A NEW REGOLITH LANDFORM MAP OF THE WESTERN VICTORIAN VOLCANIC PLAINS, VICTORIA, AUSTRALIA

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The Western Victorian Volcanic Plains are part of the Newer Volcanic Province of southeastern Australia Geological and regolith mapping by Honours students of the northern part of the Plains has distinguished some fifteen Regolith Landform Units, elaborating on the four major units presented on the Hamilton 1:1 000 000 regolith map (Ollier & Joyce 1986) which were based in turn on earlier soil mapping by Gibbons and Gill (1964). K/Ar and radiocarbon dates have been used to provide numerical ages for the parent materials of the Regolith Landform Units on the lava flows, and the regolith map is unusual in that the units must all have formed during the last 5 Ma Mapping units are based on landforms and regolith development The landforms range from young stony rise flows, through degraded stony rises, to undulating to flat clay plains on flows of 1 to 3 Ma, with dissected clay plateaus on the oldest flows of 3 to 5 Ma In turn, the regolith ranges from almost-bare basaltic lava outcrop, through initial shallow soil development in depressions, to 1 to 2 m deep clay soils with gilgai, to mottled and pallid kaolinitic profiles many metres deep. Field mapping using air photos, photomaps and Landsat imagery has been supplemented with the use of maps of original vegetation and current land use Radiometric imagery has been used to link the areas mapped by Honours students and add further detail The use of radiometric and other imagery, as well as other data sets, to map Regolith Landform Units on basalt plains have been evaluated Regolith maps of this type allow a detailed landscape history to be developed, including the sequence of volcanic activity and related drainage changes, and also allow deductions about climatic change; regolith mapping will now be extended to cover the whole of the Newer Volcanic Province

Key words: regolith mapping, basalt, Victoria, chronosequence, radiometric imagery, landscape history, volcanic activity

INTRODUCTION

NEWER VOLCANIC PROVINCE OF SOUTHEASTERN AUSTRALIA

Young basaltic landscapes due to areal volcanism are found in many parts of the world, including northern Queensland and southeastern Australia, and usually consist of many small scoria cones and lava shields, sometimes maar craters, and extensive flows either confined in pre-existing valleys or forming extensive plains or plateaus

The Newer Volcanic Province of southeastern Australia is estimated to cover 15,000 km^2 and to have nearly 400 points of eruption Activity in the late Tertiary to Holocene Newer Volcanics has been described as of the areal type, defined as "numerous small, short-lived central type volcanoes of basaltic composition" (Joyce 1975 p 169) Analogies have been drawn with Strombolian-type activity, where both explosive and effusive (Hawaiian) eruptions are important A major feature of the activity in southeastern Australia has been the development of maar (Surtseyan) volcanoes.

In the Central Highlands sub-province eruptions from some 250 scoria and lava volcanoes have resulted in the development of valley flows and small lava plains on an already uplifted and dissected upland On the Western Plains of Victoria, which extend from the plains north of Melbourne and across the adjacent Werribee Plains and the Western Plains proper almost to the South Australian border, volcanoes have been more scattered than in the Highlands, and the flows have spread thinly and more extensively over a level plain developed on weathered Tertiary sediments The Mt Gambier sub-province, separated by an extensive tract of non-volcanic country from the nearest Victorian activity, consists of a small group of earlier volcanoes with few flows, and the later young maars and cones of Mt Gambier and Mt Schank.

The southeastern Australian basaltic province of central and western Victoria and southeastern South Australia demonstrates a chronosequence of regolith, landform and drainage, as first shown in soil studies of far-western Victoria by Gibbons & Gill (1964)

Lava flows and regolith

An initial basaltic volcanic landscape progressively changes with time as a result of weathering and soil formation, the development of drainage systems, and related alterations to the original volcanic landforms

The earliest flows in the Newer Volcanic Province, dated by K/Ar at 3 to 5 Ma, show deep pallid kaolinitic profiles with mottling and occasional development of ferruginous nodules, and suggest the effects of a late Tertiary climate with deep weathering conditions Valleys are incised into and sometimes below the base of the flows

In contrast flows of intermediate age (1 to 3 Ma) have only 1 to 2 metres of red to black swelling clay soil and form undulating to level, relatively stone-free plains, often with well-developed gilgai. Valleys are narrow and shallowly incised, but small lakes and swamps are numerous Flows of less than 1 Ma, many of which are late-Quaternary in age and some less than 10,000 ka, have well-preserved flow features including a varying surface relief of 10m or more (locally known as stony rises) and little or no soil cover. These young flows are associated with lakes and swamps both at the margins and on the flow surfaces, due to disrupted drainage

Flows of less than 3 Ma post-date the effects of a late Tertiary wet and possibly warmer climate, and have relatively shallow profiles developed under more arid climatic conditions This striking change in weathering is seen elsewhere in southeastern Australian e g the lateritic or Walther profiles of the Karoonda Surface on the Tertiary shorelines ridges of the Murray Basin, the Dundas Surface of the Dundas Tablelands at the western end of the Victorian highlands, and similar weathering surfaces on exposed marine and non-marine Tertiary sediments to the south of the Volcanic Plains all ceased developing about the same time A "warm, wet early Pliocene" ended with "The significant cooling that recommenced during the Middle Pliocene at 3.4 to 3 2 million years ago. " (White 1994 p 125); Bowler (1982) puts this change later-"At 2 5 million years ..Deep weathering and sesquioxide mobilization .. came to an end"-and notes that it marks the end of a summer rainfall regime and the onset of cooler winter precipitation across southern Australia

During the last 2.5 to 3 million years, climate has fluctuated from possibly warmer and wetter than the present to semi-arid and seasonally cold and windy, as typified by late-glacial conditions 25 000 to 15 000 B.P (Bowler 1976) Western Victoria has numerous lake-lunette systems which were last active during late-glacial times, and may be a source of aeolian quartz additions to basaltic soils which have been noted by Jackson et al. (1972). For the last three million years the weathering of basaltic lava flows has been strikingly slow, and seems to match the rate for soil development on similar flows in semi-arid tropical north Queensland (Pillans 1997)

A chronosequence of regolith, landform and drainage development through time can be drawn up, and preliminary mapping of five major units (Figure 1) has been carried out over much of the Province (Joyce 1982; 1987), and incorporated into a regolith map of parts of Victoria and South Australia (Ollier & Joyce 1986)

THE STUDY AREA

The Willaura and Skipton 1:100 000 map sheets form part of the Ballarat 1:250 000 Mapping Accord area The Geological Survey of Victoria is currently completing geological maps of the Ararat, Beaufort, Creswick and Ballarat sheets (Figure 2) and AGSO has mapped the geology of the two sheets forming the study area but these remain unpublished King (1985) provides an explanatory note to the 1:250 000 Ballarat Geology sheet which was published as a provisional map in 1965

The study area has been selected as a suitable part of the Newer Volcanic Province to map Regolith Landform Units (RLUs) in greater detail, because the Mapping Accord has provided new and detailed airborne geophysics, and also because a range of other data sets is available, including detailed mapping by Honours students-these data sets are discussed below This study is to be followed by further work in the Highlands Subprovince, around Creswick, the plains north and west of Melbourne, and the remaining areas of the Plains to the south, to complete a Regolith Landform map for the whole Newer Volcanic Province

DATA SETS

The Hamilton Regolith Terrain Unit (RTU) map of Ollier & Joyce (1986) covers the study area at 1:1 000 000 scale (see Figure 3) Soil-Landform mapping has been carried out by the Victorian State Government and published at 1:250 000 scale (Maher & Martin 1987) Vegetation and land-use maps are also available (Land Conservation Council 1980) and a map of the original vegetation before European settlement in the mid-nineteenth century is available at approximately 1:1 000 000 scale (Everett 1869)

The area is covered by Victorian government air photos at several scales including 1:25 000 and 1:85 000 scale (RC9) black and white air photos flown in the 1960s for National Mapping, and these were used in the Honours mapping projects. Use was also made of 1:100 000 photoindices published by National Mapping in 1966. These black and white, uncorrected and poor quality photomosaics can be used to distinguish between the young (Eccles and Rouse) and older (Dunkeld and Hamilton) RTUs, but add little to the detail shown on the maps produced by the students using stereo air photos and field mapping.

Landsat MSS hard copy at 1:250 000 with colour allotment BGR 457 was used in the study, and also a 1:100 000 Landsat TM Willaura sheet with colour allotment BGR 247 prepared for another project and made available by the Department of Conservation and Natural Resources.

A series of Honours mapping projects on the volcanic plains has included mapping of volcanic centres, of flow boundaries and flow surface features, and streams, lakes and swamps, establishing the sequence of drainage and landforms, and developing Regolith Terrain Units for the volcanic areas.

The Ballarat 1:100 000 Regolith-exploration map sheet (Taylor & Joyce 1996) provides an example of recent regolith mapping nearby, and includes an adjacent part of the volcanic plains. It covers an area with extensive historical gold production including from sub-basaltic deep leads, and was published to assist in the planning of geochemical exploration sampling programs, as the first of a series of Regolith Landform maps to cover the Ballarat region.

DISCUSSION

EARLIER REGOLITH LANDFORM MAPPING BY HONOURS STUDENTS

In the late 1980s, several Honours mapping projects of the area were carried out, with detailed field work and air photo interpretation (MacInnes 1985), early use of Landsat imagery (Oppy 1986) and image analysis techniques (Valle 1991). In a related Honours project on the volcanic plains just to the east of the study area, Halewood (1991) studied groundwater recharge and discharge areas using seasonal Landsat imagery.

This mapping, carried out largely at air photo scale, increased the detail for the study area compared with the earlier Ollier & Joyce (1986) mapping at 1:1 000 000 scale. In one area, MacInnes (1985) was able to divide the original four units into 15 units, distinguishing two separate volcanic centres and their flows in the Mt Hamilton area which had been previously mapped by the Geological Survey as one large flow, and also dividing the Dunkeld RTU into an earlier and a later unit.

A compilation of the three Honours student maps, with interpretation of the other data sets, especially the soil and vegetation maps and the drainage features as shown on topographic maps, with interpolation to cover the areas in between, and field checking, provide inputs to a new RLU map of the study area.

USE OF LANDSAT IMAGERY

Landsat imagery characteristically gives a broader view than that of air photos and usually shows aspects of lithology, structure and broad geomorphic regions, but often it is simply the vegetation and land use which are most evident.

However Landsat images show clearly the different units mapped by MacInnes (1985) in the Mt Hamilton area. Distinctive colours, textures and patterns can be assigned to most of the previously mapped units (see Table 1). This is largely because the area is predominantly grassland, with only occasional planted windbreaks of trees along fence lines, and in the imagery the soil colour can often be seen on older units because of cultivation. In contrast the younger lava flows show distinctive bluish colours because of rock outcrop on the stony rise ridges.

USE OF RADIOMETRIC IMAGERY

As work on the Ballarat 1:100 000 Regolith-exploration mapping has shown (Taylor & Joyce 1996) airborne radiometrics can allow subdivision of flows by the degree of weathering and rock outcrop, and the soil types formed on the flows.

For this study a 1:250 000 Radiometric Ternary Ratio Image (Geological Survey of Victoria 1998) was specially prepared by David Moore and David Bibby of the GSV (Figure 4), with the area of basaltic plains processed to show maximum colour differentiation, using a clipped linear stretch. The imagery was flown in 1992 with line spacing of 400m at an elevation of 100m, with a fixed wing aircraft along east-west traverse lines and has been gridded to a cell size of 80m, with counts presented as K=red, Th=green and U=blue.

Most of the units previously mapped by the three Honours students can be readily distinguished on the radiometric image, with a progression of colours and to some extent also changes in texture and pattern with the age of the flows The youngest flows and cones (Eccles RLU) show as a bright red colour on the imagery, which becomes red-brown on older stony rise flows (Rouse RLU) and with increasing age progressively changes from blue-green through yellow-green to greenish-yellow Details are summarised in Table 1

After the boundaries of the earlier mapping had been adjusted in some areas to reflect the interpretation of the radiometric image, a new Regolith Landform map was produced (Figure 5)

EVALUATING RADIOMETRIC IMAGERY FOR BASALTIC LAVA PLAINS MAPPING

The use of radiometric imagery for mapping young basaltic rocks has so far received little attention in Australia, although a series of studies carried out by Dickson & Scott (1991) on the Western Victorian Volcanic Plains to the south and southwest of the study area using older less-detailed radiometric imagery has been reported

In these studies imagery with a line spacing of 1500m was compared with the results of laboratory analyses of rock, regolith and soil samples from sites across the plains, with the Ollier & Joyce (1986) RTU map used as a sampling guide These results are also briefly described and more readily available in Dickson & Scott (1997)

In their studies, Dickson & Scott (1977) noted that basalt soil shows a loss of up to 50% of K compared with the parent basalt, and increases of four times in U and two times in Th They point out that in basalt flows which are intensively weathered the depletion of K and the concentration of U and Th can result in soils with radioelement signatures similar to those of weathered granite In an area with basalts of various ages, flows can be distinguished by the way their K and Th changes with weathering (Dickson & Scott 1997, p 190)

The analytical results of Dickson & Scott (1991, 1997) help to explain the observations of the relationships between the radiometric imagery and the field mapping seen in the Willaura-Skipton area A sequence of colours and textures can be seen on the radiometric image as flows have weathered from stony rises to undulating and then level plains, their soils have deepened, and scattered lakes and swamps have given way to integrated surface drainage patterns and incised valleys (Table 1)

Dickson & Scott (1997, p 191) also note that "U and Th are closely associated with the finest fractions of soils" and can be concentrated in clay and Fe-oxide accumulations formed by eluviation in subsoils In the Willaura-Skipton area pisolitic iron oxide develops in large amounts in the clay-rich subsoils of the flows from 1 Ma to 3 Ma (Dunkeld RLU) and is commonly visible over parts of the surface due to gilgai formation and resulting loss of topsoil from the gilgai crests This may explain the characteristic blue-green colours seen on radiometric imagery of the Dunkeld RLUs; with increasing flow and regolith age, the radiometric imagery shows an increase in green and yellow colours, possibly reflecting a relative decrease in the amount of U or a relative increase in the amount of Th present in the surface of the older Hamilton RLUs

Aeolian quartz additions to basaltic soils, increasing with the age of the soils, were noted in soil mapping by Jackson et al (1972) and Dickson & Scott (1997, p 191) also note that quartz is commonly found in soils over basalt in Western Victoria They suggest that pure quartz dilutes but does not affect the relative proportions of the radioelements The radiometric colour would not be expected to change much but may be darkened if much quartz is present e g on the older flows

The fine sand and silt size quartz grains deposited on the basalt plains were often accompanied by calcium carbonate, and radioelements sourced from beyond the basalts may also have been brought in over time The greatest affect should be seen on the oldest soils; this has still to be investigated

Other than weathering changes and addition of windblown material, a further factor which should be considered as possibly affecting the radiometric signature is the original composition of the lava (Alan White pers comm) Dickson & Scott (1991) have suggested the youngest Newer Volcanic lava flows are more alkaline and so may have an initially higher K content than the earlier more tholeiitic flows Although petrological and geochemical studies of the Newer Volcanic Province suggest little variation in composition over time, this may require further investigation

CONCLUSIONS

Regolith landform mapping of basaltic lava flows makes use of a combination of landform and drainage, soil colour and vegetation, and air photos and Landsat imagery as valuable supplements to field mapping However for mapping extensive areas of lava flows with ages greater than 1 Ma where original landform diversity has been replaced by almost uniform level plains, radiometric imagery provides a unique key by recognising variations in the amounts of K, U and Th in the surface soil which change in a regular fashion over time

MAKING USE OF THE NEW RLU MAP

The map developed from field work, air photos and Landsat imagery, and in particular radiometric imagery, provides information which can be used to interpret the landscape evolution of the area Correlation of RLUs with available K/Ar and radiocarbon dates will allow ages to be assigned to flows and eruption points, and estimates to be made of flow volumes and numbers of associated eruption centres through time (e g Joyce 1987) Without regolith mapping providing an indication of the age of regolith and flows, most of the weathered flows greater than 1 Ma, which make up much of the Plains, could not be mapped in detail and so such deductions could not be made In addition the movement of centres with time can be traced and the possibility of further activity considered. From such new information, the volcanic evolution of the Newer Volcanic Province of southeastern Australia will be able to be described in greater detail than is possible at present

FUTURE MAPPING

To complete this project, a program of further field mapping including the use of radiometric imagery is planned:

- Extending RLU mapping to the Creswick-Ballarat inland lava plains A Regolith Landform map of the Creswick area at 1:100 000 scale is available (Hough 1996) but the lava flows of the area have not yet been fully mapped Mapping these flows will complete the RLU mapping of the volcanic units for the proposed Ballarat 1:250 000 Regolith Landform map sheet

- Extending RLU mapping to the plains north and west of Melbourne. A number of available Honours mapping projects cover much of the plains, and will allow a similar study to the present one to be carried out, although radiometric cover is not available for the whole area

- Further mapping of the Plains area south of the present study area, using the available older radiometric imagery, and incorporating many past student mapping projects (e g Joyce & Sutalo 1996) will then complete a detailed RLU map of the Newer Volcanic Province of SE Australia.

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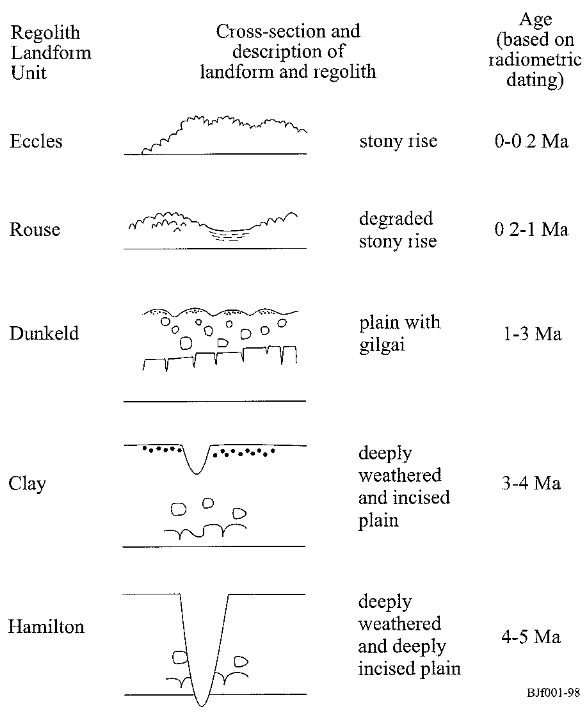

Figure 1: *Regolith Landform Units of the basalt plains of the Newer Volcanic Province of southeastern Australia (see Table 1) Each profile approximately 20 m vertically*.

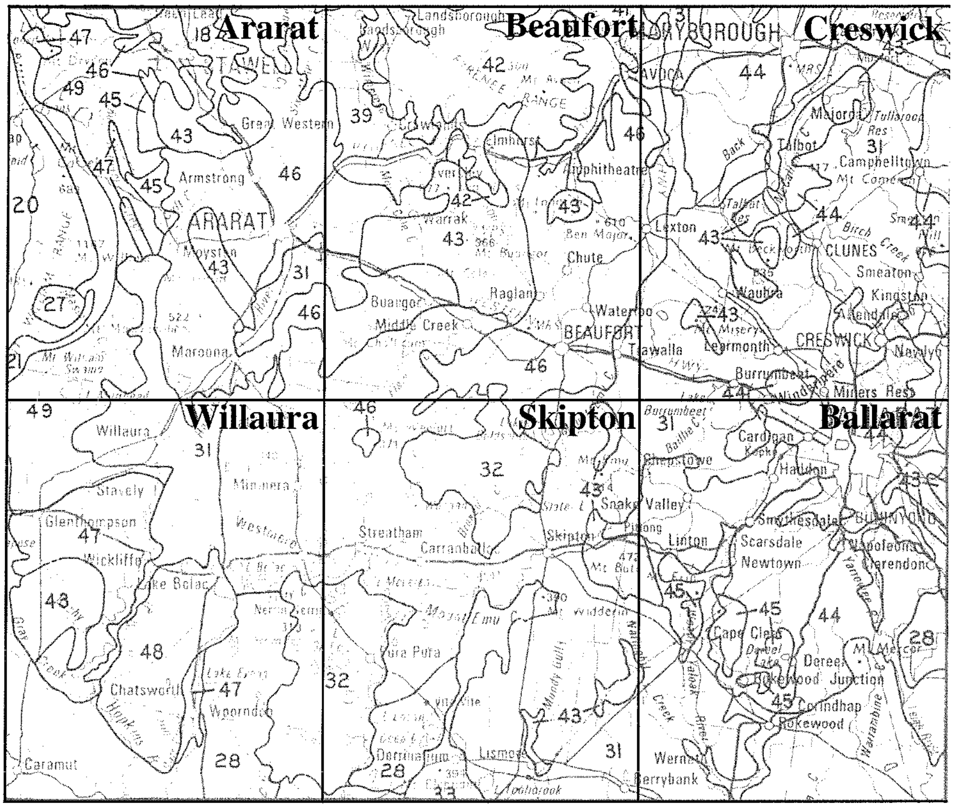

Figure 2: *Locality map showing the Willaura and Skipton 1 100 000 sheet areas within the Ballarat 1 250 000 sheet area, with Regolith Terrain Units of Ollier & Joyce (1986)*

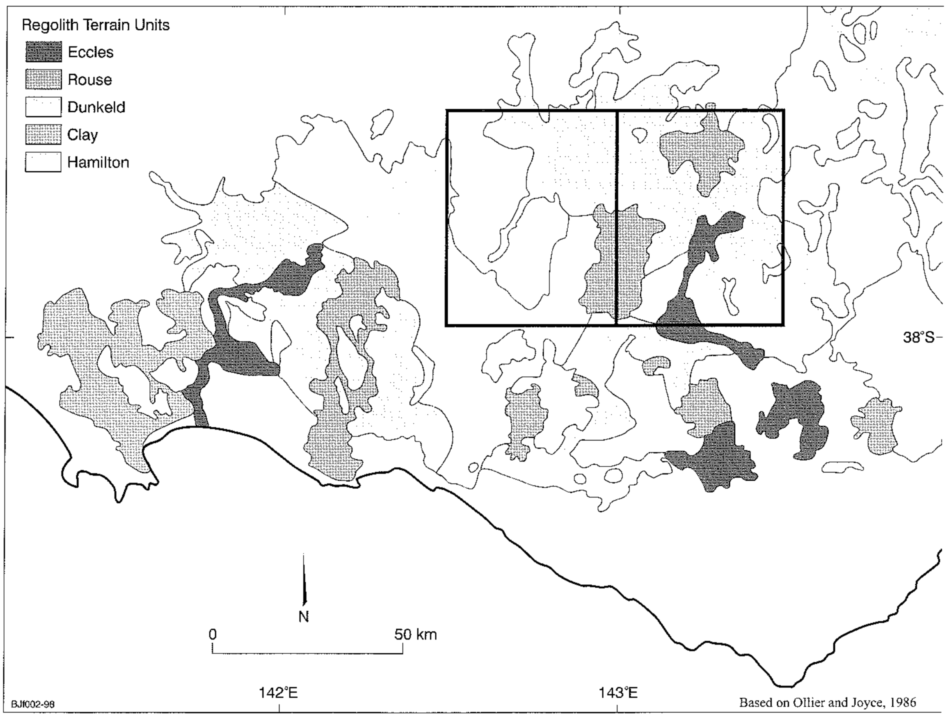

Figure 3: *Regolith Terrain Unit map of the basalt plains of Western Victoria based on Ollier & Joyce (1986), with the Willaura and Skipton 1 100 000 map sheet areas outlined (see Figure 1 for details of the RTUs shown)*

Table 1: *Keys to mapping Regolith Landform Units on the basaltic lava flows of the Western Victorian Volcanic Plains*

REGOLITH LANDFORM UNIT	LANDFORMS & DRAINAGE	SOILS & REGOLITH	LAND USE
Eccles	well-preserved stony rises of angular blocks, largely within earlier drainage lines, with closed depressions up to 10m deep, irregular lakes & swamps on flow & at edges, rare lateral streams	shallow reddish-brown to black friable stony loams with rough-ped fabric and rock outcrop on rolling rises	small dairy farming, mainly in depressions; parks & reserves, largely still treed, but with bracken
Rouse	degraded stony rises, largely within earlier drainage lines, with soil-filled depressions, larger smooth-shoreline swamps and some lakes on flow & at edges, lateral streams & minor drainage integration	shallow red friable loams with rough-ped fabric, up to 1m deep in places with rounded corestones of basalt on undulating rises, & black, heavy, cracking clays in depressions	grazing on largely-cleared grassed rises, drainage & cultivation of larger depressions
Dunkeld (later)	shallowly incised valleys on undulating ridge & depression plain, some lateral streams at edges, some integration of drainage; small irregular swamps & dry lakes	hard pedal red to black swelling clay mottled-yellow duplex soils 1 to 2m deep with some iron pisolites in subsoil & gilgai surface, with angular to rounded corestones at depth over weathered basalt, on gently undulating rises	woolgrowing, dry land grazing, improved pastures
Dunkeld (earlier)	moderately-incised valleys on undulating to flat plain, lateral streams at edges, integrated parallel drainage pattern; many small swamps & dry lakes, some with lunettes	hard pedal red to grey mottled-yellow duplex soils 1 to 2m deep with abundant iron pisolites in subsoil & gilgai surface, with rounded corestones at depth over weathered basalt on gently undulating plains	woolgrowing, dry land grazing, improved pastures
Clay (= later Hamilton)	large moderately to deeply-incised valleys, parallel drainage pattern, a few large lakes	hard grey to red pedal mottled-yellow duplex soils with ferruginous concretions over deep pallid profiles on gently undulating rises	woolgrowing, dry land grazing, improved pastures, tree planations; scattered remnants of red gum
Hamilton	large deeply-incised valleys, parallel drainage pattern, a few large lakes	hard grey to red pedal mottled-brown duplex soils and red smooth-ped earths over deep mottled & pallid profiles to 10m, on undulating low hills	woolgrowing, dry land grazing, improved pastures, tree planations; scattered remnants of red gum

ORIGINAL VEGETATION	BLACK & WHITE AIR PHOTOS	LANDSAT IMAGERY	RADIOMETRIC IMAGERY
all woodland of manna gum	black stippled texture (small scale), black & white sinuous ridge and depression pattern (large scale)	red colour (trees), uniform to stippled texture	flows bright red (high K); scoria cones bright red
savannah woodland of manna gum & blackwood on rises, wet-tussock grassland on swamps in depressions	grey stippled texture (small scale), grey sinuous ridge and depression pattern; stone fences, windmills & water troughs (large scale)	greyish-blue colour, broadly stippled texture	flows red-brown (medium K); scoria cones red
natural native grassland	grey stippled texture (small scale), black & white pattern of sinuous ridges & depressions; lakes & swamps, stone fences & many small dams (large scale)	uniform reddish colour, pattern of paddocks	flows dark blue-green (low K, high Th & U); irregular texture; some cones red to brown
natural native grassland	grey-white mottled texture (small scale), black & white pattern of paddocks; planted wind breaks and scattered lakes and swamps, some stone fences, many small dams (large scale)	uniform bluish tone, pattern of paddocks	flows blue-green (high Th)
dry sclerophyll forest, savannah woodland, grassland	stippled texture (scattered red gums), otherwise uniform grey tone with pattern of small paddocks	uniform pinkish tone, pattern of paddocks	flows yellow-green with orange stipple (high Th)
dry sclerophyll forest, savannah woodland, grassland	stippled texture (scattered red gums), otherwise uniform grey tone with pattern of small paddocks	uniform bright pinkish tone, pattern of paddocks	flows bright greenish-yellow with bright yellow and orange stipple (high Th)

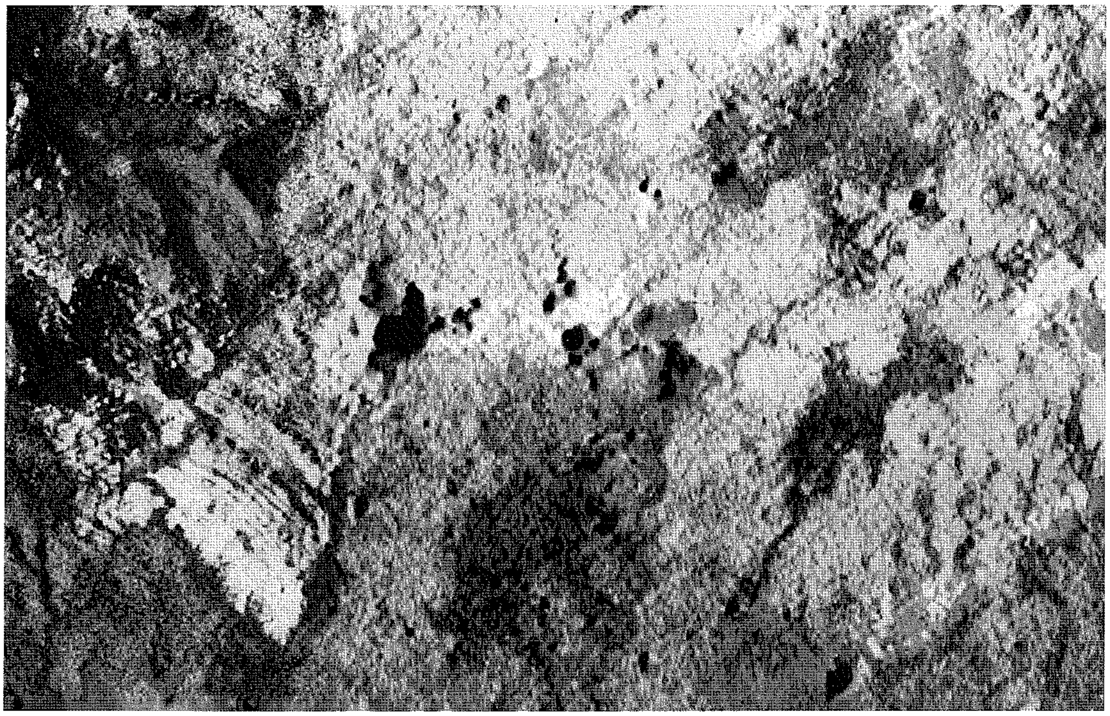

Figure 4: *Radiometric Ternary Ratio image covering the Willaura and Skipton 1:100 000 map sheet areas (by permission of the Australian Geological Survey Organisation and the Geological Survey of Victoria)*

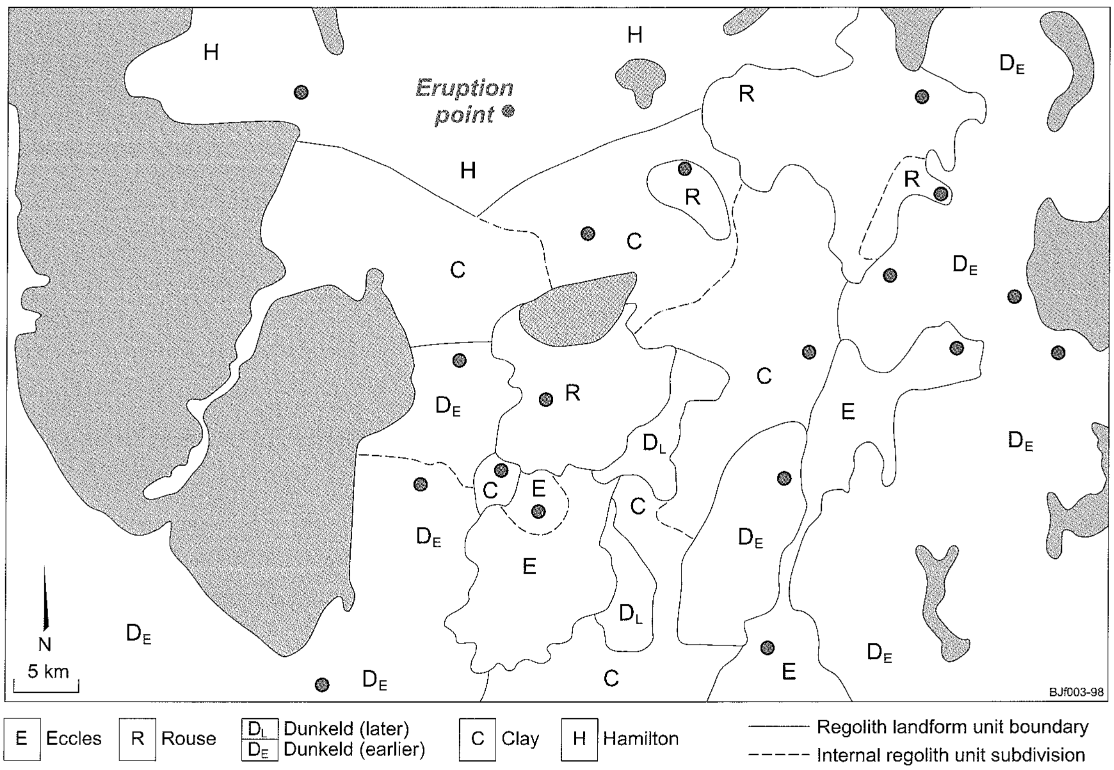

Figure 5: *Regolith Landform map of the Willaura and Skipton 1:100 000 map sheet areas (see Table 1 for details of RLUs shown)*