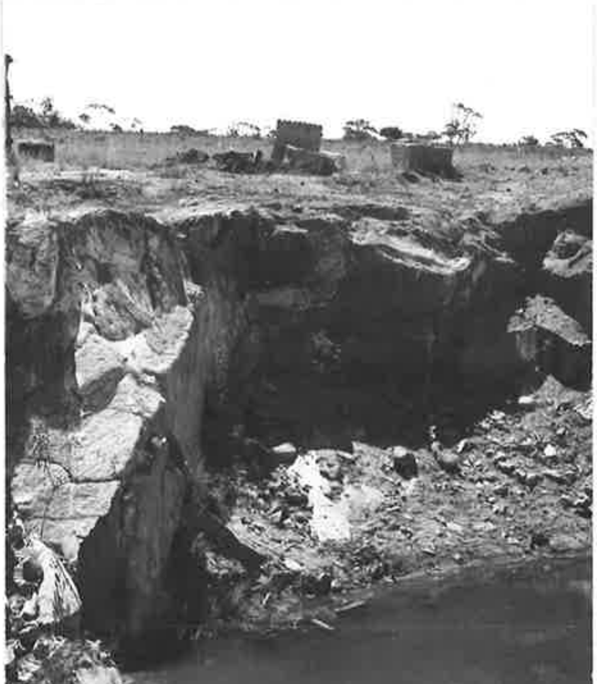


Plate 40. Long Ridge Quarry 1977, still holding water.

evaporation. The rock near the surface in the quarry is very massive and lacking in joints, thus, avenues for through-flow are restricted (Mr. J. Rowley, pers. comm.). This has resulted in the retention of rain water in the quarry, and poor drainage in its vicinity.

This evidence suggests that the montmorillonite and the illite in the joints and weathering profiles 1 and 2 on the granodorite have formed under impeded drainage conditions.

However, the presence of calcium carbonate along the joints and in the near-surface samples of profiles 1 and 2 needs to be accounted for in the explanation, since this mineral occurs randomly intermixed with the montmorillonite and illite.

Keller (1956) suggests that the presence of calcium carbonate is a pre-condition for illite formation, so the presence of illite in the weathering sequence is readily understandable.

Craig and Loughnan (1964, p.231) have noted calcium carbonate occurring randomly, at depth, in a profile on basalt associated with montmorillonite and forming under impeded drainage conditions.

Precipitation of calcium carbonate occurs when there is a change in the micro-environment which does not allow the free ions to remain in solution. Such conditions may occur in the saturated zone, where a lack of through-leaching results in an abnormally high concentration of calcium and carbonate ions in solution, forcing precipitation of some of the dissolved salt. Alternatively, precipitation may be forced by evaporation of ground water during the summer months.

Thus, the coexistence of montmorillonite, illite and calcite as residual weathering products in the joints and weathering profiles 1 and 2 at Long Ridge may be due to the impeded drainage in the vicinity of the quarry, which has created a different micro-environment for weathering to take place.

Profile 2, however, has montmorillonite and illite at depth while the near-surface samples contain illite, randomly interstratified material and some kaolin as does sample I at 1.2 m. This overall change in mineralogy with depth may indicate that the drainage is impeded at depth, but that the near-surface samples are subject to an upward movement of groundwater by evaporation, due to the semi-arid climate.

Sample I is low in calcium, magnesium and iron and high in silicon relative to the rest of the profile. This chemistry suggests that the fresh rock must have been quartz-rich and biotite-poor, relative to other sampled fresh rock (Table 2). Thus, it appears that the chemical and mineralogical inconsistency in profile 2 is the result of the random distribution of fresh rock of differing chemistry through the rock mass, and that these variations have persisted into the weathering sequence.

In conclusion, field and laboratory evidence from Long Ridge suggests that the weathering of the granodiorite along the joints and in profiles 1 and 2 has occurred under conditions of impeded drainage. This condition may only occur periodically as the presence of insoluble iron oxides indicates that oxidizing conditions prevail for some length of time during the weathering of the granodiorite at these sites.

On Black Hill the montmorillonite in the joints contains 12.5% iron, which classifies it as a nontronite. The formation of nontronite during weathering is rare. Sherman *et al* (1962) have recorded it in semi-arid, moderate rainfall and tropical rain forest areas forming on basic igneous rocks. In this study the nontronite occurs in freely drained situations which maintain a continually high concentration of iron, magnesium and silicon in solution. The need for a continual supply of iron and magnesium during the formation of nontronite, and to ensure its stability, is under debate (Yaalon, 1970). However, the norite at Black Hill contains sufficient iron and magnesium to act as a source of free ions for nontronite formation, thus no outside source needs to be invoked.

The presence of nontronite may also be indicative of impeded drainage, as the reducing conditions which prevail enable the iron to be incorporated into the crystal lattice of clay minerals, rather than being oxidised to insoluble iron oxides.

The presence of the vein of amorphous silica, along some of the joints in the norite and associated with the nontronite also needs explanation. Amorphous silica usually forms as a transient product, breaking down rapidly under through-leaching conditions, but it is stable under supersaturated, stagnant conditions (Loughnan, 1969).

Field evidence at Black Hill indicates that at present water moves rapidly through the joint system. Rain water which accumulates in the Martin Quarry drains through the rock into the Monier Quarry and then out into the surrounding rock within 3 days (Mr. J. Attrill and Mr. D. Fletcher, foremen, pers. comm.).

Thus, the weathering products developed along the joints at Black Hill appear to be indicative of impeded drainage in the rock mass sometime in the past, and probably for a prolonged period of time. Furthermore, the present climate is not wet enough to bring about equilibration of these products with the prevailing environment.

Having examined all available evidence it can be concluded that the montmorillonite and illite in the joints and weathering profiles 1 and 2 on Long Ridge and the iron-rich montmorillonite, nontronite and the amorphous silica in the joints at Black Hill have formed under impeded drainage conditions.

Weathering profile 3 on the granodiorite is located down slope, to the east of the quarry. It displays a similar chemistry to profiles 1 and 2 but a different mineralogy. Illite, kaolin and randomly interstratified material are present and a layer of calcite has developed between 25 and 50 cm. No montmorillonite was detected. The soil formation at Black Hill was sampled near the Old Martin Quarry (Figure 3). The near-surface samples have a chemistry similar to weathering profile 3 on the granodiotie, with kaolin, illite, haematite and randomly interstratified material present and a layer of calcite between 10 and 20 cm. At depth montmorillonite is present. Randomly interstratified material is a complex of clay minerals, including illite, montmorillonite and kaolin, which has an overall layer spacing of 18A^{O}. This is similar to montmorillonite, but it does not give the sharp peak of montmorillonite on a diffractometer trace. Instead it often registers a broad complex peak. The conditions favouring its formation are not well understood. It occurs predominantly in soils in the semi-arid areas of Australia on varied rock types, usually in freely drained situations (Stace *et al*, 1968), but has not been found to be present in the soils of the northern hemisphere and tropical areas (Mr. J. Pickering, pers. comm.).

Thus, the semi-arid climate, which promotes the upward movement and evaporation of groundwater from the profiles, appears to have been the major influence determining the mineralogy of these two freely drained weathering profiles.

The presence of montmorillonite at depth in the profile on the norite and not on the granodiorite illustrates the role that the parent rock can play in determining the mineralogy of the weathering products. The norite is a magnesium-rich rock which facilitates the formation of montmorillonite in a semi-arid climate (see discussion pp. 92-93).

The disturbed site at the Council Quarry at Black Hill resulted in an incomplete profile being collected, as there was no A horizon containing organic matter and no clay B horizon. Sampling at undisturbed sites close to the quarry and to the east of it indicated that the probable structure of the profile which was removed from the sampling site by quarrying was 20-40 cm of sand-size material containing plant material. No clay horizon was present beneath the sandy horizon and above the hard carbonate layer. Few norite fragments occurred in the sandy horizon. It was noted, however, that the hard carbonate layer was not present at all sites. Where there was no hard carbonate layer, nodular carbonate was present, as was a clay B horizon containing fragments of norite. Thus, the site which was sampled and analysed may be regarded as representing a profile which had a sandy A horizon, containing no norite fragments but lacked a clay B horizon. This may indicate that the hard carbonate layer resting on essentially fresh but granular norite is a deposit, rather than a product of the weathering of the norite.

The carbonate horizons in this profile are a mixture of calcite and dolomite near the surface, but dolomite alone is present at depth (Table 13). Amorphous silica was also detected in the carbonate horizons (see p.72).

This predominance of dolomite in the carbonate fraction, the presence of amorphous silica and the absence of clay minerals is in marked contrast to the mineralogy of the dark brown soil profile developed on the norite. The dark brown soil appears to contain the typical assemblage of weathering products for the contemporary climatic conditions. Thus, the hard carbonate layer at the Council Quarry may have formed as a sediment rather than by pedogenesis. Its chemical composition indicates that it may have accumulated in a shallow saline ephemeral lake similar to those near the present Coorong in the south of South Australia, where dolomite is currently forming (von der Borch, Lock & Schwebel, 1975). The formation of amorphous silica is also favoured by such conditions (see p.100).

Dixon (1978, pp.65-67, 70-77) discusses the mineralogy of the calcite and dolomite in the Council Quarry profile. Palygorskite is present in the samples, which he suggests, indicates a shallow saline lake as the environment needed for the formation of the carbonates in the profile. Dixon's evidence strongly supports the findings of this study.

The quarries at Black Hill stand at least 35 m above the surrounding Murray basin soils and the calcareous deposits which Firman (1965) associates with the Pleistocence Lake Bungunnia. It seems that the inundation of Black Hill was not related to Lake Bungunnia, but more likely to the Tertiary, particularly the Miocene, marine transgressions.

Thus, the sediment preserved at the Council Quarry site and the nontronite and amorphous silica along joints is evidence for climatic change in the Murray Basin.

The present height of the lake deposits above sea level may be due to regional uplift as the outcrop is on a fault block delineated by the Milendella fault in the west and the Morgan fault in the east. This area was subject to faulting during the late Tertiary, as was the whole of the Mt. Lofty Range (Twidale & Bourne, 1975), though evidence for such faulting has not been found in the study area.

GRANULAR DISINTEGRATION OF THE NORITE

The granular weathering exposed in the Council Quarry at Black Hill has no equivalent developed on the granodiorite. Granular disintegration similar to that in the Council Quarry has been described by a large number of workers, among them Wahrhaftig (1965), Nettleton, Flach, and Nelson (1970), Basham (1974), and Isherwood and Street (1976), all of whom attribute the granular disintegration or grussification, to the partial alteration and expansion of biotite.

However, the results indicate that the biotite induced grussification, described by other workers, is not occurring in the rock at the Council Quarry site (see p. 74).

Other evidence needs to be considered to account for the nature of the weathering of the norite at the Council Quarry. If, in fact, this site did have a more dense joint system as suggested previously (p. 73) and these joints were open, then perhaps the small amount of clay present (5%) is enough to cause the granular disintegration of the norite at this site (see pp.83-86).

The density and openness of the joint system in this part of the norite would allow a greater amount of the rock to be exposed to weathering and clay formation by infiltrating groundwater than was possible at other sites where the norite is more massive.

One possible source of groundwater to exploit the joint system is the drainage from the norite outcrop at higher elevations. Another could be the inundation of the rock mass by lake waters (see discussion, pp.103-104). which would have allowed extensive penetration of water into the rock at this site.

Thus, the formation of dolomite and amorphous silica appears to have occurred under impeded drainage conditions, which have also exploited the structure of the rock bringing about the granular disintegration of the rock mass at the Council Quarry site.

The above discussion has illustrated the important role which the micro-environment plays in influencing the nature of the weathering products on two different rock types.

Where drainage was impeded on both rocks montmorillonite clays formed, despite differences in the mineralogy of the rocks. In freely drained situations the influence of the semi-arid climate was predominant in that similar clays formed on both rocks. Also, at the freely drained site on Black Hill, the influence of the mineralogy of the parent rock in determining the nature of the weathering products was illustrated.

Furthermore, the micro-environment has been shown to vary markedly on one rock outcrop at any point in time throughout its history.

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