SOILS AND LANDFORMS IN A SEMI ARID LATERITIC TERRAIN IN SOUTH WEST AUSTRALIA (THE TUTTANNING RESERVE)

A Thesis Submitted

by

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ABSTRACT

Geomorphology formed the basis for the mapping of soils in the Tuttanning reserve. This lies astride a major drainage divide on the Great Plateau of Western Australia and is an area in which a laterite weathering mantle has been modified by erosion.

Structural control on drainage is demonstrated by the good relationship between the orientation of the main first and secondary order elements of the drainage systems and the lines of basic dykes. Duricrust dipping down towards the nearby valleys is evidence that the major elements of the present valley system were in existence prior to lateritization. Fresh rock exposures at different levels in the landscape illustrate the highly variable basal surface of weathering in the area, which is partly responsible for the complex soil pattern.

Twenty two soil mapping units have been recognized and these have been classed within the broad framework provided by the concept of the "old" and "new" plateaux. Lateritic duricrust, sandy gravels and deep sands dominate the units of the old plateau remnants, while a range of duplex yellow soils (podsolics or lateritic podsolics) occur extensively in the mapping units of the new plateau.

Rollability, a functional shape property of sand, was used together with granulometric analysis and quartz-feldspar ratio investigations to characterize the types of sand plains present at Tuttanning. The investigations revealed that yellow sands can be distinguished from gray sands and that both sands are possibly valley fills derived from local and probably contrasting sources.

The vegetation of the reserve occurs in formations which are, to a large extent, related to the relief and to the soils. The nature and character of these vegetation formations, together with the nature of the surface soil, give rise to patterns represented by different photo tones and textures. Water repellency of some of the surface soils has been related to some of the eucalypts and the characteristic is partly responsible for the deep ravines cut into the saprolite.

CHAPTER 1

INTRODUCTION

Purpose and Scope

The main aims of this study were as follows:-

(i) To describe, classify and map the soils of the Tuttanning fauna and flora reserve.

(ii) To consider proposals as to the reasons for the soil patterns.

(iii) To characterize and consider the origin of sand bodies which form a substantial part of the regolith.

(iv) To consider certain relationships between soils and vegetation.

Preliminary field inspections showed that this area is in a region in which a deep lateritic weathering mantle occurs extensively and further that this phenomenon has been modified by erosion. Detailed studies have been made of portions of this region by other authors such as Mulcahy and Hingston (1961) who showed that there was a close relationship between landforms and soils. Thus, in addition to describing and classifying the soils of the Tuttanning reserve, their relationship to the physical environment in particular landform and geology was considered. Several types of sand bodies locally known as sand plains occur in the area and as a basis for investigating their origin, particle shape and size studies were made along with some mineralogical and chemical analyses.

Preliminary field inspections also indicated sharp boundaries between some of the plant communities and these appear to be related to some of the most prominent photo-patterns. The relationship

between these patterns and the soils is considered rather than a detailed study of the vegetation of each pattern element. In addition, water repellency was seen to be a frequent feature of many of the surface soils and an investigation was undertaken to see if this relates to any particular flora.

As a background to these studies an extensive review of the literature on Western Australian laterites granulometric analyses of clastic sediments, particle shape studies and water repellency was carried out.

Site and Situation

The Tuttanning reserve is located some 45 kilometres north-east of Narrogin and about 20 kilometres south-east of Pingelly township in south-western Australia. It covers an area of about 30 km^2 and can be defined within the co-ordinates 32^{o} 31' - 32^{o} 36' south latitude and 117^{o} 16' - 117^{o} 23' east longitude (Fig. 1.1).

The Physical Environment

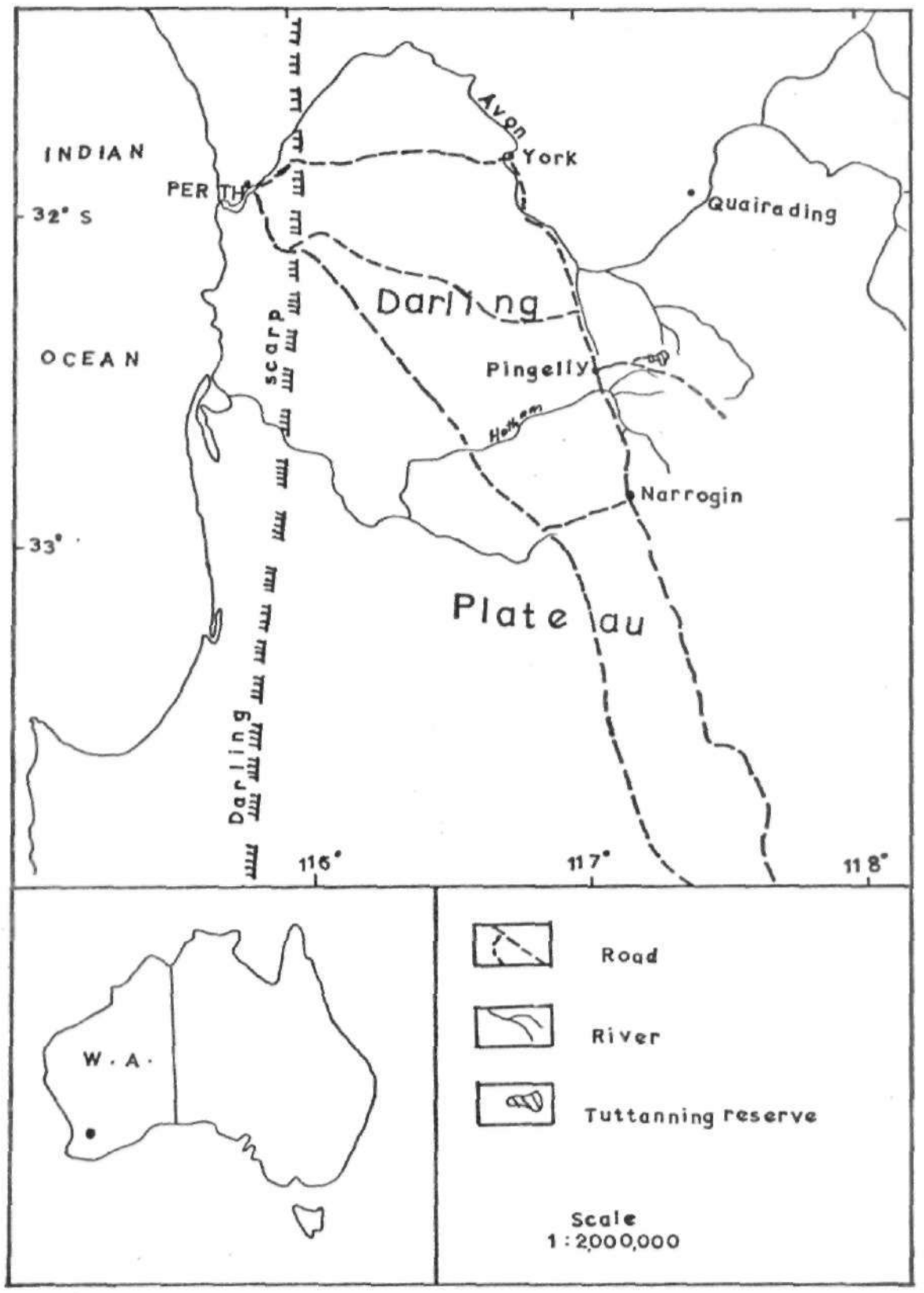
The general features of the geomorphology, geology, soils and vegetation are presented below as a background to subsequent discussion. More details of these are developed subsequently. Details of climate, however, are treated in this section.

Geomorphology

The Tuttanning reserve occurs on the Great Plateau of Western Australia, the major physiographic feature of the south-western part of the continent. It lies astride the divide between the Avon and the Hotham river drainage basins. The landscape is dominated by a number of laterite-capped residuals or mesas of varying sizes and shapes, generally separated from each other by steep breakaways

Fig1-1

LOCATION OF STUDY AREA



(scarps) and concave pediment slopes or by incipiently stripped zones. The crests of the residuals are at about 410-450 metres above sea level and about 30-35 metres above the main drainage features; these comprising first order streams, the upper elements of the Avon and the Hotham drainage systems. Outcrops of large masses of country rock are also an important feature.

The generally irregular shape of the residuals with the occasional flanking spurs and a number of ravines and large rock outcrops close to breakaways contribute to the fairly rugged nature of the area.

Geology

The study area lies in a region underlain by rocks of the western Precambrian shield of Australia (Jutson 1914). Outcrops indicate that the main country rocks are coarse-grained granites and gneisses intruded by quartz and by dolerite dykes. These latter features occur as elongate outcrops and show the major structural lineament as trending NW to SE and NE to SW; an orientation that the main drainage features have apparently followed (Wilson 1958).

Much of the detailed geology is buried by an extensive and apparently deep regolith, part of which is transported detritus and part comprises elements of a deep mantle of laterite weathering. The complete laterite profile may be exposed in the face of breakaways and comprise an indurated ferruginous zone which merges with depth to a more friable and clayey mottled zone, thence to a pallid zone in which the fabric of country rock is clearly evident, and finally through a transitional zone often of pinkish clays, to country rock. This array of horizons was described by Walther (1915) and Stephens (1946) as being typical for laterite profiles in

Southern Australia. The depth of this weathering mantle in the study area may be gauged from its exposure in the face of high (20-25 metres) breakaways. Variable depth to the weathering front is also suggested in such sites where fresh rock may be exposed in parts of the breakaway adjacent to sections with the weathering mantle apparently continuing with depth.

Soils

Regional mapping such as that of the Atlas of Australian Soils (Northcote *et al.* 1967) show this area as one dominated by soils with duplex profiles having yellow clay B horizons (i.e. the Dy subdivision of the Primary Profile Form). These soils have also been placed in the lateritic podzolic and yellow podzolic Great Soil Groups (Stephens 1963). These soils tend to occur on erosional and depositional surfaces below lateritic residuals, the latter often having yellow and gray sands, lateritic gravelly sands and duricrust as the main elements of the soil mantle.

Climate

The climate of the study area, along with much of south-western Australia, is classified as a Mediterranean (Csb) type according to the Koppen (1931) System. Gentilli (1947) classified it as dry summer humid mesothermal (BB's) using the 1931-33 classification scheme of Thornthwaite.

It is the consequence of the migration of the high and low pressure belts towards the poles in summer and towards the equator in winter such that it is the sub-tropical anticyclones that dominate much of south-western Australia in summer (Sayer 1969).

Rainfall data for Pingelly to the west and Landscape Hill which lies to the east of Tuttanning are used for the description. For temperature and wind, the nearest station with published data is Narrogin.

Tables 1.1 and 1.2 give the average monthly and annual rainfall totals and the highest daily rainfall per month respectively. Annual rainfall totals are small (around 430 mm or 17 inches) though enough to support grain crops. Rainfall is seasonal, falling mainly in winter (low rainfall intensity) while the summers are relatively dry. Some rain falls in summer however and it usually comes in heavy downpours (50-70 mm in a few hours) characteristic of thunderstorms (Gentilli 1956). Hence, the summer monthly rainfall totals (Table 1.2) are represented by only a few sporadic falls from depressions.

TABLE 1.1

AVERAGE RAINFALL IN MM (ANNUAL/MONTHLY)

Station	Number of years	M O N T H S												Total
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	
Pingelly	74	8.25*	11.75	17.25	26.25	26.25	60.00	85.75	64.25	40.75	26.25	13.22	12.00	454
Landscape Hill	52	12.75	8.00	24.00	18.50	24.00	60.25	76.50	57.00	34.50	24.00	11.25	9.75	420

TABLE 1.2

HIGHEST DAILY RAINFALL IN MM (24 HOURS ENDING 9 A.M.)

Station	Number of years	M O N T H S												YEAR Max/ day
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	
Pingelly	74	56.25*	85.50	66.25	36.25	85.50	66.25	53.25	55.00	40.00	61.00	28.75	55.00	85.5
Landscape Hill	52	60.00	66.25	66.75	40.50	72.50	55.00	48.00	45.00	30.00	35.00	28.75	59.75	72.5

Source: Climatic Survey, Region II - Great Southern Western Australia - Commonwealth Bureau of Meteorology - Melbourne 1976.

*Figures converted to mm from points, where 1 point • 0.01 inches.

TABLE 1.3

TEMPERATURE FIGURES (C^{O}) FOR NARROGIN (39 YEARS RECORD)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
1	31.1*	30.0	27.2	22.8	18.3	15.0	14.4	15.0	17.8	20.6	25.6	28.9
2	13.3	13.9	12.2	10.0	7.8	6.1	5.0	5.0	5.6	7.2	9.4	11.7
3	43.9	42.8	41.1	35.6	31.1	26.1	21.1	25.0	30.6	37.8	40.0	43.3
4	4.4	3.9	3.3	0.0	-1.1	-2.2	-2.8	-2.8	-2.8	-1.7	0.0	1.7

1 = Average Maximum
2 = Average Minimum
3 = Highest Record
4 = Lowest Record

Source: Climatic Survey, Region II - Great Southern Western Australia - Commonwealth Bureau of Meteorology - Melbourne 1976.

*Figures converted from degrees Fahrenheit to degrees Centigrade.

Hail falls are experienced every year and occasionally are severe enough to cause damage to crops. The greatest risk of damage comes with the occasional heavy thunderstorms of the summer months, when hailstones of large size are not infrequent. Although hail occurs also with the winter storms, it is usually of smaller size. It is least frequent in the autumn months.

Temperatures are cool to mild during the wet winter and warm to hot during the dry summer months (Table 1.3). Extreme high temperatures in excess of 38°C are possible during the five summer months (November-March). On the other hand, several degrees of frost may be experienced during winter cold spells, giving a fairly wide range of extreme temperatures. Snow, however, very rarely falls.

Wind direction is generally erratic. However, from November to April the most frequent wind direction is south-east due to the relatively southerly track of the anticyclones which affect the region in this part of the year (Bureau of Meteorology - Melbourne 1976). From May to October, the most frequent wind direction is north-west. Wind speeds of 22-27 knots are often recorded. There are more calms in the morning than in the afternoon.

Vegetation

The Tuttanning reserve lies within the sclerophyllous woodland zone of south-western Australia (Gardner 1944) and coincides with "the drier eastern side of the higher rainfall zone" of Prescott (1931) which is dominated by mallet, wandoo and York gum. It forms part of the "area around Narrogin" described by Lange (1960) as being transitional between the wet forested areas to the west and the dry semi-desert to desert areas to the east. Lange has related tree species to the framework of erosional and depositional surfaces proposed by Mulcahy and Hingston (1961) for the York-Quairading area of

Western Australia further north.

Sheoak (*Casuarina huegeliana*), mallet (*Eucalyptus astringens*), wandoo (*E. wandoo*) and powder bark wandoo (*E. accedens*) are by far the most dominant tree species. Other commonly-occurring tree species include York gum (*E. loxophleba*) and jam (*Acacia acuminata*). The trees attain an average height of 10-15 metres and carry a low shrubby or herbaceous undergrowth. There is a general paucity of grasses except those of a harsh, tussocky nature.

Dryandra sp., *Xanthorrhoea preissii*, *Isopogen divergens*, *Hakea* sp., tea tree, (*Melaleuca* sp.) and *Acacia pulchella* are amongst the commonly occurring lower storey plants of the upland residuals, while box poison legumes (*Oxylobium parviflorum*) and *X. preissii* occur very frequently in the valleys. Areas of heath exhibit a great variety of species.

The relationship between vegetation and soils has been treated elsewhere (Chapter IX).

CHAPTER II

LITERATURE REVIEW

The literature review covers the following topics which are also the main areas of investigation in this thesis.

1 Western Australian laterites and the effects of erosional modification on them.

2 Particle size and shape analyses on clastic sediments.

3 Water-repellent soils.

1 Western Australian Laterites

Terminology

Laterites

Prescott and Pendleton (1952) indicate that the Australian view of the term "laterite" is completely in line with that of the United States Soil Survey Staff as outlined by Kellogg (1949). Kellogg reported that the word laterite be confined to such ferruginous materials as harden on exposure and to the relics of such material, and should therefore include

(i) Soft mottled clays that change irreversibly to hard pans and crusts when exposed.

(ii) Cellular and mottled hard pans and crusts.

(iii) Concretions

(iv) Consolidated concretions.

In Southern Australia Stephens (1946) recognised laterite and its associated horizons as a complex parent material giving rise to an assemblage of soil types having characteristic mutual relationships. In other words, in Australia the word laterite is not brought

forward into the field of soil description but left with its original geological meaning, and as a parent material (Prescott and Pendleton 1952).

Lateritic Soils:

Lateritic soils are regarded as soils derived from material of the laterite profile. Such material include the ferruginous, mottled, pallid and transitional zones (Stephens 1946, 1953, Mulcahy 1960, Stace *et al.* 1968). Non-lateritic soils are those formed from fresh rock material. In lateritic landscapes, the fresh rock occurs below the laterite profile except where the latter has been removed.

Duricrust:

The term "duricrust" was first proposed by Woolnough (1927) to group together all representatives (ferruginous, aluminous, siliceous and calcareous) of "durable crusts" in Australia that were supposedly formed "in the same manner during the same geological period". The term has been used more recently for any exposed or truncated indurated surface that was formed on the surface or within a soil (Prescott 1931, Stephens 1946, Playford 1954). Duricrust is in part regarded as a pedologic residual (Finkl 1971), or paleosol. It is usually rich in iron which occurs mainly in the form of goethite but also as hematite and maghemite. Duricrusts very rich in aluminium are commonly termed bauxite or bauxitic duricrusts (Grubb 1966).

Lateritic duricrusts have also been variously referred to as massive ironstone pavements (Mulcahy 1959, Mulcahy and Hingston 1961) laterite sheets or ironstone sheets (Vine 1949), pisolitic hardcap zone (Grubb 1966), pisolitic or nodular ironstone (Frankel and Baylis 1966), cavernous iron enriched crusts (Prider 1966). In this

thesis, the word duricrust refers solely to lateritic duricrusts.

Breakaways:

The term "breakaway" is commonly used locally to refer to lateritic scarps (Jutson 1914, Prescott 1931, Whitehouse 1940) that often mark the edges of mesas and buttes - the upland residuals (Mulcahy 1959) and form boundaries between the ancient laterites of the old plateau surface (Jutson 1930) and the pediments below them.

The physical environment in which the Western Australian laterites occur:

Climate:

In Australia laterite occurs under widely different conditions of climate (Woolnough 1918) from tropical in the north, through Mediterranean to the extreme south. In southern Western Australia Prescott (1931), Prider (1966), Mulcahy (1967, 1973) report on laterites in the more than 25 inch rainfall belt, 15-25 inch belt and less than 15 inch belt and indicate that the characteristics of the laterites, particularly in the depth of the pallid zone and the extent of preservation of the duricrust, appear to vary with the rainfall amount.

Teakle and Samuel (1930) and Prescott (1931) call attention to the acid nature of the lateritic soils of the sand plains region which is almost arid and suggest this as evidence for the fossil character of these laterites. Also, Mulcahy (1973) reports that the "older laterites" except in the highest rainfall areas now contain appreciable quantities of soluble salts in their pallid zones and suggests that this indicates that the necessary leaching conditions for their development are no longer operative".

Relief:

Prider (1966) reports that the distribution of laterite in Western Australia coincides essentially with the surface of the Great Plateau described by Jutson (1914) and that there are some smaller areas in front of the Darling Scarp of the so-called "low-level laterites" of Fermor (1911), Simpson (1912), Campbell (1917) and Woolnough (1918); that the Great Plateau dominates Western Australia as a physiographic feature apart from the narrow coastal plain. This feature has been dissected extensively though to varying degrees. Hills (1961) described it as an "ageless and undatable old land". It slopes down gently west and south-west, rises again marginally in the Darling Range and ends 220 metres above sea level at the Darling Scarp (Gentilli and Fairbridge 1951).

Woolnough (1927) observed the almost accordant summit levels of the duricrust capped residuals (mesas, buttes) of the Great Plateau and concluded that "the laterite capping serves as a stratigraphic horizon of no mean value". He suggested that laterite was produced under peneplain conditions when the land surface stood at a very slight elevation above sea-level and that laterite owes its present position on the summit of the plateau to the uplift of this peneplain. Jutson (1914) and Davis (1920) had earlier referred to this peneplain concept of laterite formation. Stephens (1946) also accepted it. However, later workers such as Playford (1954), Mulcahy (1965, 1970, 1973), Churchward (1970), Churchward and Bettenay (1973), Finkl (1971) were not in full agreement with the view that peneplain conditions are necessary for laterite formation and contended that the residuals of the Great Plateau "cannot be uncritically accepted as any kind of time marker or datum".

Playford (1954) drawing evidence from Geraldton district reported that some laterite crusts slope towards the present drainage lines at angles as high as 10^{o} and with a continuous variation in elevation of as much as 220 metres. He considered this as evidence of laterite formation following uplift dissection. Such was also the interpretation of similar features of laterite in the Darling Range (east of Perth) by Prider (1966).

Other workers reported that laterite profiles are to be found extensively in a wide range of topographic situations ranging from the Swan coastal plain (McArthur and Bettenay 1960) and alluvial terraces in well incised valleys such as the Avon River (Mulcahy and Hingston 1961) to the most extensive divides of the Great Plateau. Even on the extensive divides of the Great Plateau, Mulcahy (1960) has referred to laterite on two topographic levels and named by him the Quailing and the Kauring surfaces.

Geology:

In Western Australia laterite is developed on all types of rocks (Prescott 1931, Carroll 1944, Prider 1966). Granitic and gneissic rocks of the Precambrian shield are however the commonest parent materials (Wilson 1958). Laterite has been reported over sedimentary rocks of Jurassic and Carboniferous age (Prescott 1931), over Cretaceous marine sediments (Carroll 1944, Churchward 1970), over basic rocks (Carroll 1944, Terrill 1950, Finkl 1971), over impure limestone (Playford 1954) over quartzite with 95% quartz, sandstones, conglomerates and alluvial deposits (Prider 1966).

Terrill (1950) noted that the characteristics of the laterite such as the thickness of the crust, texture and colour of the underlying weathered material tend to differ with the type of parent material.

The origin of laterites

The various views regarding the origin of the Australian laterites may be summarized as follows:

1 By the leaching away of non-lateritic products of weathering and the concentrated accumulation of lateritic materials (Fermor 1911, Campbell 1917, Terrill 1948).

2 By chemical precipitation at the surface of soluble material leached out of the subjacent rocks during weathering (Simpson 1912).

3 An illuvial horizon accumulating in the zone of seasonally fluctuating water table (Stephens 1946, Playford 1954) or accumulating as a result of both downward and upward movement of Fe (Whitehouse 1940).

4 Laterite could have different origins such as an illuvial horizon, a residual product of rock weathering, a product of lateral seepage of waters containing Fe in solution, could have lacustrine or bog origin (Woolnough 1918, Prescott and Pendleton 1952).

5 Some of the laterites are detrital (secondary) derived from the recementation of lateritic materials (Fermor 1911, Hosking and Burvill 1938, Mulcahy 1967, Grubb 1971).

The age of laterites in Western Australia

The absence of sediments with diagnostic fossils overlying the laterites is perhaps the greatest obstacle in the way of determining the age of lateritization (Prider 1966). As a result, opinions on the topic are highly varied.

Woolnough (1927) believed that laterites developed on the Darling peneplain in Miocene times prior to the epeirogenic uplift

responsible for the formation of the Great Plateau. Similar conclusions were reached by Browne (1950) and Grubb (1971).

McWhae *et al.* (1958) suggested that the main duricrust development is not older than Upper Eocene. Teichert (1947) indicated the age of laterite formation at Pliocene and so did Sprigg (1946), Prider (1966) and Finkl (1971).

The view that there has been more than one period of lateritization is shared by Whitehouse (1940), Owen (1945), King (1950), Prescott and Pendleton (1952) and Mulcahy (1959).

McArthur and Bettenay (1960) and Lowry (1965) have respectively indicated that laterites younger than Tertiary and possibly not older than Pleistocene are present on the Swan coastal plain and low plateau. Mulcahy (1973) accepting their interpretation has gone further to suggest that the process of lateritization "may still be continuing" on the Swan coastal plain.

Soil Survey investigations

Stephens (1946) has laid down a basic framework for understanding the development and distribution of soils on dissected laterites. He noted that varying degrees of truncation of a laterite profile can leave as a surface exposure either part of the A horizon, part or all of the duricrust, part or all of the B and C kaolinitic clay horizons (mottled and pallid zones) or finally it can expose the underlying rock or other parent material. All exposures can give rise to new soils, many of them strikingly different in morphology from the original profile but nevertheless related genetically to it and the parent material from which it was derived. Light textured generally sandy material from the A horizons, laterite gravel of various sizes, clay from the B and C horizons and broken rock from the parent

material may singly or together comprise the transported material that is frequently deposited in various depths on exposed horizons lying down-slope.

Mulcahy (1959, 1960), Mulcahy and Hingston (1961) building on the observations of Stephens (1946) have proposed that the pattern of distribution of the soils of the dissected laterites of Western Australia (e.g. near York township) may be correlated with a number of erosional and depositional surfaces of possibly varying ages. They believe that, though the soils are not necessarily of the same age as the land surfaces on which they occur, there is a close relationship between soil properties and the age of the surfaces.

Table 2.1 gives a summary of soils of York-Quairading area and how they relate to the land surfaces proposed by Mulcahy and Hingston (1961).

Bettenay and Hingston (1964) studying soils and land surfaces in an arid environment and Finkl (1971) working in the high rainfall area of the Blackwood River catchment produced reports similar to those of Mulcahy and Hingston (1961) that there is a close relationship between soils, landforms and geomorphic surfaces. Finkl (1971) also indicated that, though the general soil patterns may be anticipated by a consideration of relief-layer relationship, further refinement in the understanding of the soil patterns is largely facilitated by the recognition of rock types.

Northcote *et al.* (1967), mapping on a broad regional scale, recognized a patchwork pattern of soils related to certain broad features of topography on the Great Plateau. The valley sides were reported as dominated by soils with duplex primary profile forms (Dy) and ridge crests by undifferentiated sands and gravels (Uc and KS-Uc).

TABLE 2.1

SOILS IN RELATION TO LAND SURFACES AT KAURING (MULCAHY AND HINGSTON 1961)

	Surface	Soil	Zone of laterite profile present
Old plateau and local deposits derived from it.	Quailing	Yellowish brown sands over ironstone gravel at shallow depth.	Ferruginous zone exposed by truncation, pallid zone, transitional zone.
	Kauring	Grey sands over massive pale-coloured ironstone at relatively shallow depth.	Untruncated. Grey sand A horizon, ferruginous, pallid and transitional zones.
	Quailing (depositional)	Deep yellowish brown sands.	Sandy deposits derived from ferruginous zones upslope. Mayburry pallid or transitional zones or non-lateritic surfaces. Depth varies but may be considerable e.g. 60 or 80 feet.
	Monkopen	Grey sand with ironstone gravel, and some clay at relatively shallow depth, passing below to deep yellow sand with occasional ironstone bands.	
Valleys	Belmunging	Greyish brown gravelly sand over reddish brown and yellow brown mottled clays at 8-12 in.	Ferruginous and transitional zones.
	Balkuling	Pinkish or occasionally greyish clays with a variable surface wash of greyish brown sand.	Transitional or occasionally pallid zone exposed by truncation.
	Malebelling	Light brown gritty loamy sand over yellow brown and reddish brown sandy clay loam with abundant rock fragments. Fresh rock at shallow depth.	Some ironstone at base of A horizon, otherwise none.
	York	Brown sandy loam to loam over reddish brown clay. Fresh rock at shallow depth.	None

The undifferentiated sands and gravels are very extensive eastward of the Darling Scarp but are replaced inland by duplex yellow soils, these being acid in the first place, but becoming progressively neutral to alkaline with distance from the coast.

The origin of the Western Australian sand plains

Sand plains were first described by Prescott (1931) as being composed of clearly defined groups of soils ranging from deep yellow sands to heavy ferruginous gravels with acid reactions. As indicated in the Atlas of Australian Soils (Northcote *et al.* 1960-1968) yellow earths with acid reaction trends (Gn 2.21) and yellow sands with earthy fabrics (UC 5.22) together form the sand plains and are the dominant soils of some 43,000 km^2 in the south-west agricultural region. Brewer and Bettenay (1973) suggest that probably as large an area again lies to the east of the agricultural area.

Prescott (1931, 1944) suggested a relationship between these soils and laterite, a fossil soil formed during a previous - Tertiary - cycle. In many areas, the original eluvial horizons were thought to have been long removed by denudational processes, and the characteristic capping (duricrust) to be in effect a fossil B horizon. However, in the case of the extensive sand plain belt it was thought probable that surface denudation had been at the minimum and that with minor redistribution, the whole fossil soil is preserved. Carroll (1939) after carrying out heavy mineral and grain shape studies on the sand plains of the Yilgarn Goldfield concurred with the findings of Prescott. She pointed out that there are a few localities in which there has been recent wind drifting of sand. Teakle (1938) referred to sand plains as "broken and rounded residuals" of the old plateau.

After a detailed appraisal of the properties and distribution patterns of sand plains in the York-Quairading area, Mulcahy (1960, 1964) and Mulcahy and Hingston (1961) concluded that here, sand plains are deposits derived by transport of materials weathered from lateritic ferruginous zones. Repeated weathering and transport was postulated as a mechanism by which the resistant quartz sands were retained within the landscape, while the less resistant primary and secondary minerals were progressively destroyed. They regard the "deposits" as multiple and the youngest though also derived from pre-weathered materials, may be quite recent.

Bettenay and Hingston (1961, 1964) working further east near Merredin suggested in like manner that duricrust is formed by truncation of the laterite profile down to the mottled zone, which is indurated by dehydration and cementation and that subsequent disintegration gives rise to rather skeletal in-situ soils consisting of ferruginous concretions and fine earth. However, the sandy material so derived is moved for limited distances downslope under the combined influence of gravity, wind and water to form colluvial deposits often more than 4.5 metres thick.

Prider (1966) disagreed with the above conclusions and reiterated the belief that the sand plains constitute the upper part of the laterite profile "and for the most part have formed in situ". He cites the presence of abundant kaolinite spherulites of fine sand size in the yellow sand at Boorabbin which he considers to be soft and brittle and to indicate that there has been little or no movement of this particular sand. He also observed at Jimperding, W.A., about 16 kilometres west of Toodyay, a band of andalusite schist several hundred feet wide that passes beneath the laterite and which is covered with a sandy soil. He traced the andalusite schist band

through the sand plain over the laterite by the residual andalusite in the soil, till he came to a breakaway in the laterite which contained crystals of andalusite and which was underlain by kaolinized andalusite sillimanite-muscovite schist. Prider contended that this indicated that the laterite (or ferruginous duricrust) of the sand plains area was not necessarily an indurated material - at least not until it has been desiccated on exposure to the atmosphere for a short time. Hence duricrust is found exposed around the margins of the sand plain areas or where the sand has been stripped.

Churchward (1970) considered that the soils at Dandaragan, W.A., were "related to a number of colluvial sheets resulting from erosion". Sedimentary structures such as interbedded gravels were reported for these sandy materials and regarded as supporting the views of Mulcahy (1964) on the origin of the Western Australian sand plains.

A typical earthy sand from near Merredin was described by Stace *et al.* (1968). According to them the micromorphology of the profile suggested that it developed on a transported sedimentary parent material and that the source of the sediment was a pre-existing soil. Brewer and Bettenay (1973) could not support Prider's (1966) contention that soft kaolinite spherulites would not survive transport. They re-examined the morphology and micromorphology of the earthy sand profile near Merredin in great detail and concluded that this profile had formed in a colluvial sedimentary deposit derived from physically weathered material similar to the underlying indurated lateritic material. They recorded a maximum of 14% clay in all the horizons of the profile and concluded that the earthy sand could not have been formed by "repeated cycles of weathering and transport" and that sandplains are not necessarily very low in total clay as suggested by Mulcahy (1964).

Glassford and Killigrew (1976), Killigrew and Glassford (1976) have proposed that the yellow sands (sand plains) in much of south Western Australia are aeolian in origin, i.e. they originated from the drier country to the east and were transported to their present sites during arid phases by the process of saltation.

Economic importance of laterite in Western Australia

The land surface associated with the laterite of Western Australia is of great economic importance (Prider 1966). Associated with this surface are important aluminium, manganese, iron ore, and nickel deposits. Some of the old drainage lines are important for the location of minerals such as alluvial tin and lead (Campbell 1906, Hobson and Metheson 1949, Mulcahy 1973) since they drain catchments now deeply weathered. However, the lateritized surface generally is regarded as a hindrance (Prider 1966, Mulcahy 1973) to prospecting for ore deposits throughout the great part of the Precambrian shield.

The soils are regarded as being of very low natural fertility (Carroll 1944, Turton *et al.* 1962, Prescott and Pendleton 1952); an absolute infertility which until more clearly understood, did not respond to chemical fertilizer treatments. However, with the identification of nutrient deficiencies (Carroll 1944) which limit crop and pasture establishment on the lateritic soils and with the growth of a fertilizer technology, the soils are now used extensively for wheat growing and pasture development (Mulcahy 1973).

2 Particle size analysis

For many years geologists have measured the grain sizes of clastic sediments and much has been written concerning the interpretation of grain size distribution curves. Some of the prominent authors include Udden (1898, 1914); Wentworth (1927, 1929, 1936); Krumbein (1934, 1936, 1938); Doeglas (1946, 1950); Bagnold (1941, 1960); Inman (1952); Pettijohn (1957); Folk (1957, 1958, 1966); Friedman (1958, 1961); Rogers (1959, 1963).

Methods of grain-size investigation range from the complex statistical computation of moments (Friedman 1961; Wentworth 1929, 1936) to the more simple graphic approach (Inman 1952, Folk and Ward 1957, Spencer 1963). Parameters usually used in grain size analysis include the mode, mean-size, standard deviation, skewness and kurtosis. These parameters were defined by Sahu (1964) as follows:

Mean-size indicates the central tendency or the average size of the sediment. In terms of available energy, it indicates the average kinetic energy (velocity) of the depositing agent. However, the average size of a sediment is dependent also upon the size distribution of the available source material.

Standard deviation measures the sorting of a sediment and indicates the fluctuations in the kinetic energy (velocity) conditions of the depositing agent about its average velocity.

Skewness measures the asymetry of the frequency distributions and marks the position of the mean with respect to the median. If the skewness is negative, the sample is coarsely skewed, i.e. the mean is towards the coarser side of the median. For a normal distribution, the skewness is zero.

Kurtosis is a ratio of sorting within the 90% of the distribution to the sorting of the central 50%. For normal distributions, the kurtosis is unity.

Mode applies to the highest point reached on a size frequency diagram (Harris 1957).

The most widely used formulae for graphic determination of these grain-size parameters (e.g. Roger 1959; Manson and Folk 1958; Shepard and Young 1961; Spencer 1963; Folk 1966; Van Rooyen and duBurger 1974) appear to be those of Folk and Ward (1957) which are modifications from Inman (1952). Sahu (1964) believed that the modified statistics of Folk and Ward (1957) are mutually independent and can be applied to normal as well as non-normal distributions.

Formulae by Folk and Ward (1957)

Mean-size:

$$M_Z = \frac{\phi 16 + \phi 50 + \phi 84}{3}$$

Standard deviation (sorting):

$$\sigma_I = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

Skewness:

$$SK_I = \frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)}$$

Kurtosis:

$$K_G = \frac{\phi 95 - \phi 5}{2.44(\phi 75 - \phi 25)}$$

For plotting kurtosis values, the transformation formula

$K_G 1 = \frac{K_G}{K_G + 1}$ is usually used.

Plotting of the cumulative curves is usually done on arithmetic or log-probability paper using the phi (ϕ) scale (Krumbein 1934), where $\phi = -\log_2$ of the diameter in mm (Inman 1952; Folk and Ward 1957; Folk 1966; Manson and Folk 1958; Rogers 1959; Sahu 1964). According to Hazen 1914 (reported in Inman 1952) the cumulative curve when plotted on arithmetic probability paper results in a straight line for a normal distribution and thus facilitates curve fitting and visual interpretation of the data. Such a plot expands the tails of the distribution and makes interpolation between data points much more accurate (Folk and Ward 1957).

Manson and Folk (1958) applied student's t test (Brownless 1948) to mean-size, standard deviation, skewness and kurtosis values of beach, dune and aeolian flat sands to bring out any significant differences between them. They also plotted the particle-size parameters one against the other as scatter diagrams in order to find out whether the three environments could be segregated. Van Rooyan and duBurger (1974) who studied the sands of the north-west Orange Free State (South Africa) obtained a decrease in mean-size and improved sorting with increasing distance downwind. They interpreted that the decrease in mean-size was caused by selective lagging behind of coarse grains owing to differences in fall velocity between coarse and fine grains (Bagnold 1960).

Manson and Folk (1958) and Friedman (1961) reported that frequency distribution curves for sand deposits indicated that dune and river sands are positively skewed with a tail in the fines while beach sands tend to be negatively skewed and coarse tailed. According to Bagnold (1941) similarity of maximum and minimum grain sizes may be expected to occur in aeolian sands.

Asamoa and Protz (1972), van Rooyen and duBurger (1974) and Price *et al.* (1975) performed particle-size analysis on a clay-free basis. The rationale of this method of expressing particle-size was that it should minimise the effect of clay movement due to pedogenesis.

Particle-shape studies

Several approaches exist to the study of the shapes of sand grains. Some of these include the use of pivotability charts (Shepard and Young 1961), the wind tunnel (Richard Mattox 1955), the mechanical grain formimeter (Krygowsky 1964), the automated grain-shape classifier (Glessen and Ludwick 1963), the swinging gutter (Kuenen 1963) and rollability (Winkelmolen 1969).

Price *et al.* (1975) indicated that rollability is the most up-to-date method for the study of particle shapes of sands.

Rollability was devised by Winkelmolen (1969) after his experiences with Kuenen's (1963) "swinging gutter". Rollability is the measure of ease with which grains can be transported over a smooth surface by rotational movements. It is measured on the inside of a slightly inclined revolving cylinder mantle. During the rolling, shape segregation takes place, the more rounded and spherical grains travelling faster than the more angular and platey ones. Rollability is measured per sieve fraction and is expressed as the time it takes for the median weight to emerge from the cylinder. This time is found by measuring the distance between the midpoint of the cumulative weighing curve and the time marker of the starting point. For convenience the graphic distances are taken as a measure for the rollability instead of the time. The repeatability is 1% plus or minus. Since the measurement is completely automated, personal bias is excluded.

For plotting absolute rollability values are always transformed to relative rollability values. The relative rollability values are plotted into shape distribution character (SDC) diagrams. Fig. 2.1 shows the diagnostic SDC diagrams of Winkelmolen (1969a).

According to Winkelmolen (1969a, 1971, 1974) shape selection phenomena are best understood in connection with Kuenen's deposit-repository concept which he described as follows: when a population is split by a transport mechanism into two (or more) different populations, these populations have complementary characteristics as regards size shape and density. Such a twin relationship comes out very clearly in the SDC's of the deposit and its repository.

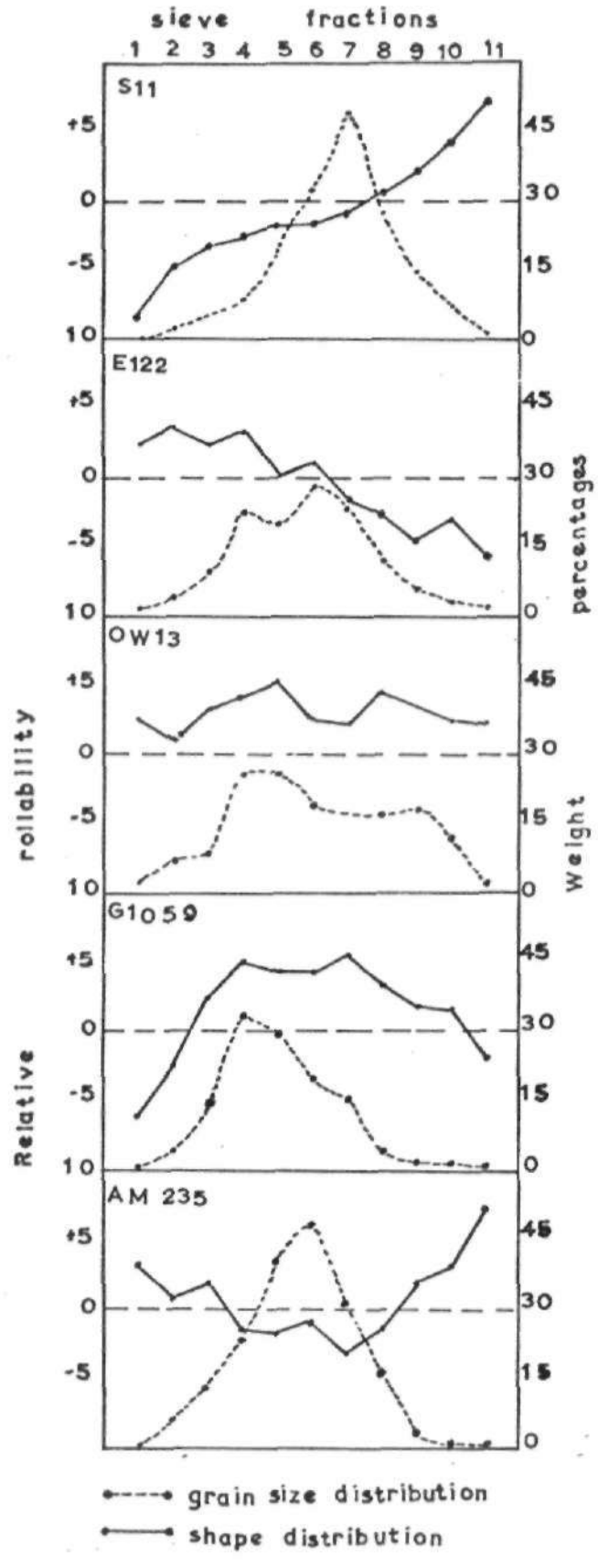
Winkelmolen (1974) warned that particle-size or shape alone cannot produce indisputable facts about a depositional environment and should therefore never be used in isolation, hence the rollability procedure intimately involved particle-size analysis. Shepard and Young (1961) carried out environmental studies in which particle size, particle shape, heavy mineral studies and carbonate concentration were given equal emphasis.

3 Water repellent soils

The tendency of some soils (particularly sandy soils) to repel rather than absorb water has probably been noticed for a long time (e.g. Schreiner and Shorey 1910; Greig-Smith 1911; Prescott and Piper 1932; Jamison 1942). However, widespread interest and research in the phenomenon has been recent, covering only the last two decades (Bond 1969). Water repellent soil appears to have a world wide occurrence since it has been reported under different climates (rainfall and temperature) and vegetation in Alaska, Australia, New Zealand, United States, England, Scotland, France, Spain, Israel, Nigeria and

Fig. 2.1

DIAGNOSTIC SDC CURVES OF A. WINKELMOLEN (1969a)



R = Rising curve
Receiving material (accretion)

D = Down sloping curve
Losing material (Lag)

H = Horizontal curve

B = Bridge-like curve
Receiving material at more than single energy conditions

V = Valley-shaped curve
Losing material at more than single energy conditions

various parts of Africa (DeBano 1969; Jamison 1969; Roberts and Carbon 1971).

Much of the literature on water-repellent soils is contained in the "Proceedings of the Symposium on water-repellent soils" held at the University of California, Riverside (DeBano and Letey ed. 1969). At the end of this symposium it was concluded that:

1 A wettable soil is one which shows no visual characteristics of repelling water.

2 Water-repellent soils may be distinguished by degree, e.g. slightly, moderately, highly, extremely.

3 A non-wettable soil should be the opposite extreme to a wettable soil and the term could be used particularly if, for all practical purposes, the soil is impossible to wet with water.

4 It would not be appropriate to call a soil hydrophobic or hydrophilic. However, these terms might be very useful in describing materials that are responsible for the qualities of the soil, i.e. a hydrophobic chemical could be added to the soil to make the latter water repellent.

Water repellence in soil can easily be demonstrated (Pelishek *et al.* 1962; Bond and Harris 1964; Adams *et al.* 1969; DeBano 1969) by placing a water droplet on the surface of the soil sample. In contrast to the normal soil, the water droplet will not be absorbed into the water-repellent soil but instead will tend to "ball-up" and remain on the soil surface for a variable length of time. Bond and Harris (1964) used the water drop penetration time (WDPT) of more than 5 seconds as a standard for classifying soils as being water repellent. They also indicated that, when small aggregates of sand were added to the surface of water, samples exhibiting severe water

repellence floated while sands that were non-repellent sank immediately. Adams *et al.* (1969) regarded soils with WDPT of less than 10 seconds as non-repellent, with WDPT of 10-60 seconds as slightly repellent and with WDPT greater than 60 seconds as strongly repellent. Other methods of characterizing water repellency are measuring the liquid-solid contact angles (Letey *et al.* 1962) and the diffusivity (Jamieson 1946).

Most workers have agreed that a coating of organic matter on the surface of the soil particles imparts the water-repellent characteristics (Smith 1949; Bond 1960, 1964; Savage 1969; Holzhey 1969; Roberts and Carbon 1972) but the composition of the active components of the organic matter have not yet been identified. Bond (1964, 1969) believed that such organic coatings on sand grains were produced by fungi growing in the soil. Similar interpretations were reached by Krammes and Osborn (1969) and Savage (1969).

Differences were found in the wettability of the soil beneath different plant cover (Bond 1964; Jamison 1946; DeBano 1969; Van't Wondt 1959). Bond (1964) maintained that in Australia, the most severe water repellency was found in very sandy soils maintained in pasture. Several workers have reported that water-repellency can be induced in soils by burning of the vegetation and in such situations the repellency may not be restricted to any particular vegetation species (Countryman 1964; DeBano and Krammes 1966; Savage *et al.* 1969; Rice and Osborn 1970; Debyle and Packer 1970; DeBano and Rice 1973).

According to Hotzhey (1969) water repellency is primarily a phenomenon of the surface soil horizons and decreases with depth together with the organic matter content below the litter zone. Such

were also the conclusions of Scholl (1971). Holzhey (1969) also noted that wettable A horizons beneath the repellent layers are characteristically slightly hard.

Bond (1969) reported on the seasonal variation in water-repellency at 36 sites in South Australia in a Mediterranean-type climatic region. He noted that at all sites the soil became markedly more repellent after the first heavy falls of rain; the water repellency persisted throughout the winter period with some decrease in intensity, but the largest decrease occurred in the late spring and summer.

CHAPTER III

METHODOLOGY

SOIL SURVEY PROCEDURE

The survey was carried out in six stages.

Stage I (First indoor preparation)

Before field work started, time was spent in the office studying maps, aerial photographs and reading the relevant literature in order to construct a mental picture of the main features of topography, the drainage pattern, the vegetation, the climate, the types of soils to be expected and the main motorable tracks in the area to be studied.

Black and white aerial photographs were used in this preliminary study. The boundaries of prominent upland residuals (often marked by breakaways) showed up clearly under the stereoscope and were drawn on the photographs. These mapped upland residuals were useful locational aids, together with other features on the aerial photographs, during the first visit to the field.

Stage II
Field Reconnaissance and Preparation of a Skeleton Legend

After the first indoor preparation a field reconnaissance study lasting seven days was undertaken. The aims of this were (1) to study the tracks and become familiar with the area (fortunately the Tuttanning reserve has an intricate network of motorable tracks), (2), to determine what the main photo patterns (on both black and white and coloured prints) represented on the ground in terms of relief, vegetation and soils and (3), to determine approximately the range of soils present. This was done by driving along the tracks and making

inspections of the soils with the Jarret auger. Changes in relief, vegetation, soil colour, texture, structure and consistency were observed.

No mapping was carried out but notes were taken on the different kinds of soils encountered, and a few profiles sampled with the Jarret auger. On return to the office a skeleton legend based on the field notes, the relevant literature and laboratory analyses on the auger-hole samples was prepared. This skeleton legend was to aid the interpretation of the aerial photo-patterns and in the preparation of a base-map.

Stage III

Interpretation of aerial photographs

"When a field observer has learnt what a certain set of features represent in the field, he knows what to look for and recognise on aerial photographs" (Clarke and Beckett, 1971). Hence, after the field reconnaissance study of the Tuttanning reserve, a fairly detailed interpretation of the aerial photographs was made using the Condor T-22 stereoscope. This stereoscope allows for two different magnifications (1.5^{x} and 3^{x}) of the images. Also it has two scanning stereoscopes arranged in such a way that two persons can view a stereoscopic pair of aerial photographs simultaneously and mutually discuss features seen thereon.

The coloured photographs were used since these showed up the patterns much more clearly (i.e. relief, tone, texture and colour), than the black and white photographs with smaller scale. With the coloured photographs, features such as massive rock outcrops, upland residuals, spurs and ridges, basic dyke lines, deep gray sands, low-land heaths, quartz gravelly flats, saline patches, faint drainage

lines or floors could readily be picked out.

Soil boundaries were tentatively drawn on the aerial photographs and the soil units indicated as spelt out by the skeleton legend. At the end of this stage it was apparent that large areas on the aerial photographs could not be mapped with any degree of certainty in the office. The definition of soil units and delineation of boundaries for such areas was reserved for a later stage of fieldwork.

Stage IV

Preparation of a base map

The base map was prepared from the stick-down photo-mosaic of the reserve prepared by the Western Australian Fauna and Flora Department, Pingelly district. Transparent paper was placed over the photo-mosaic and the two held together with transparent Sellotape. Base data included the outline of the Tuttanning reserve as marked out by the surrounding paddocks and their characteristic fence lines, the main road traversing the reserve, all the tracks, the major drainage lines and the camping site (the hut). The preparation of photo-mosaics has been treated to some detail by Clarke and Beckett (1971).

The photo-mosaic was prepared at the same scale (1:16,000) as the coloured photographs used in the soil survey, thereby allowing for a direct transfer of information on the photographs onto the base map. Soil boundaries delineated in the office were therefore traced on the base map and labelled accordingly.

Stage V

Establishing Ground-truth (field soil survey)

Field mapping lasted a period of 4½ months and required a certain amount of hard manual labour, endurance and determination. The level of detail that was to be mapped was in part influenced by the time available, the scale of the base map (1:16,000) and whether the units could be mapped accurately and consistently.

During this stage the soil units delineated by the indoor aerial photo interpretation were confirmed. Further, soil units that were not evident in the earlier stage of photo interpretation were recognised and mapped. Other aspects of this stage of the work involved the digging of soil pits for detailed examination, description, photographing of representative profiles and sampling for laboratory analysis.

Items used in the field included:

1 A Land-Rover

2 Mirror Reflective Stereoscope

3 Jarret auger with an extension

4 A long and narrow spade

5 A broad spade

6 A pick-axe

7 Geological hammer

8 Hand lens

9 Steel tape

10 Coloured aerial photographs

11 Topographic map (2-metre contour interval)

12 Base map

13 Pocket notebook

14 Munsell soil colour chart

15 A pH kit

16 A wash bottle

17 Soil register

18 Writing materials

19 Sampling bags and rubber bands

20 Knife

21 Camera

The first units to be investigated were those of the upland residuals. The investigation aimed at establishing whether the residuals comprised entirely of duricrust or whether other materials were present as well.

The investigation of units other than the upland residuals involved establishing whether these units comprised one kind of soil or not, whether the soil of the unit was the same as the one expected (mapped in the office) and whether the boundaries needed any alterations. The units were checked off the nearest track. Investigations were made at several carefully selected points using the Jarret auger or a long narrow spade and notes were taken where necessary. New types of profile encountered were described in detail and the units left unclassified. Changes in the soil profile were found to occur in any one of the following circumstances:

1 Change in the nature of the lithologic material.

2 Change in topography or slope.

3 Change in the native vegetation.

4 Change in the colour of the surface soil or material brought out from ant holes.

5 Difference in the sound produced or feel to the feet when walking or stamping.

6 Nature of the subsoil exposed by fallen trees or giant bushes like *Xanthorrhoea preissii*.

Stereoscopic examination of the photographs in the field was made by placing the stereoscope on the engine bonnet of the Land-Rover. It proceeded side by side with the field investigations so that results of the latter could be drawn on the photographs (using omnichrome coloured pencils) while still in the field.

Portions of the study area in which soil boundaries were not related to clear physiographic changes proved the most difficult to map since they were the least amenable to stereoscopic study. Here, the work involved a lot of semi-controlled traversing and auger-hole investigation. It was carried out in sections derived from the network of tracks, drainage lines or floors and occasionally dyke lines. For field location, use was constantly made of key points or positions such as the corner of a nearby fence line, a track intersection or a prominent bend, nearby massive rock outcrop, prominent bend in the line of breakaway, and relationship to an already mapped unit.

The soil units identified were mapped on the aerial photographs. Units that fell within those of the skeleton legend were labelled accordingly while others were left unclassified. The classification of these units was left to the end of the survey after the profiles were studied in detail and the legend drawn up.

On return to the office after each period of fieldwork, soil boundaries were rechecked using the Condor T-22 stereoscope and slight boundary alterations made where necessary.

Collection of samples

Sample collection took place throughout the course of the survey. For detailed soil profile descriptions, samples were taken mainly from the face of pits though auger-holes provided additional material. Other soil samples were mainly surface (10-15 cm depth) and used for specific experimental purposes. Duricrust samples from breakaways and rock samples for identification were also obtained.

Soil pits

Pits were dug at sites representative of a number of soil units. The pits ranged from 80 to 120 cm deep. The face of the pit was oriented to allow maximum lighting and to facilitate description and photography. Twelve samples were taken from every soil pit using the Specifications of the Soils Division of the C.S.I.R.O., Australia (i.e., 0-5 cm, 5-10 cm, 10-15 cm, 15-20 cm, 20-30 cm, 30-40 cm ..... 90-100 cm). The samples were placed in polythene bags, secured with rubber bands, labelled and brought back to the laboratory for analyses.

The profile description was recorded on a field soil description sheet with observations listed under the headings of site details and profile details thus:

Site details	Profile details
Profile number	Horizon depth and clarity
Locality	Colour
Series type	Texture
Elevation, relief and aspect	Stoniness, size and amount
Drainage of site and profile	Structure
Parent material	Consistency
Natural vegetation	Organic matter

Profile details (continued)

Roots

Moisture conditions

Fauna

Concretions of pedological origin

Presence of carbonates

pH

Stage VI

Preparation of soil map and legend

The notes on representative profiles of the unclassified soil units were carefully studied and new soil groupings created. An additional brief field trip was found necessary to check mapping and classification. Finally a legend was prepared. Each unit was designated by a letter and a diagnostic description of soil conditions in each was made. The soil legend was arranged physiographically, the soil units being classified according to the landforms with which they are associated. The basis for this classification of the soil units has been treated elsewhere in this thesis.

The map was then drawn with the legend, date, direction of north and scale (both representative fraction and linear).

Geomorphological surveys

Geomorphological investigations proceeded alongisde with the soil survey since geomorphology formed a prime basis for the soil mapping. There was however no attempt at producing a geomorphic map showing the distribution of surfaces (e.g. Mulcahy 1959; Bettenay and Hingston 1964; Finkl 1971). Structural features were searched for because other workers (Woolnough 1919; Jutson 1912, 1914; Ivano 1946; Parry and Smith 1952; Finkl 1971) had previously commented on the

structural control of drainage patterns and landforms in south-western Australia. The main structural features investigated were photo lineaments. The general 'lie of the land' was carefully studied from aerial photographs under stereoscope.

Experimental Procedures

(A) Rollability

This is a method of measuring a property of sand grains dependent on grain shape, already reviewed in Chapter II. The procedure followed is strictly in line with that of Winkelmolen (1969a).

Preparation of samples

One hundred surface (10-15 cm depth) samples taken from different sand bodies of the study area (yellow sands, gray sands, stream channel sands, rock apron sands). 50 grams of each sample were obtained and treated with Calgon and NaOH to disperse any aggregated clay that might be present, though the samples generally contained little clay. The sand fraction was extracted by decantation. Sands that still contained organic matter after decantation were treated with H_2O_2. Heavy minerals were removed by the heavy liquid (bromoform) separation method, leaving only the lighter grains (<2.9 specific gravity) for the measurement of rollability. The samples were generally deficient in carbonate and yellow coatings on the grains were minimal and did not seem to affect the rollability measurements (see Table 3.1 in appendix), therefore no HCl treatment was made.

The sands were sieved with ¼ phi sieves. Eleven sieve fractions ranging from 600μ to 90μ were extracted from each sample, since fractions falling above or below this range are not suitable for rollability measurement. Each sieve fraction had a specific sample weight

for rollability measurement in order to allow a fairly uniform number of grains for the measurements. Table 3.2 gives the weight of sample used per sieve fraction.

TABLE 3.2

Weights of Sample used for Rollability Measurements

Size Range	Weight
500 - 600μ	200 mg
420 - 500μ	200 mg
355 - 420μ	150 mg
300 - 355μ	100 mg
250 - 300μ	100 mg
212 - 250μ	100 mg
180 - 212μ	70 mg
150 - 180μ	50 mg
125 - 150μ	50 mg
106 - 125μ	30 mg
90 - 106μ	30 mg

The Rollability Apparatus

The essential part of the rollability apparatus is a cylinder mantle that rotates around its axis. To prevent the development of static electricity on quartz sand and also the skidding of the grains, the inside of the cylinder was painted with a water-based emulsion paint in which 20% graphite powder was mixed. The paint was put on with a very soft good brush in four layers.

The cylinder diameter was 60 cm, length was 1 metre, axial inclination $2\frac{1}{2}^{o}$ to horizontal. The cylinder rotated once every 7 seconds. The grains that emerged from the end of the cylinder were collected via a funnel into a small cup that was placed on an electro-balance.

The registration of the weight was cumulative and was obtained using a potentiometric recorder which was provided with a time marker. The chart speed was maintained at 250 mm/min. The rollability apparatus is shown in Photos 3.1(a) and 3.1(b).

Interpretation of Rollability Values

A rollability curve together with its reading (absolute rollability value) is shown in Figure 3.1. Absolute rollability figures are hardly ever used for environmental interpretation. The figures were converted into relative rollability values before plotting. To produce relative rollability figures, an inventory of the spectrum of shapes present in the depositional area was prepared. The inventory was made separately for each sieve fraction (Fig. 6.3 in appendix). The arithmetic mean of the rollability values was calculated for each sieve fraction. These mean values differed from sieve fraction to sieve fraction but were all represented on the zero line for relative rollability plottings. The relative rollability values were expressed as percentage (positive or negative) deviation from these means. The unfortunate phenomenon that a poorer rollability is expressed by a higher numerical value in the absolute rollability values was removed by changing positive relative rollability values to negative and negative to positive.

The new relative rollability values were plotted into simple graphs (shape distribution character (SDC) graphs) to show shape sorting. The obtained shape distribution character curves were compared with those of Winkelmolen (1969a) for interpretation. Kuenen's (1963) deposit-repository concept was used to indicate shape selection (see literature review). Composite rollability diagrams derived from using the mean values of every three adjoining samples were used to establish shape sorting trends in the presumed direction of transport.

PHOTO 3.1(a)

THE ROLLABILITY APPARATUS

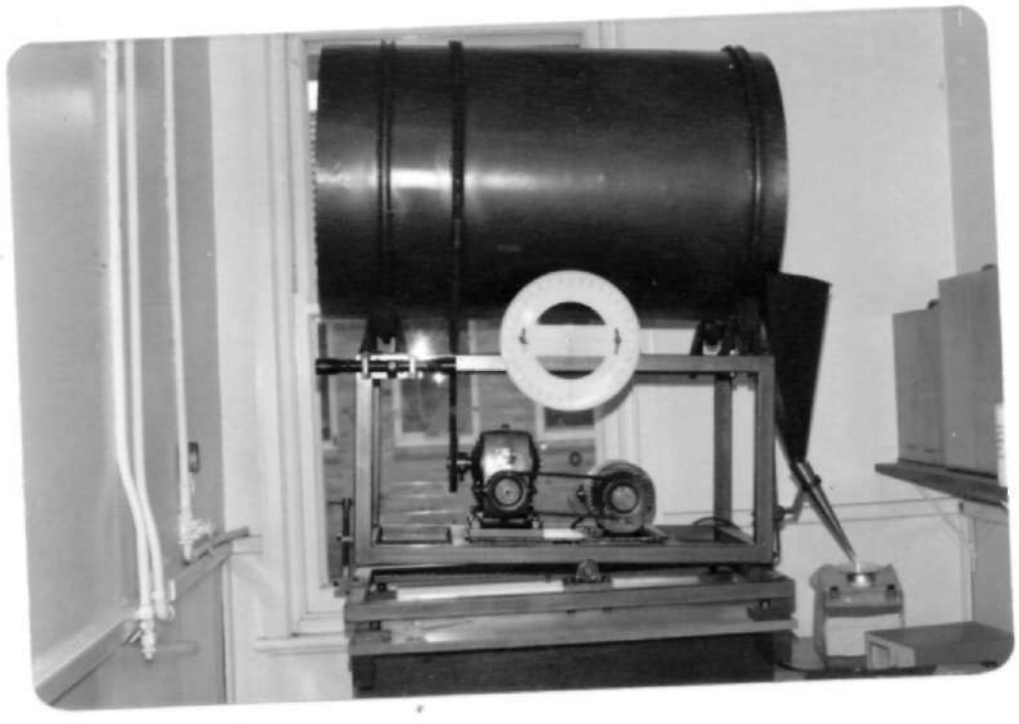


PHOTO 3.1(b)

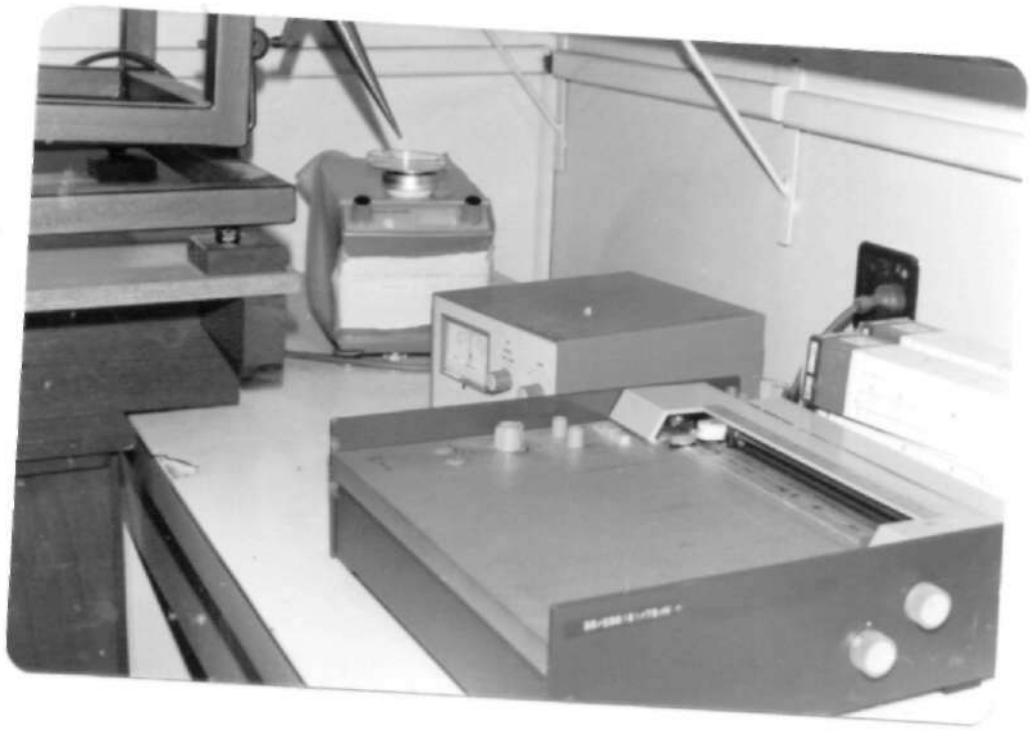
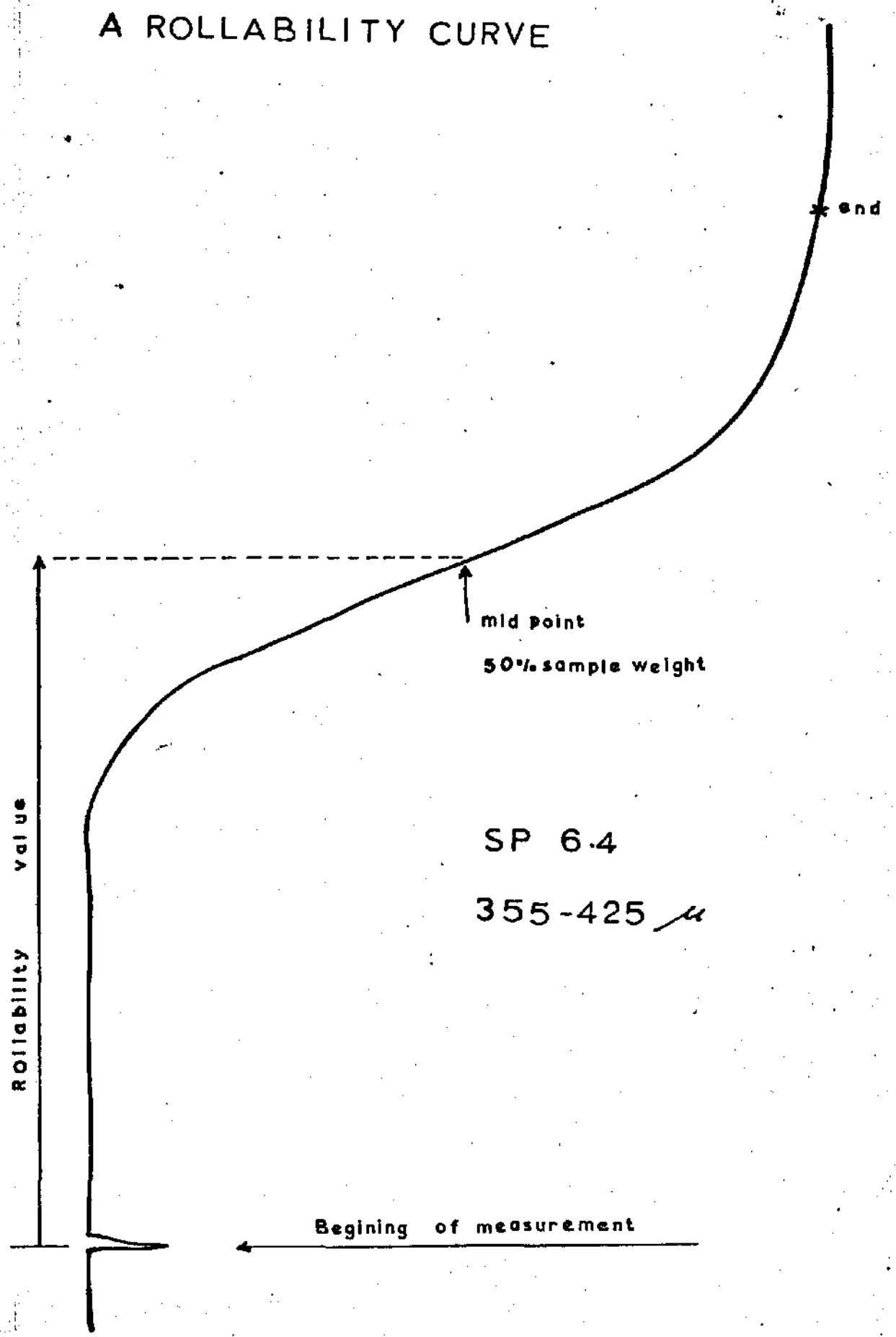


Fig. 3.1

A ROLLABILITY CURVE



SP 6.4

355-425 μ

Scatter plots were used to distinguish yellow sands from gray sands, and compared with sands of known provenance (rock apron sands).

(B) Particle-size (Granulometric) Analysis

Forty eight samples (20 yellow sands, 18 gray sands, 10 rock apron sands) taken at 10-15 cm depth were used for the analysis which was performed on a clay-free basis to avoid differences caused by clay eluviation (Brewer 1968; Asamoa and Protz 1972; Price *et al.* 1975). The air dry sample was disaggregated by hand and passed through a 2mm sieve and the <2mm fraction obtained. The sample was thoroughly mixed and 60 grams extracted. The 60 gram extract was dispersed by adding 10 ml of IN NaOH and 20 ml of 10% Calgon in a milk shake mixer cup with about 350 ml of water and stirring with a milk-shake machine for 15 minutes. The solution was then transferred into a 1-litre cylinder and allowed to stand for 24 hours after which the >45μ fraction was extracted by repeated decantation of the <45μ fraction.

The sample was next dried at 105°C. Fifty grams were weighed out and sieved through a set of ½ ϕ sieves for 30 minutes and the sieve fractions weighed to 0.01 grams. Fractions smaller than 1 gm were weighed to 0.001 gm. Sample weight for sieving was maintained at 50 gm because samples much larger than this may give incorrect results because the sieves may become choked by sediment thus preventing some grains of smaller size than the sieve openings from passing through. On the other hand, samples that are too small neither provide sufficient material on individual sieves for accurate measurement, nor are they representative of the whole sediment as is a larger sample (Rogers 1959). Data from sieve analyses with less than 99.9% recovery was ignored and considered not usable.

Results were plotted as cumulative curves on probability paper using the phi (ϕ) scale (Krumbein 1934; Otto 1939; Inman 1952; Manson and Folk 1958; Rogers 1959; Folk 1964[6]). The use of probability percentage ordinate makes normal curves plot out as straight lines and is much superior to the arithmetic percentage ordinate for interpolation.

Statistical parameters used in describing the grain-size properties of the sands are those proposed by Folk and Ward (1957). These include mean grain size (M_2), standard deviation or sorting (σ_I), skewness (SK_I) and kurtosis (KG_I). They were chosen because of their general acceptance by other workers (e.g. Spencer 1963; van Rooyen and Du Burger 1974; etc.) and because they apply to both unimodal and bimodal distributions.

Trend diagrams showing standard deviation (sorting) and mean size against distance were plotted following the procedure of van Rooyen and Du Burger (1974). Scatter plots similar to those of Folk and Ward (1957), Manson and Folk (1958) and Friedman (1961) were made in order to differentiate yellow sands from gray.

(C) Mechanical Analysis

The samples analysed were mainly for soil profile descriptions and water repellency investigations. Twenty five grams of air dry sample were used. Some of the samples were treated with H_2O_2 to remove organic matter. The international pipette method was followed and involved the dispersion of the sample in a dilute solution of NaOH and Calgon with the aid of a milk-shake mixer. Deionized water was used in preference to tap water in producing the solution. The soil particles were allowed to sediment in a 1000 ml sedimentation cylinder before 20 ml samples for the <45μ, <20μ and <2μ fractions

were taken at a depth of 10 cm at prescribed times (Brown 1961, p.42). These samples were dried at 105°C, weighed and the % by weight of each fraction calculated.

(D) Semi-Quantitative Determination of Feldspar Content

Thirty samples (10 yellow sands, 10 gray sands, 10 rock apron sands) were analysed for feldspar content. The feldspar to quartz ratio for the light fraction was estimated using the X-ray diffraction method on a Philips diffractometer combined with a chart recorder. Cobalt Kα radiation was used. The investigation was limited only to the 90-106μ size fraction - the fraction that contained the highest levels of feldspar (Fitzpatrick 1971, p.83; Carrol 1945).

Heavy minerals were removed using the heavy liquid (bromoform) separation method to eliminate the possible effects of minerals like topaz, kyanite and enstatite on the peak intensity of feldspar at 3.2Å which was selected for the analysis. The extraction of heavy minerals also meant that apart from a few grains of kaolinized feldspar only quartz and feldspar were left in the sample. For quartz, the reflection by spacing of 2.28Å was considered a suitable choice.

The light grains were finely ground using ethanol as a lubricant in an agate mill, dried at 50°C and mounted in an aluminium holder as random powders for the analysis (Klug and Alexander 1954, p.300). Samples were run from 30° to 33° and 45° to 48° 2θ at 2° per minute with 2×10^2 rate meter setting, time constant 4 and 1° slits. Feldspar peaks which were off scale were rerun at higher (4×10^2) rate meter setting. Peak heights occurring at the selected spacings were measured and the ratio of feldspar to quartz calculated.

Percentage feldspar in the light fraction of the 90-106μ separate was found by reference to a standard curve produced by plotting ratios of peak heights obtained from standard quartz-feldspar mixtures.

(E) Clay Minerals

Clay minerals were identified by XRD using oriented clay films on porous ceramic plates. Diffraction patterns were obtained after magnesium and glycerol saturation of clays following the procedure described by Brown (1961).

(F) Chemical Composition

A number of trace elements were determined using the X-ray fluorescence spectrometer by Mr. M. Hart at the C.S.I.R.O. laboratories at Floreat Park, Western Australia. A powder was obtained by dry grinding approximately 8 grams of sample in an agate mill at 760 rpm for 5 minutes. Preparation of the pressed powder discs involved the high-pressure compression of the sample powder into a boric acid base as outlined by Norrish and Chappel (1967). Concentration of the elements except Ca, K, S, P, TiO_2, Na_2O (shown as % whole sample) is given as ppm of the element.

(G) Organic Matter Determination

The amount of organic matter present in surface soils was determined on samples collected for soil wettability experiments. The titration method of Walkley Black (1934) was employed. This method is described in detail in Jackson (1958) and in Black ed. (1965).

(H) Soil Wettability

Samples were air-dried and gently disaggregated to pass a 2 mm sieve. Soil wettability was determined by an infiltration method based on the time required for a drop of water to disappear from the soil surface - the 'water drop penetration time' method (Bond and Harris 1964). This was done by applying at the surface a 0.04 ml drop of deionized water from a burette and with a stop watch recording the time required for the drop to completely disappear. A clock was used for samples with very high resistance to wetting. Duplicate samples were used and disappearance time was determined for five drops on each sample and the mean value calculated.

Samples that showed non-wetting characteristics were placed in ceramic pressure-plates maintained at $^{1}/_{3}$ and 15 bar pressure under nitrogen, and as the samples slowly took up moisture, water drop penetration time measurements were made at regular intervals (Scholl 1971). The % moisture content of the soil was determined in order to relate moisture content of the soils to the degree of water repellence.

In the field, wettability of the soils under different vegetation species was investigated. Water from a wash bottle was applied to loosened soil very close to the plant and watched. A rough classification of the plant species into those whose organic residue promote non-wetting and those that do not was made.

CHAPTER IV

GEOMORPHOLOGY

Jutson (1934) has proposed a conceptual framework for the genesis of landforms on the Great Plateau of Western Australia upon which Tuttanning reserve is sited. Within this concept, Jutson pictured an ancient plateau of very little local relief which was once covered by a lateritic mantle of weathering. This ancient surface, which he referred to as the "old plateau", was modified by erosion with a consequent evolution of a lower surface, the "new plateau" (see Photo 4.1). Details of the geomorphology of the Tuttanning reserve indicate that this concept has some important limitations. However it is useful for presenting a general picture in the first place.

The surface of the old plateau

In the Tuttanning area ideal examples of the old plateau are the upland residuals which are tabular features (capped by duricrust) and flanked by scarps (or breakaways). The elevation of these crests range from 390 to 395 metres above sea level towards the western end of the reserve to an average of 450 metres to the east, a phenomenon which may possibly be related to some past regional tilting. In detail, however, the surfaces of the mesas often dip towards the local drainage lines, a phenomenon which has been recorded by Playford (1954) for the Geraldton district north of Tuttanning. The slope is usually pronounced (5-10^{o}) where the mesas occur close to the drainage lines. One such strongly dipping residual occurs in the paddock south of Gnow track. Near the crest of the divide, the slopes of the residuals are much less than 5^{o}.

PHOTO 4.1



The general landscape scene at Tuttanning. The uncleared portion is dominated by elements of the old plateau; the cleared portion (the valley) comprising the new plateau.

The "old plateau" surface often has broad shallow depressions which may terminate at breakaways. However these depressions, usually occupied by gray or yellow sands, often extend from the upland almost to the main drainage axes. A good example of one of these features occurs on the upland north of the reserve hut, where it is traversed by the Echidna and Tammer tracks. It is about 100 metres wide and slopes gently (2-3^{o}) towards one of the drainage channels of the Hotham. In other examples, the sand bodies of the upland concavities extend to the lowland along depressions which gradually become deeper and are flanked by ever increasingly prominent lateritic scarps. Eventually, the sand sheet blends with the mid and lower valley slopes as an unconfined feature. Such phenomena appear to have the essential morphology of *spillways* described by Mulcahy and Hingston (1961). The duricrust surface often dips towards the breakaways flanking these features suggesting that they are relics of the ancient surface somewhat incised by an early phase of erosion and now partially filled with yellow sands. Possum track is in one such depression and parallels another such depression to the south. Both of these features form lineaments having the ENE orientation of major elements of regional geological structure.

The surface of the new plateau

According to Jutson (1934) the new plateau comprises erosion relief developed by the variable stripping of the deep laterite mantle of weathering from the old plateau. Depositional surfaces associated with these are however also included. Features such as breakaways, pediments and terrain associated with rock exposures are ideally parts of this surface and are treated in detail below. However it will also be seen that there are some features (spurs and low ridges) which although being closely associated with the more

classical features of the new plateau surfaces have features of relief and soils somewhat intermediate between these major surfaces.

The breakaways

The lateritic cliffs (breakaways) that often separate the old plateau surface from the "new plateau" vary from about 3 metres to 25 metres with an average of about 15 metres. Where they surround extensive mesas, they form a sinuous outline with deep indentations as well as tongue-like projections. A most dramatic elongate shape is displayed by the residual near the western corner of Gnow track (south). This residual is about 80-100 metres wide where it is traversed by Gnow track and the breakaways on either side are low (about 3-5 metres). The residual runs northward and then northeastwards gradually becoming narrower and gaining elevation until at its end (about 400 metres distance) the two breakaways on either side join at an angle of about 20^{o} with an elevation of 15 metres.

Where the ancient plateau surface is reduced to only a few square metres (e.g. 8-20 square metres) the surrounding breakaways form conical hills.

It appears, the laterite cap (duricrust) and the underlying saprolite in combination have had a pronounced influence on the shapes of the landforms i.e., the breakaways and the fairly flat surfaces above them (Jutson 1934). Massive duricrust greatly protects the underlying saprolite from erosion, but as the duricrust is removed, the saprolite is quickly stripped. The result is that steep cliffs are formed. There are however exceptions to this generalization as will be illustrated below.

Figure 4.1 illustrates the nature of the breakaway where (a) the duricrust cap is present and (b) where the duricrust cap is absent. It shows that where the duricrust is present, the breakaway comprises three slope elements made up of a free face at the top (usually less than 90^{o}), a middle steep rectilinear or constant slope (Penck 1924), and a lower concave slope that marks the upper limit of the pediment. Where the duricrust is removed without the accompanying removal of the underlying material, the breakaway loses its steepness, there is no free face and a convexo-concave slope results. The reasons why stripping of the deeply weathered materials in certain places does not immediately follow the destruction of the duricrust have not been investigated and are not a major concern in this thesis except to say that such materials are usually gravelly and porous near the surface and often contain laterite boulders. Breakaway morphology has been used together with the degree of stripping (Chapter VIII) in explaining the distribution of gravelly and earthy pediments in Chapter VIII.

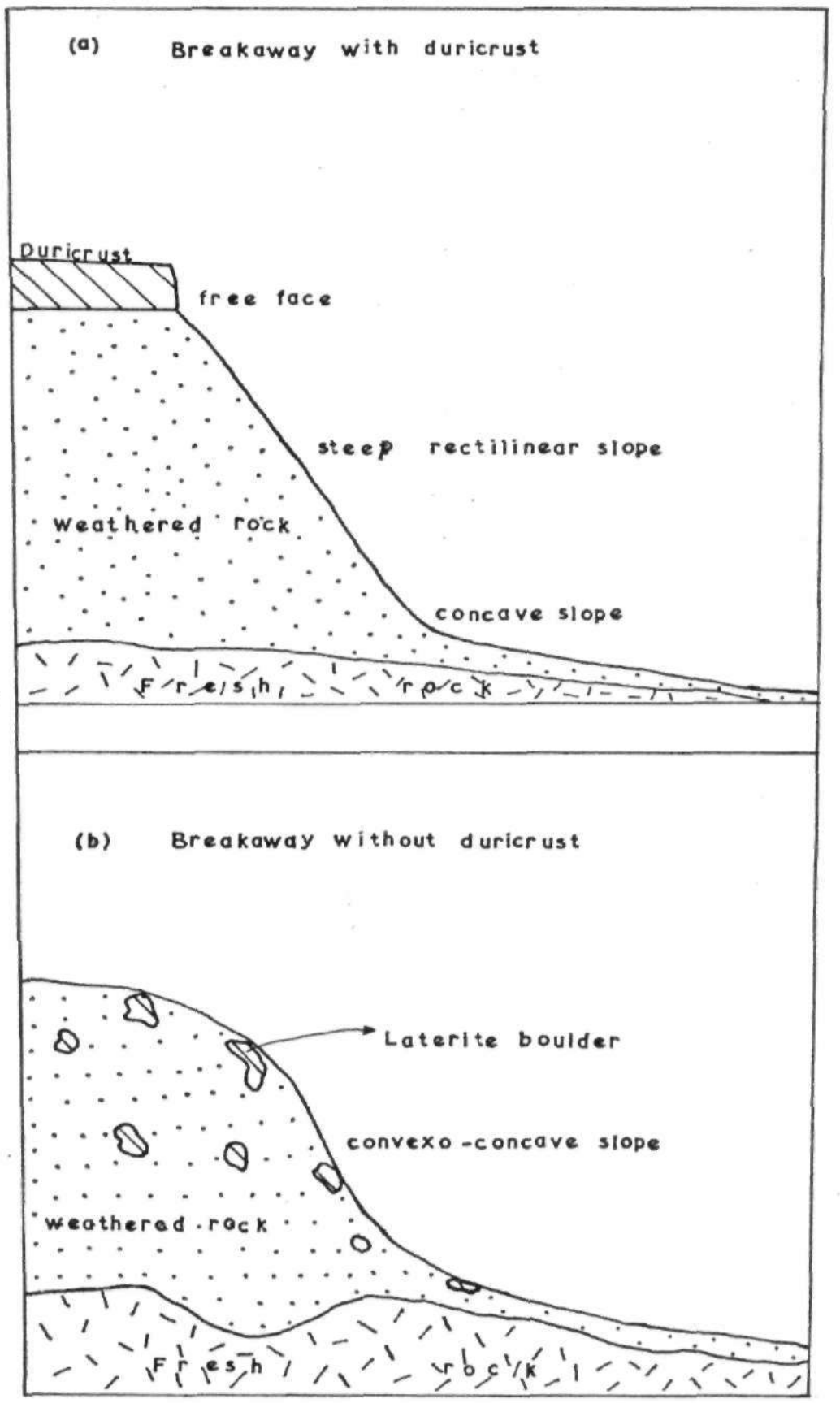
Most of the breakaways of the Tuttanning reserve appear to be non-active at present, i.e. they are no longer receding but seem to have been stabilized by vegetation, and by the recementation of iron-stone gravels and laterite boulders. One of the very few breakaways where erosion is currently active is situated a few metres to the south of Rosella track.

The Pediments

The breakaways often give way downslope to gently inclined surfaces, the pediments formed by the retreat of the scarps (Bryan 1923; Penk 1924; King 1948). The boundary between the breakaways and the pediments is often marked by a distinct break of slope. In cross section, pediments are concave with slope angles ranging from 7^{o} on

Fig. 4.1.

THE EFFECT OF A DURICRUST CAP ON THE NATURE OF THE BREAKAWAY



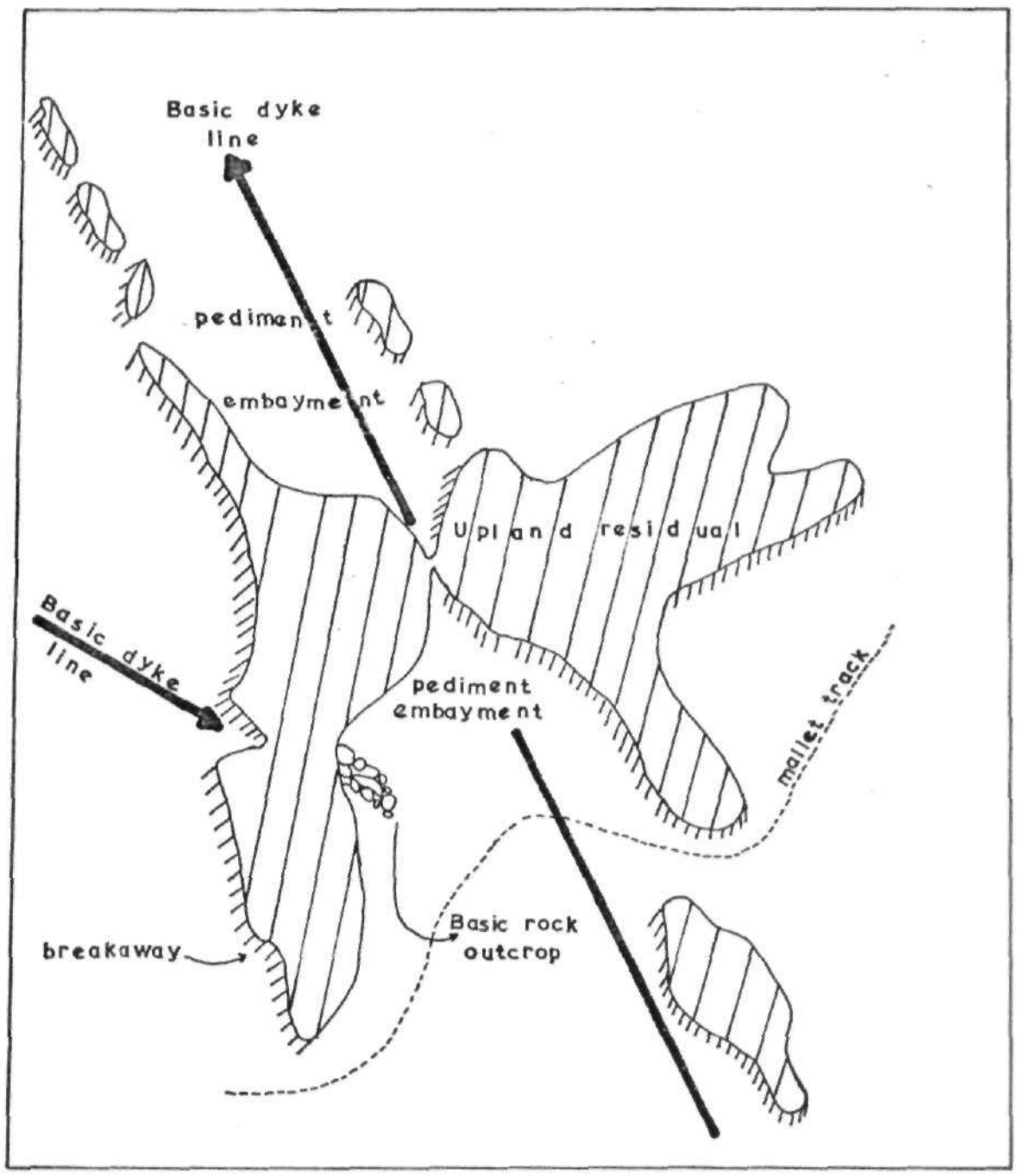
the upper pediments to only $\frac{1}{2}^{o}$ on their lower margins. The pediment surface, often cut in material which is transitional to fresh rock (Mulcahy and Hingston 1961), is buried by detritus derived from the destruction of the breakaway. This detritus is usually shallow on the upper pediment but becomes progressively deeper and sometimes finer downslope.

Where the line of breakaway is sinuous, pediment embayments are found extending into the upland residuals. As an example, the pediment embayments into the upland residual adjacent to Mallet track are illustrated in Fig. 4.2, and are probably geologically controlled since they follow the line of a basic dyke. Here the duricrust, and the deeply weathered mantle associated with the basic rocks are stripped in preference to the material associated with the sides of the dyke. The pediments together with the long gentle slopes which continue down from them, form a large proportion of the "new plateau" (Jutson 1934).

Spurs and low ridges

Spurs sometimes extend from the upland residuals towards the drainage lines. The boundary between such spurs and the upland surface is often transitional, though occasionally an identifiable break of slope is present (e.g. Rocky Spurs). In other cases some of the spurs appear to be "nipped off" from the uplands by a zone of erosional terrain and appear as low ridges on the new plateau often with a low breakaway on their upslope flanks. The spurs and low ridges generally have local relief of about 2-3 metres, slope gently ($1-2^{o}$) towards the drainage lines, have smooth convex crests and smooth concave side slopes.

Fig. 4.2 PEDIMENT EMBAYMENTS ASSOCIATED WITH BASIC DYKE LINE



Rock Outcrops

Stripping of the duricrust and the underlying mantle of weathering has exposed fresh rock at several sites on the new plateau and in a few places on the ancient plateau and revealed the highly irregular basal surface of weathering. Topographically, these rock outcrops are expressed in various forms.

Granites: Most of the rock outcrops are granitic. These granites outcrop as massive domes, small island hills, spurs, boulders and floors. The granitic hills usually occupy only a few square metres, have local relief of 7 to 10 metres and outcrop fairly close to the breakaways. The hills' present rounded outlines are due to the exfoliation of the rock surface on which are tors of various shapes and sizes, some of which are hollowed out from below upwards in a remarkable manner which often results in grotesque forms being produced. It is at the foot of these island hills and more particularly the massive domes that 'soaks' occur. The relationship between granitic soaks and some of the headwater streams of the Tuttanning reserve has already been mentioned in this chapter. The widespread weathering of the granitic masses has resulted in the accumulation of deep, coarse sands on long, gentle, apron-like slopes which flank them.

Dolerites: Basic igneous rock largely comprising dolerites may outcrop as narrow NW-SE and NE-SW trending low (1-2 metres) boulderly ridges. These represent dykes which have intruded the granites. In other situations it appears that the dolerites have been deeply weathered. These zones appear to have been preferentially eroded leaving elongate trenches now partially filled by sediment. It is suggested that this is the case for the elongate depression which runs north-eastward from Numbat

track. It "lines up" with a prominent basic dyke to the south-west of the reserve hut while its northern extremity features a large dolerite outcrop.

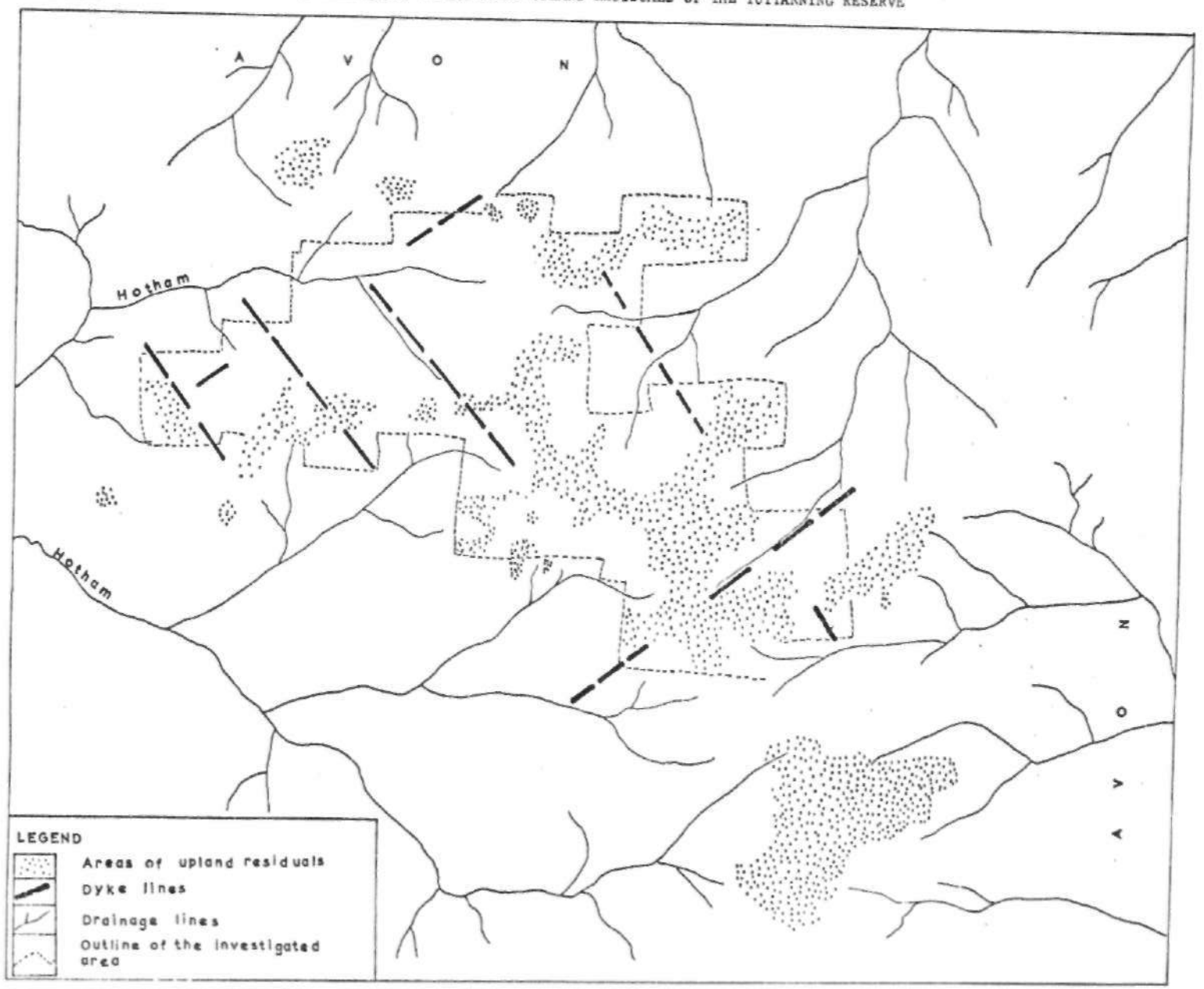
Quartz: Quartzites or quartz porphyries are also intimately associated with the granites, gneisses and meta sediments. On account of their strong resistance to erosion, quartzites generally tend to rise above the surrounding rocks in places as high prominent ridges and in others as small low knobs. The most prominent quartz ridge in the Tuttanning reserve occurs to the west of Kangaroo track and has local relief of about 5 metres. A rather interesting feature in connection with this quartz reef is the amount of detrital quartz that is shed from it. This detritus covers the ground for a hundred metres or more from the quartz reef revealing that the reef is being lowered by denudational processes.

Drainage

There is a good relationship between the orientation of the main first and second order elements (Horton 1945, Strahler 1957) of the main co-ordinated systems which drain this area and the orientation of exposed features of geological structure such as basic dykes. Two of the most important streams drain south-westwards to the Hotham, an orientation which is taken up by north-east trending elements of the Avon drainage (see Figure 4.3).

In some situations it is evident that basic dykes have been weathered to produce topographic 'lows' which become first order stream channels. An example of this is the drainage channel that cuts through the western half of the paddock surrounded by Nuytsia track. This first order element of the Hotham is perfectly in line

Fig. 4.3 DRAINAGE PATTERNS, STRUCTURAL FEATURES AND UPLAND RESIDUALS OF THE TUTTANNING RESERVE



Source - OVERLING SHEET 2332-1 1 : 50,000 (June 1971) Lands & Surveys, Perth, W.A.

with the dyke that cuts through the scattered granite outcrops to the east of Eagle track.

Some of the minor first order streams are not necessarily part of the co-ordinated drainage. Some of these occupy deep ravines which "head" in soaks at the base of massive granite rock outcrops or pediment embayments.

Excessive runoff from pediments resulting in channelled flow is discussed in Chapter IX of this thesis where the characteristic is related partly to water-repellent sands. Drainage channels that head in granitic soaks if not represented by ravines, remain bogged for long periods of the year.

General comments

From the material presented above, it appears that the major elements of the present valley system were in existence prior to lateritization. Many of the present landforms are merely a consequence of erosional modification of an ancient landscape which had a general form rather similar to the present one. Furthermore, elements of the "old" plateau as residuals are not always completely separated from terrain of the "new" plateau but appear to blend with elements of the "new" plateau. It is on these grounds that the terms "old" and "new" plateau are not entirely satisfactory as a basis for a genetic framework.

CHAPTER V

THE NATURE AND PROPERTIES OF SOILS

Soils form a continuum over the land surface and lateral changes within it may occur over a short distance and provide a readily mapped soil boundary. This is particularly so if the changes are in the surface horizons and are consistently associated with changes in the subsurface morphology. More frequently however changes in the soil characteristics are gradual and subtle and for various reasons it is not possible to examine sufficient points on the continuum to enable a map to be drawn on soil characteristics alone. On the other hand, if there is a relationship between the soils and more readily mapped elements of the environment, the mapping might be facilitated with the available resources of labour and time. As a consequence the resultant units usually contain a considerable amount of information on certain aspects of the environment as well as the soils.

The initial reconnaissance of the study area suggested a good relationship between soil and topography while the dearth of country rock outcrops limited opportunities to use geology consistently as a prime basis for mapping. Twenty-two soil mapping units were recognised at Tuttanning. Within these the soils were insufficiently uniform for the units to be regarded either as types or as series. Therefore, a relatively non-specific term, the soil mapping unit (Cihlar and Protz 1973) was used and is frequently abbreviated to SMU in the manuscript. Boundaries separating the SMU's fall into several categories. For example, the boundaries separating the soils of the upland residuals (e.g. duricrust) from the pediment soils are sharp, easily recognizable on the photos and in the field, and can be regarded as first order. Many other boundaries are gradational and as a result must be regarded as third order and their positions on the map could probably vary with individual workers.

The soil mapping units (SMU's) have been grouped according to their general topographic position and to the dominant soil materials contained along with the respective mapping symbols. The resultant framework of classification is as follows:

1 Units dominated by lateritic gravels and sands, usually occupying upland situations.

(A) Soils are very gravelly

a_1 Tuttanning SMU - shallow gravels and extensive massive duricrust.

a_2 Dutarning SMU - deep sandy gravels.

(B) Deep sands

b_1 Possum SMU - deep yellow sands.

b_2 Echidna SMU - gray sands over massive duricrust.

2 Valley slope units.

Minimal rock outcrops

(C) Pediments (upper concave slopes)

c_i Rosella SMU - thin veneer of earthy material over pinkish or pale-reddish and grayish massive sandy clay.

c_{ii} Gravelly phase of c_i.

c_3 Chat SMU - lower pediment soils; deeper finer A horizon material than c_i.

c_4 Pingelly SMU - basic pediment; deep reddish or reddish brown clayey soils.

(D) Low gently sloping ridges and spurs - may extend across upper, mid and lower slope situations

d_1 Marshall SMU - sandy ironstone gravels over mottled sub-indurated light clay.

d_2 Magpie SMU - shallow gray loamy sand over mottled sub-indurated light clay.

(E) Lower slopes, sometimes to mid slopes

e_1 Goanna SMU - sandy loams with a tendency to set hard over mottled light clay with rock fabric.

e_2 Woyerling SMU - grayish brown, coarse loamy sand (often friable) A horizons overlying mottled clays with partially weathered at shallow depth.

e_3 Bungara SMU - deep gray sands over sub-indurated mottled sandy clay.

e_4 Dailyerking SMU - massive sandy-clay exposures showing rock fabric at depth.

(F) Rock outcrops have a major influence on the soils

f_1 Bare rock surfaces

f_2 Woiylie SMU - deep gritty grayish brown sands with rock fragments and partially weathered rock at depth.

f_3 Bandicoot SMU - scattered acid rock outcrops and associated soils.

f_4 Mopoke SMU - scattered basic rock outcrops and associated soils.

f_5 Gnow SMU - compact sandy soils with high content of quartz gravels.

3 (G) Units of the drainage floors

g_1 Wambenger SMU - deep brownish to grayish brown sands, with bleached A_2 horizons and water-logging at depth.

g_2 Hotham SMU - complex of soils associated with the drainage lines.

g_3 Quail SMU - deep sandy and waterlogged soils with surface efflorescence of soluble salts.

DETAILED DESCRIPTION OF SOIL MAPPING UNITS (SMU'S)

1 Units of the uplands

a_1 Tuttanning SMU

Topography - May occupy the entire surface of a mesa or butte (upland residuals) or the higher elements (convexities) where this surface contains erosion scars.

The soils - Comprise shallow gravelly sands over duricrust, and associated with extensive exposures of duricrust. The duricrust as evident from the breakaways is often underlain by a weathered zone of variable depth (30 metres or less than 5 metres) comprising mottled, pallid and transitional zones (see Photo 5.1 and Photo 5.2).

a_2 Dutarning SMU

Topography - Usually occupies the lower elements (broad concavities or gently sloping ground) on the surface of upland residuals, where this surface contains erosion scars.

The soils - Are predominantly ironstone gravels with little or no duricrust exposed or occurring at shallow depth. In a typical profile the surface 10-15 cm may contain 45-60% sandy material below which the sandy matrix is usually less than 10% of the mineral material. The gravels are usually sub-rounded near the surface, but become more angular and larger with depth. At 35-45 cm depth some lateritic boulders may be present. The ironstone gravels often give way at about 45-50 cm depth to fragmented or partially fragmented sub-indurated mottled sandy clay or sandy clay loam which in turn passes into pallid material (Photo 5.3). Occasionally this unit contains small pockets of yellowish brown sandy soil (Possum SMU) 15-35 cm deep, resting on the gravels.

PHOTO 5.1



Massive duricrust - with mallet vegetation

PHOTO 5.2



Pallid zone beneath duricrust exposed in the face of a breakaway.

PHOTO 5.3



Deep ironstone gravels (Dutarning SMU) developed in the weathered acid country rock.

Where the soil unit is over basic parent material, the gravels are often more rounded and smooth (pisolitic) and the matrix between them is usually redder and finer in texture (Photo 5.4).

Profile description of Dutarning soil, developed over acid parent material - (T.112)

Site	Vegetation
- on 1° slope, in a dissection, on the surface of upland residual about 15 metres from breakaway and upslope from deep yellow sands. It is adjacent to the western extremity of Gnow track.	Dryandra sp. Isopogen sp. Grevillea sp.

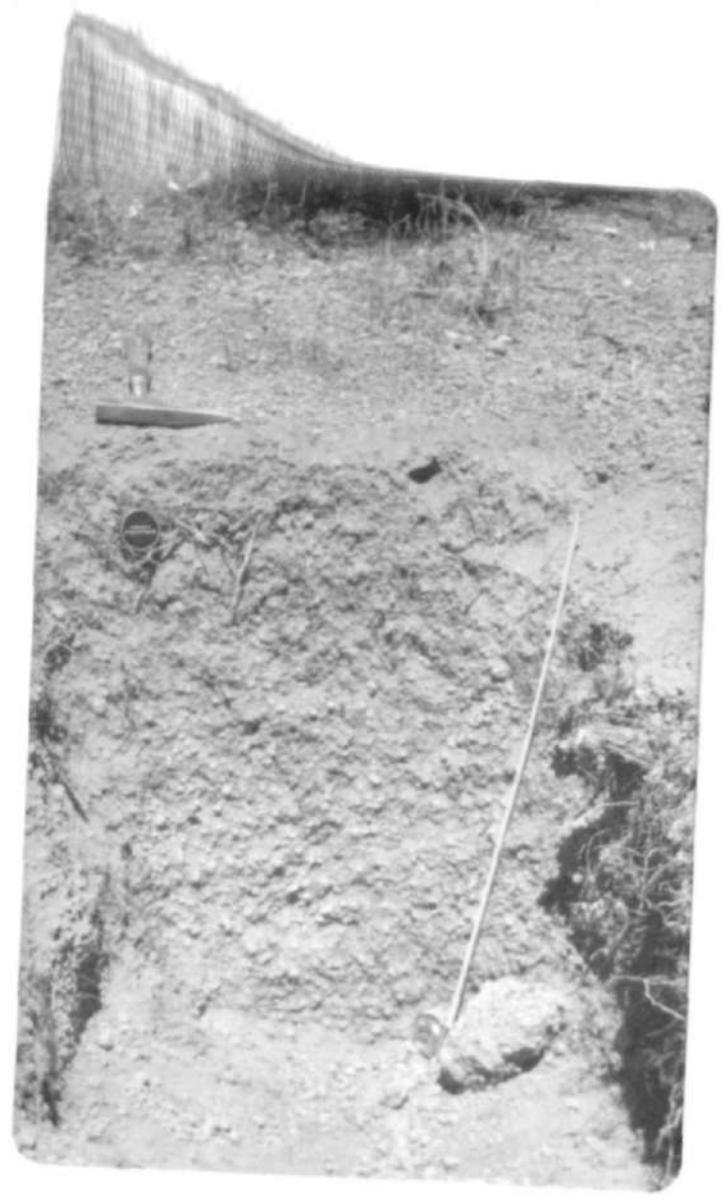
0 - 15 cm Grayish brown (10 YR 5/2) loamy sand, weak crumb, loose, 45-50% ironstone gravels of variable shapes and sizes, pH 5.

15 - 40 cm Light yellowish brown (10 YR 6/4) sandy loam matrix (less than 10%) in irregularly shaped ironstone gravels gradually increasing in size. pH 5.

40 - 60 cm Light yellowish brown (10 YR 6/4) sandy clay loam, mottled dark red, reddish brown and yellowish brown; sub-indurated and fragmented along cleavage lines; fragments coated with clay. pH 5.5.

60 - 90 cm As above, except that fragments are bigger, only slightly indurated and carry only a trace of clay coatings.

PHOTO 5.4



Deep ironstone gravels (Dutarning SMU) over basic country rock and showing pisolitic nature of the gravels.

90 - 100 cm Light yellowish brown (10 YR 6/4) sandy clay loam, mottled dark-red and yellowish brown; massive, sub-indurated, high content of quartz grit. pH 5.5.

b_1 Possum SMU

Topography - comprises concavities and elongate narrow depressions on the residuals; gentle slopes below gravelly pediments; flanks of gravelly spurs.

The soils are deep yellowish brown sands. The depth of the sands and the clay content are highly variable as is the nature of the underlying material (which may be ironstone gravels, mottled zone, pallid zone, transitional zone to fresh rock, weathered country rock, etc.). Depths of more than 260 cm and less than 70 cm have both been recorded and clay contents of less than 5% and up to 12% have also been encountered. Usually there is a slight increase in clay content and a brighter yellow colouring with depth. Ironstone gravels of all shapes and sizes are often encountered at the interface between the sands and the underlying material. Where the underlying material is clay, fairly soft to hard rounded gravels with concentric iron-rich banding are intimately associated with the upper parts of the substrate.

Profile description of deep yellow sands (T.33)

Site	Vegetation
- in a slight concavity on upland residual adjacent to Gnow track and 10 metres downslope of Dutarning profile (T.112)	heath communities; dominated by Swan River myrtle, Melaleuca sp. and Isopogen sp.

0 - 5 cm Brown (10 YR 5/3) sand; stained with organic matter; loose with many fine roots. pH 6.

5 - 10 cm Light yellowish brown (10 YR 6/4) loose.

10 - 100 cm Brownish yellow (10 YR 6/6 - 6/8) loamy sand; loose, very friable. pH 5.5.

100 - 160 cm Yellowish brown (10 YR 5/8) loamy sand; loose, pH 5.0.

160 - 260 cm Yellowish brown (10 YR 5/8) loamy sand; becomes slightly sticky when wet. Clay content 10.1%, trace of sub-rounded ironstone gravels. pH 6. Continuing. (See also Photo 5.5)

b_2 Echidna SMU

Topography - Occupy broad upland concavities.

The soils comprise 70-90 cm of gray coarse sands over massive duricrust. The soil is extremely low in clay, often less than 2%. A thin zone (about 5 cm) of sandy gravels usually occurs between the sands and the duricrust. Occasionally the sands become pale brown at depth, indicating some slight iron (yellow) coating on the grains.

Site	Vegetation
- in shallow, broad concavity on upland residual, by Jarrah track.	Heath

0 - 5 cm Light gray (10 YR 6/1) coarse sand, loose, single grain, small amount of organic matter, a few fine roots, less than 1% clay. pH 6.

5 - 20 cm Light gray (10 YR 6/1) loose coarse sand.

20 - 40 cm Light gray (10 YR 7/1) loose coarse sand. pH 6.

PHOTO 5.5



Deep yellowish brown sands - with massive structure

40 - 50 cm Light gray (10 YR 7/2) loose coarse sand.

50 - 70 cm Light gray (10 YR 7/2) loose coarse sand; trace of irregularly shaped ironstone gravels; less than 1% clay. pH 6.5.

70 - 90 cm Ironstone gravels and boulders with light gray (10 YR 7/2) sand matrix. pH 6.5.

90 cm + Massive duricrust. (See also Photo 5.6)

2 Valley Slope Units

Minimal rock outcrops

c_i Rosella SMU

Topography - concave pediment slopes below breakaways.

The soils generally comprise a gritty sandy loam (20-30 cm deep) over a pinkish or pale reddish brown and occasionally gray massive sandy clay. The boundary between the surface sands and the underlying clay is always sharp. The surface sands are often extremely water-repellent and may become finer and deeper downslope. The clay subsoil is typical of the pale kaolinitic clays of the deeper parts of the deep profile of weathering. Such clays were regarded by Mulcahy and Hingston (1961) as representing the transitional zone (where clay is pinkish) or pallid zone (where the clay is gray) of truncated laterite profiles. The surface horizons are detrital, derived mainly from erosional products of the weathering profile exposed in the breakaway face, and there may be a stone line at the interface in some profiles. Rosella SMU's with gravelly A horizons (c_{ii}) are also present and appear to be related closely to breakaway morphology (see Chapter VIII).

PHOTO 5.6



Profile showing gray sands over duricrust (Echidna SMU)

Profile description of gravelly Rosella (T.3)

Site	Vegetation
- on 4° slope, on acid pediment, below low breakaway near Tammer track.	Powder bark wandoo.

0 - 5 cm	Light brownish gray (10 YR 6/2) gritty sandy loam, weak crumb structure, loose, about 25% content of ironstone gravels; surface cover of irregularly shaped ironstone gravels; extremely water repellent. pH 5.5.
5 - 20 cm	Light gray (10 YR 7/2) gritty sandy loam, weak crumb, loose and friable, water repellent; 10-15% ironstone gravels. pH 5.5.
20 - 30 cm	Very pale brown (10 YR 7/4) sandy loam, weak sub-angular blocky soft, about 20% ironstone gravels; water repellent; sharp boundary. pH 6.
30 - 50 cm	Light yellowish brown (10 YR 6/4) sandy clay loam, with reddish brown (10 YR 5/4) and gray (10 YR 7/2) diffuse mottles. Massive, dense and compact; tongues of A horizon material penetrate to about 50 cm; trace of ironstone gravels. pH 6.5.
50 - 60 cm	Very pale brown (10 YR 7/4) sandy clay loam, massive, dense and compact. Trace of iron-stone gravels. pH 7.0.
60 - 100 cm	Very pale brown (10 YR 7/4) sandy clay, massive, compact. pH 7.5.

c_3 Chat SMU

Topography - Lower pediment slopes; 3^o to $\frac{1}{2}^o$ declivity.

The soils comprise loamy sands or sandy loams (40-50 cm deep) over pale reddish or reddish yellow compact massive light clay. The surface sands usually contain some sub-angular ironstone gravels. The main differences between the soils of Chat and those of the Rosella SMU's are that the former usually have a deeper, less gritty and much darker surface horizon and the gray clay sometimes associated with the latter is completely absent. Chat soil may be regarded as developed on transitional material to fresh rock which is mantled by the finer tail of pedisediment.

Profile description of soil of Chat SMU (T.106)

Site	Vegetation
- on gentle ($2-3^o$) slope; on lower pediment near Rosella track; extreme north-east of the reserve.	Powder bark wandoo and a few sheoak.

0 - 10 cm Brown (10 YR 5/3) loamy sand; weak crumb; friable, soft, trace of very fine ironstone gravels.

10 - 20 cm Yellowish brown (10 YR 5/4) loamy sand; weak medium crumb; friable, soft, trace of very fine ironstone gravels.

20 - 30 cm Light yellowish brown (10 YR 6/4) loamy sand; fine weak sub-angular blocky, soft; trace of sub-rounded ironstone gravels.

30 - 45 cm Light yellowish brown (10 YR 6/4) loamy sand, friable, a few fragments of moderately hard and brittle sandy clay loam.

45 - 70 cm Reddish yellow (5 YR 7/6) sandy clay loam, massive, moderately hard and brittle - continuing.

c_4 Pingelly SMU

Topography - pediment slopes and may extend to mid and lower slopes.

The soils comprise deep reddish or reddish brown clays developed on basic country rock. Often there is a surface horizon of less clayey (loams and clay loams) material. Fresh rock or partially weathered basic rock is encountered at a depth of about 100-120 cm. Variations within unit include the more sandy types developed over quartz-dolerites while other profiles comprise fairly deep (35 cm or more) friable A horizons over the compact reddish clays. The content of ironstone gravels (some of which are rounded and/or black) though generally low is also variable.

Profile description of deep red clays - shallow A horizon (T.29)

Site	Vegetation
- on pediment slope, on basic dyke, between Goanna and Eagle tracks.	Sheoak with mallet and wandoo.

0 - 5 cm Dark reddish brown (5 YR 3/2) gritty clay loam, loose, friable, fine crumb, rich in organic matter, trace of fragments of basic rock; wavy boundary. pH 6.5.

5 - 20 cm Reddish brown (5 YR 5/4) gritty clay, weak medium sub-angular, blocky. Moderately hard; plastic when wet; tongues of A horizon material. Trace of fine rock fragments. pH 6.5.

20 - 40 cm Reddish brown (2.5 YR 4/4) clay with trace of grit; weak coarse angular blocky; hard; very sticky and plastic when wet.

40 - 60 cm Dark red (2.5 YR 3/6) clay; weak coarse angular blocky to almost massive; compact and hard when dry. pH 5.5.

60 - 80 cm Red (2.5 YR 5/6) clay, massive, compact and very hard when dry; trace of pinkish (5 YR 7/4) rock fragments.

80 - 90 cm Red (2.5 YR 5/6) gritty clay; massive, compact, hard, trace of fragments of fresh rock. pH 4.0.

90 -100 cm Light red (2.5 YR 6/6) gritty clay, with pink (5 YR 7/3) mottles; massive, compact, hard; a few fragments of fresh rock.

100-120 cm As above, except that fragments of fresh rock are increasing.

Deep red soils - with deep A horizon (T.38)

Site	Vegetation
- in a pediment embayment near Mallet track.	Dense mallet

0 - 5 cm Reddish brown (5 YR 5/3) gritty loam, fine crumb, soft, friable, abundant organic matter; extremely water repellent, trace of basic rock fragments. pH 4.5.

5 - 15 cm Reddish brown (5 YR 4/3) gritty loam, crumb, friable, strong water repellence, trace of rock fragments. pH 5.0.

15 - 30 cm Reddish brown (5 YR 4/4) loam; weak fine sub-angular blocky, friable; slightly water repellent; trace of rock fragments becoming coarser. pH 5.5.

30 - 60 cm Reddish brown (5 YR 4/4) sandy clay loam; weak fine sub-angular blocky; friable, inclusions of moderately hard sandy clay fragments; trace of fine rounded black ironstone gravels and rock fragments. pH 5.5.

90 - 120 cm Red (2.5 YR 4/6) gritty clay, faintly mottled reddish yellow (7.5 YR 6/6); moderately friable, trace of partially weathered rock fragments; increasing grit. pH 4.5.

(See also Photo 5.7)

(D) Low gently sloping ridges and spurs

d_1 Marshall SMU

Topography - occupy convex slopes of spurs and low ridges. The soils comprise grayish brown sand with abundant closely packed ironstone gravels changing fairly sharply at about 30-40 cm to fragmented or partially fragmented, sub-indurated mottled sandy clay. This gives way at depth to a "transitional zone" of pinkish or light brown sandy clay and finally to fresh rock. A gray sandy A horizon is sometimes present. A perched water-table sometimes develops at the interface between the gravelly A and the clayey B horizons in winter. Where the soil has developed over basic rock, it is brownish to dark reddish brown and the matrix in the gravels is heavier textured. The sub-indurated B horizon may be absent. The main differences between soils

PHOTO 5.7



A red earth typical of the Pingelly SMU. Poorly expressed stone line may be seen mid-way down the profile.

of Marshall and Dutarning SMU's are that the latter have deeper gravelly zones, are well drained throughout the year and are underlain by usually deep pallid zones.

Profile description of soil on Marshall SMU (T.15)

Site	Vegetation
- on the crest of a gently sloping spur; close to the paddock near Bee-eater track; between Wallaby and Casuarina tracks.	Sheoak is dominant; also wandoo, jam and *Xanthorrhoea preissii*; undergrowth of box poison legumes.

0 - 5 cm Very dark brown (10 YR 3/2) sand; rich in organic matter, trace of irregularly shaped ironstone gravels of various sizes. pH 6.0.

5 - 15 cm Dark grayish brown (10 YR 4/2) sand, loose, single grain, trace of ironstone gravels, sharp boundary, pH 5.5.

15 - 20 cm Light brownish gray (10 YR 6/2) sand; loose, about 30-35% ironstone gravels; trace of quartz fragments. pH 6.0.

20 - 40 cm Pale brown (10 YR 6/3) loamy sand matrix in coarse sub-angular ironstone gravels; sharp wavy boundary. pH 6.0.

40 - 60 cm Very pale brown (10 YR 7/4) sandy clay loam, mottled yellow(10 YR 9/8) and yellowish red (5 YR 4/8); massive sub-indurated fragmented along cleavage lines into blocks; blocks coated with clay; tongues of A horizon material down to 50 cm. pH 6.0.

60 - 70 cm Brownish yellow (10 YR 4/6) sandy clay loam, coarsely mottled dark reddish brown (2 YR 3/4); massive, sub-indurated, fragmented into blocks;

60-70 cm continued clay concentrated along cracks and voids.

70 - 80 cm Sandy clay loam, intricately mottled, pale yellow (2.5 Y 7/4) and dark reddish brown (2.5 YR 3/4). Massive. pH 6.0.

80 - 100 cm As above except that the material is becoming softer. (See also Photo 5.8)

d_2 Magpie SMU

Topography - may comprise the convex slopes of spurs or the dip slope of cuesta-like low ridges.

The soils comprise shallow (10-15 cm) gravelly gray sands which pass sharply into sub-indurated mottled clay. It has poor internal drainage and a perched water table usually develops in winter at the interface between the surface gray sands and the clay only a few centimetres below the surface. Unlike the Echidna SMU, the surface gray sands of Magpie usually contain appreciable amounts of clay (13% or even more). The gravelly zone of the Magpie is thin in comparison to that of Marshall SMU. Local variations within Magpie SMU's may include deeper sandy A horizons or complete absence of this mantle of loose sands. Magpie SMU is nearly always associated with low heath communities.

Profile description of soil in Magpie SMU (T.99)

Site	Vegetation
- on the dip slope of a cuesta-like low ridge. East of Nuytsia track and south of Tuttanning Road.	Low heath communities

0 - 5 cm Gray (10 YR 5/1) sand, loose, non-coherent, trace of ironstone gravels and quartz fragments. pH 5.0.

PHOTO 5.8



Profile showing gravelly A horizon over sub-indurated mottled B horizon (Marshall SMU)

5 - 15 cm	Grayish brown (10 YR 5/2) loamy sand, gritty slightly sticky when wet, abundant ironstone gravels (45 - 50%), sharp boundary. pH 6.0.
15 - 30 cm	Light brownish gray (10 YR 6/2), sandy clay loam, mottled red, yellow and brown; massive, compact, sub-indurated; fragmented along cleavage lines into big blocks which have prominent clay coatings. The cleavage lines are often occupied by A horizon sands. pH 6.0.
30 - 50 cm	Yellow (10 YR 7/8 - 7/6) sandy clay loam, strongly mottled yellowish brown and dark red; compact, sub-indurated. pH 5.5.
50 - 90 cm	Yellow (10 YR 7/6), sandy clay loam, strongly mottled reddish brown (5 YR 4/4); massive compact, isolated quartz-rich pockets present, some of the reddish mottles are round but have no shells, neither are they separated from the rest of the mass. pH 5.0.
70 - 90 cm	Very pale brown (10 YR 8/3) gritty sandy clay loam, strongly mottled reddish brown and yellow; massive, hard clay concentrated along cracks and in voids; material becoming slightly softer. pH 4.5.
90 - 100 cm	Very pale brown (10 YR 8/3) gritty sandy clay loam, strongly mottled brownish yellow (10 YR 6/6); reddish brown and red (2.2 YR 4/8) increase in amount of quartz grit. pH 4.5. (See also Photo 5.9)

PHOTO 5.9



Profile of soil in Magpie SMU

(E) Lower slopes sometimes to mid slopes

e_1 Goanna SMU

Topography - comprises very gently sloping elements (2^{o}-$\frac{1}{2}^{o}$ declivity) between incipient drainage floors of the undulating plains (new plateau).

The soils comprise grayish brown sands (40-55 cm deep) with a tendency to set hard (Northcote 1971) over mottled light clay. The whole profile is usually massive, largely devoid of peds. The mottled light clay which may or may not be sub-indurated is underlain by partially weathered rock. Often, the hard setting characteristic is most prominent within the 30-50 cm layer which remains virtually dry for most of the year. Some sub-angular ironstone gravels are usually present in the sandy A horizon and sometimes extend into the B horizon where a few rounded pisolitic gravels may also be present. This unit sometimes contains soils of the Woyerling and/or Bungara SMU's (described below).

Profile description of soil in Goanna SMU (T.76)

Site	Vegetation
- on very gentle slope ($\frac{1}{2}$ - 1^{o}) south of Jam track	Scattered wandoo and sheoak; a few jam; very little undergrowth.

0 - 10 cm Brown (10 YR 5/3) loamy sand; slightly hard, massive, a thin surface crust or flake present.

10 - 25 cm Very pale brown (10 YR 7/4) coarse loamy sand, brittle, massive, a trace of fine ironstone gravels.

25 - 40 cm Very pale brown (10 YR 7/3) loamy sand, moderately hard, massive, abundant (30-35%) sub-angular ironstone gravel; sharp boundary.

40 - 50 cm Very pale brown (10 YR 7/3) gritty sandy loam; diffusely, mottled brownish yellow (10 YR 6/6); hard and brittle, very dry; some (10-15%) ironstone gravels.

50 - 70 cm Very pale brown (10 YR 7/3) gritty sandy loam to sandy clay loam, faintly mottled brownish yellow; very hard and brittle; trace of ironstone gravels.

70 - 80 cm Very pale brown (10 YR 7/4) sandy clay loam; strongly mottled brownish yellow (10 YR 6/6) and red; hard and brittle.

80 - 90 cm Yellow (10 YR 7/8) sandy clay loam, diffusely mottled yellowish brown (10 YR 5/8); massive, hard and brittle (continuing).

e_2 Woyerling SMU

Topography - comprises gently sloping surfaces flanking minor drainage floors.

The soils - This unit is dominated by brown or light brown gritty and friable sand or loamy sand overlying yellowish brown sandy clay loam with some rock fragments. Fresh rock is usually at a shallow depth (90-120 cm). Ironstone gravels occur sporadically in small amounts towards the base of the sandy A horizon. The main differences between typical profiles of Woyerling and Woiylie SMU's are that the former often have more coherent, slightly less gritty A horizons and the underlying saprolite is much more weathered and occurs at shallower depth than the latter.

Profile description of soil of Woycrling SMU (T.75)

Site	Vegetation
On gently sloping surface between a gravelly rise and the drainage floor; by Nuytsia track (East).	Sheoak dominant; wandoo and jam also present.

0 - 10 cm Brown (10 YR 5/3) loamy sand, weak fine crumb, friable, some organic matter and fine roots.

10 - 20 cm Yellowish brown (10 YR 5/4) loamy sand. Weak crumb, soft, friable; a trace of fresh rock fragments, mostly quartz.

20 - 70 cm Yellowish brown (10 YR 5/6) gritty sandy clay loam with a few distinct red mottles, fairly soft, slightly sticky when wet; massive, breaks into coarse sub-angular clods.

70 - 90 cm Reddish yellow (7.5 YR 6/6) sandy clay, a few distinct red mottles; small fragments of partially weathered fresh rock; massive, fairly soft.

e_3 Bungara SMU

Topography - Broad depressions on the new plateau not occupied by stream channels; slopes flanking low ridges occupied by the Magpie SMU.

The soils comprise deep gray coarse sands over sub-indurated mottled sandy clay. The clay content of the sands, though generally low, increases slightly with depth. A perched water table develops in winter at the interface between the sands and the light clay. The sands have a yellowish hue at depth and hence become pale brown. Where a Bungara SMU occurs downslope of a Magpie SMU, a narrow zone of duricrust (usually at the shoulders of the ridge) may separate the two.

Profile description of deep gray sands - Bungara SMU (T.110)

Site	Vegetation
On concave slope flanking low interfluve; close to Magpie track.	Scattered wandoo and sheoak; understorey of shrubs.

0 - 5 cm Gray (10 YR 6/1) sand; loose, non-coherent.

5 - 30 cm Light gray (10 YR 7/2) coarse sand; loose, slightly coherent.

30 - 70 cm Very pale brown (10 YR 7/3) sand to loamy sand; only slightly coherent, a few quartz fragments.

70 - 75 cm Pale brown (10 YR 6/3) sandy loam, mottled yellowish brown, massive, brittle; a trace of sub-angular ironstone gravels.

75 cm + Pale brown (10 YR 6/3) sandy clay, strongly mottled yellowish brown and red; compact, massive, sub-indurated.

e_4 Dailyerking SMU

Topography - Comprises moderately steep (4-5°) slopes between rises and drainage floors.

The soils - These comprise grayish brown, tough, massive light clay which gives way at depth to mottled (yellowish brown and reddish brown) light clay. Partially weathered acid country rock is usually present at about a metre below the surface. Occasionally, ironstone gravels of various shapes and sizes occur scattered on the soil surface.

(F) Rock outcrops have a major influence on the soils

f_1 Bare rock surfaces - no soil except in cracks and along weathered joints.

f_2 Woiylie SMU

Topography - Gently sloping surfaces as apron to massive outcrops of granite.

The soils comprise brownish to grayish brown deep gritty sands often with partially weathered rock fragments, some of which are coated with iron oxides. Partially weathered rock is usually about a metre below the surface. Sometimes the sands contain substantial amounts of sub-angular ironstone gravels.

Profile description of acid rock apron soil (Woiylie SMU - T.68)

Site	Vegetation
- on a 2^{o} slope, about 60 metres downslope of a granitic rock outcrop near White Gum track.	Sheoak is dominant; wandoo is also present; understorey of box poison.

0 - 5 cm Very dark gray (10 YR 3/1) extremely gritty sand, loose, non-coherent, some organic matter. pH 6.0.

5 - 15 cm Grayish brown (10 YR 5/2) extremely gritty sand, loose.

25 - 30 cm Light brownish gray (10 YR 6/2), gritty sand,

30 - 40 cm Pale brown (10 YR 6/3) gritty sand, loose, moderate amount (15-25%) of sub-angular ironstone gravels most of which are fragments of partially weathered rock, coated with iron oxides.

40 - 70 cm Light gray (10 YR 7/2) gritty sand, loose. Abundant ironstone gravels (more than 40%), sharp wavy boundary.

70 - 80 cm Yellowish brown (10 YR 5/6) partially weathered rock fragments, mottled red and yellow. pH 6.0.

80 - 90 cm Brownish yellow (10 YR 6/8); partially weathered rock, mottled red and yellowish brown; moderately hard.

90 - 120 cm Yellow (10 YR 8/6) partially weathered rock with abundant feldspar grains. (See also Photo 5.10).

f_3 Bandicoot SMU

Topography - Not strictly related to topography.

The soils - This unit is essentially a complex comprising several types of soils associated with scattered outcrops of acid rocks. Skeletal soils (regosols) deep gritty grayish brown sands (Woiylie SMU) and Woyerling soil with more mature profiles usually occur as well as the bare rock surfaces. Red soils, shallow or deep, occasionally occur, associated with small isolated outcrops of basic rock. Soil depth, colour, texture and content of ironstone gravels sometimes change significantly over short distances.

f_4 Mopoke SMU

Topography - generally gently dipping stony slopes and low stony ridges.

The soils - This unit occupies narrow linear outcrops of basic rocks with occasional acid rocks. Here much of the basic rock is unweathered, and occurs isolated between zone of highly variable soils. The soils range from shallow stony fine red earths and deep red earths to more sandy soils apron to isolated acid rock outcrops and the

PHOTO 5.10



Coarse textured soil of the Woiylie SMU - showing partially weathered rock at depth.

intergrades. Where the basic rock is quartz-rich (e.g. quartz dolerite) red or reddish brown light textured soils are dominant.

Profile description of soil on quartz-rich basic rock (T.70)

Site	Vegetation
- on the crest of an incipient rise; near the junction between Tuttanning Road and Bee-eater track.	Dominated by scattered wandoo; a few sheoak and jam.

0 - 10 cm Dark reddish brown (5 YR 3/4) sandy loam; weak crumb, friable.

10 - 30 cm Reddish brown (5 YR 4/4) sandy loam; loose, only slightly coherent, a few fragments of quartz and basic rock.

30 - 50 cm Yellowish red (5 YR 4/6) gritty sandy clay loam; soft, weak, fine, sub-angular, blocky to massive; a trace of quartz and basic rock fragments.

50 - 70 cm Yellowish red (5 YR 5/6) grit with some clay; a few rock fragments (continuing).

f_5 Gnow SMU

Topography - Topography is not a diagnostic criterion except where the unit occurs on gently sloping surface flanking quartz reef.

The soils comprise grayish to grayish brown compact sands, with high content of quartz gravels throughout the profile. The underlying fresh rock is usually quartz rich and acid. A variation within this unit is where abundant quartz fragments occur in loose sandy matrix 25-40 cm deep and rest over yellowish and reddish mottled sandy clays which

eventually give way at depth to partially weathered acid rock. This variant is essentially apron to massive quartz ridges.

3 (G) Units of the Drainage Floors

g_1 Wambenger SMU

Topography - Flat terrace-like surfaces by the sides of the major drainage lines.

The soils - These comprise brownish gritty sands with bleached A_2 horizon, a mottled B and waterlogging at the A-B interface. A few fragments of fresh to partially weathered rock are often contained in the sands.

Profile description of soil in Wambenger SMU (T.98)

Site	Vegetation
- on 0 - ½° flat, bordering to drainage line; at extreme north-west of the reserve.	Jam trees dominant; a few wandoo; under-growth of water loving plants.

0 - 15 cm Brown (10 YR 4/3) coarse sand; loose, non-coherent.

15 - 20 cm Brown (10 YR 4/3) coarse sand with very pale brown 10 YR 7/3. Coarse spotty bleach; loose, non-coherent.

20 - 75 cm Very pale brown (10 YR 7/3) coarse sand; moist, a few yellowish brown (10 YR 5/6) mottles; a trace of fresh rock fragments.

75 cm + A perched water table; waterlogged soil below which is pale brown (10 YR 6/3) gritty light clay, massive, compact, hard; a few ironstone gravels at the interface.

g_2 Hotham SMU

Topography - Some drainage floors.

The soils consist of a complex of soils most of which are waterlogged for about 6 months in the year. They are essentially gritty sands and loamy sands over clay at depths ranging from 40 - 80 cm. Fresh rock outcrops may occur in the unit while bog iron ore may be present in the subsoil.

g_3 Quail SMU

It is deep sandy and waterlogged soil with surface efflorescence of soluble salts. It is associated with the major drainage line of the Hotham.

General Comment

From the material presented above, it is apparent that the grouping of units into those occurring on the elements of the "old" plateau surface and those occurring on the elements of the "new" plateau surface though helpful in understanding the distribution of the soils, is not entirely without limitations. For example, though massive duricrust and yellow sand deposits are associated with the old plateau surface, they are not completely absent on the new plateau. In certain situations yellow sand deposits extend from high level situations to cover parts of the new plateau downslope. (See also Chapter VI and Map 1, in map flap.)

CHAPTER VI

THE NATURE AND ORIGIN OF THE YELLOW AND THE GRAY SANDS

A number of proposals as to the origin of the extensive bodies of sands in Western Australia known as sand plains have been put forward. These have been discussed in the literature review but may be summarized as follows:

1 The sand plains have formed *in situ* and constitute the upper part of the laterite profile (Prescott 1931; Carroll 1939; Prider 1966).

2 The yellow sands are deposits (detrital) derived by transport of materials weathered from lateritic ferruginous zones (Mulcahy and Hingston 1961; Mulcahy 1964; Bettenay and Hingston 1964).

3 The gray sands are derived from lateritic pallid zones (Mulcahy and Hingston 1961).

4 Yellow sands in much of south-western Australia are aeolian in origin, i.e. they originate from the drier country to the east and were transported to their present sites during arid phases by the process of saltation (Glassford and Killigrew 1976; Killigrew and Glassford 1976).

Two main types of sand plains have been shown to occur at Tuttanning (Chapter II) namely, those dominated by yellow sands and those dominated by gray sands, referred to in this thesis as the Possum and Echidna sands respectively. In addition, coarse sandy materials forming aprons to the granite outcrops are another important component of surficial materials.

This study is an endeavour to characterize both the yellow sands and the gray sands and to draw conclusions as to their origin by means of particle shape (rollability) and particle size (granulometric) analyses together with field investigation. Sands of known provenance (sands on aprons flanking granite outcrops) were also analysed and used mainly as reference material. Since diagnostic data in the literature on detrital material is lacking much of the study was directed towards uncovering any aeolian characteristics that may be present in the deposits. It was thought that in this way evidence might be used to determine or elimate at least one mode of deposition namely, by aeolian activity.

Location of the investigated sand bodies

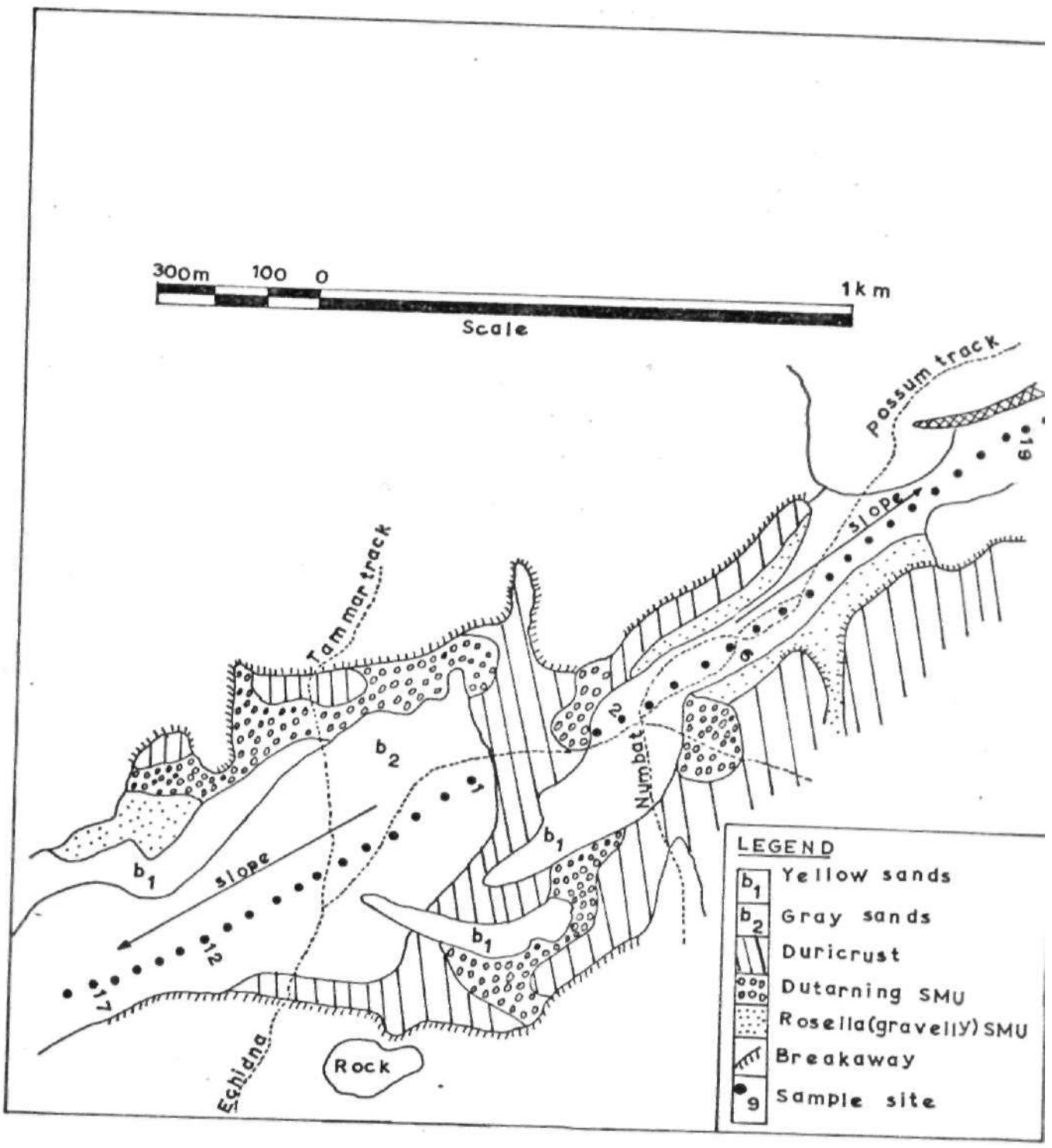
Figure 6.1 shows the location and aerial extent of the sand bodies investigated in detail and their relationship to other soil mapping units, tracks and the breakaways. A zone of duricrust separates the gray sand body from the yellow sand body. The gray sand body slopes towards the SW, and is about 660 metres long while the yellow sand body slopes towards the NNE and is about 800 metres long. The sands occupy broad, gently sloping concavities described in the chapter on geomorphology. The direction of slope has been indicated by arrows and sample sites as dots.

Results of Rollability Measurements

The results of rollability measurements on Tuttanning sands are presented below and in the appendix in tables, shape distribution character diagrams, scatter diagrams and trend diagrams.

Fig. 6.1.

LOCATION AND SAMPLE SITES FOR THE ECHIDNA-TAMMAR TRACK GRAY SAND AND THE POSSUM TRACK YELLOW SAND.



Repeatability of Measurement

Tables 6.1(a) and (b) (in appendix 1) show that, when a sample is run through the rollability instrument several times, the resulting measurements have a repeatability of less than 2% difference. Fig.6.3 (in appendix 1) shows that the difference in absolute rollability values between identical sieve fractions of different samples of Tuttanning sands generally exceeds 25%. Crushed calcite which is usually very angular (and which was used as reference material) has very high absolute rollability values. Glass beads (spherical and also used as reference material) have very low absolute rollability values. The absolute rollability values for Tuttanning sands are lower than those for crushed calcite and higher than those for glass beads. They increase with decrease in grain size, which is consistent with the observations of Winkelmolen (1969a).

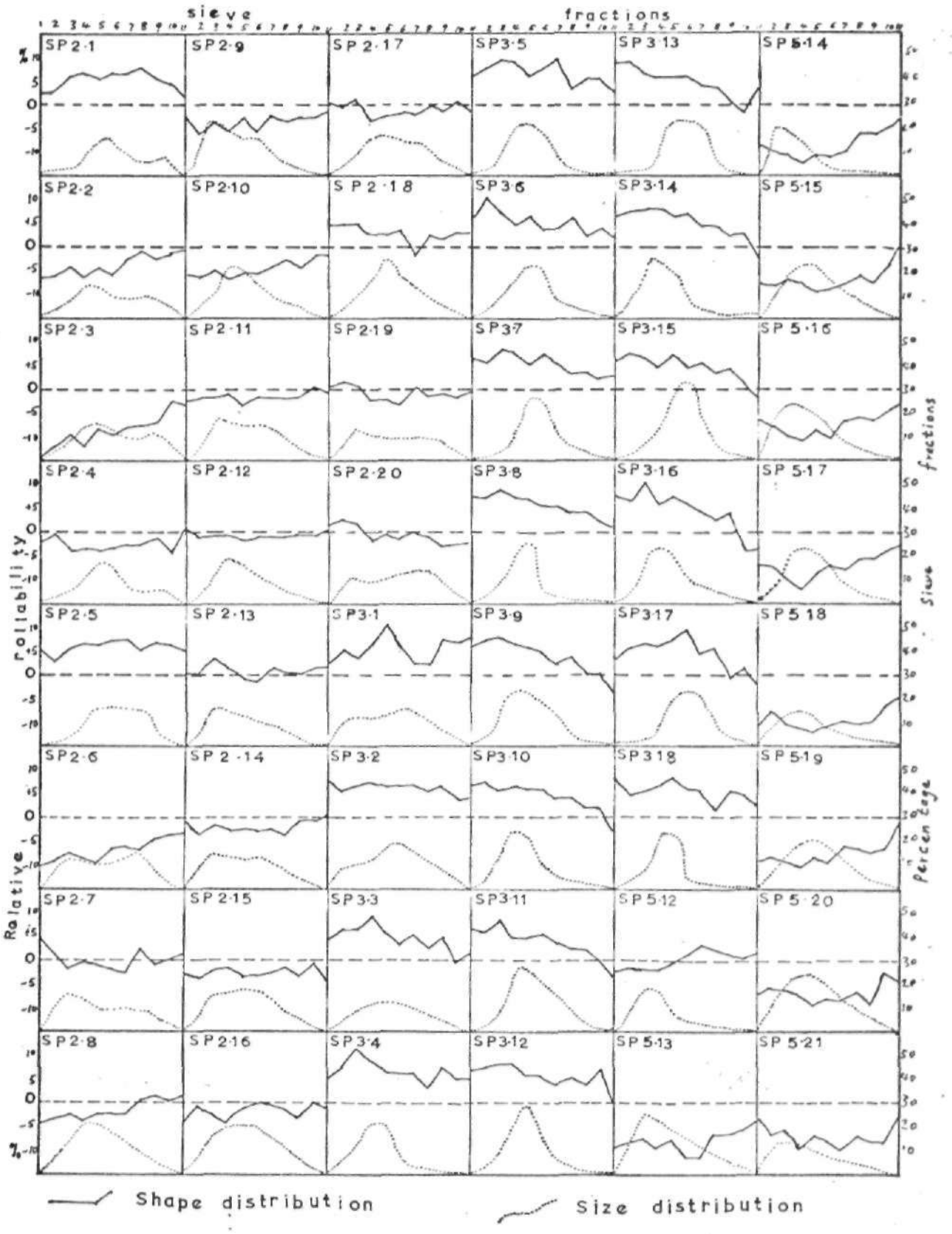
Shape Distribution Character Diagrams

Figure 6.4 shows the shape distribution character (SDC) diagrams and grain size distribution per sample for yellow sands, gray sands and rock apron sands. When compared with Winkelmolen's SDC diagrams the following results are obtained. Of the twenty yellow sand samples (sp 2.1 to 2.20) five have rising curves (R-curves), two have down-sloping curves (D-curves), there is one bridge-type curve (B-curve) and one valley shaped curve (V-curve). The remaining eleven are horizontal curves (H-curves) which are non-diagnostic. The R-curves are associated with the samples at the upslope end or beginning of the sand body, while the D-curves occur at the lower end of the sand body, thus showing complementary characteristics.

Of the 18 gray sand samples (sp 3.1 to sp 3.18), 16 have D-curves and the remaining two have H-curves. These H-curves represent samples

Fig 6.4

Shape distribution character diagrams per sample



taken at the upslope end of the gray sand body. It will be recalled (Winkelmolen 1969a) that R-curves indicate that deposition is currently taking place (accretion); D-curves indicate that the deposit is lag (i.e. mainly losing material). Rock apron samples have R-curves which is expected of an environment that is currently receiving material.

Scatter Diagrams

Figures 6.5, 6.6 and 6.7 are scatter plots for relative rollability values. The transformation of absolute rollability values to relative rollability values has already been explained in Chapter III under procedures. Figure 6.5 shows the distribution of relative rollability values for yellow sands and gray sands. Here, apart from two measurements in the fine sands which fall between -1 and zero, all other measurements for gray sands are positive, the majority of which fall between +4 and +7%. The most relatively rollable sample has a value of +10.3%.

The yellow sands on the other hand show much greater spread in relative rollability values, i.e., the values stretch from low negative through zero to high positive. There is, however, a noticeable concentration of values between -1 and -5. Extreme values for yellow sands are found at +7.4 and -12%. The above results show that, though gray sands are generally more rollable than yellow sands, a scatter plot cannot separate the two.

The plot of gray sands with rock apron sands (Fig. 6.6) shows that apart from the fine fraction of 150- 90μ in a few samples these sands occupy clear cut fields, the gray sands being much more rollable than the rock apron sands. A plot of rock apron sands with gray sand samples collected from another gray sand body gave similar results (Fig. 6.7).

Fig. 6.5. A PLOT OF YELLOW SANDS AND GRAY SANDS

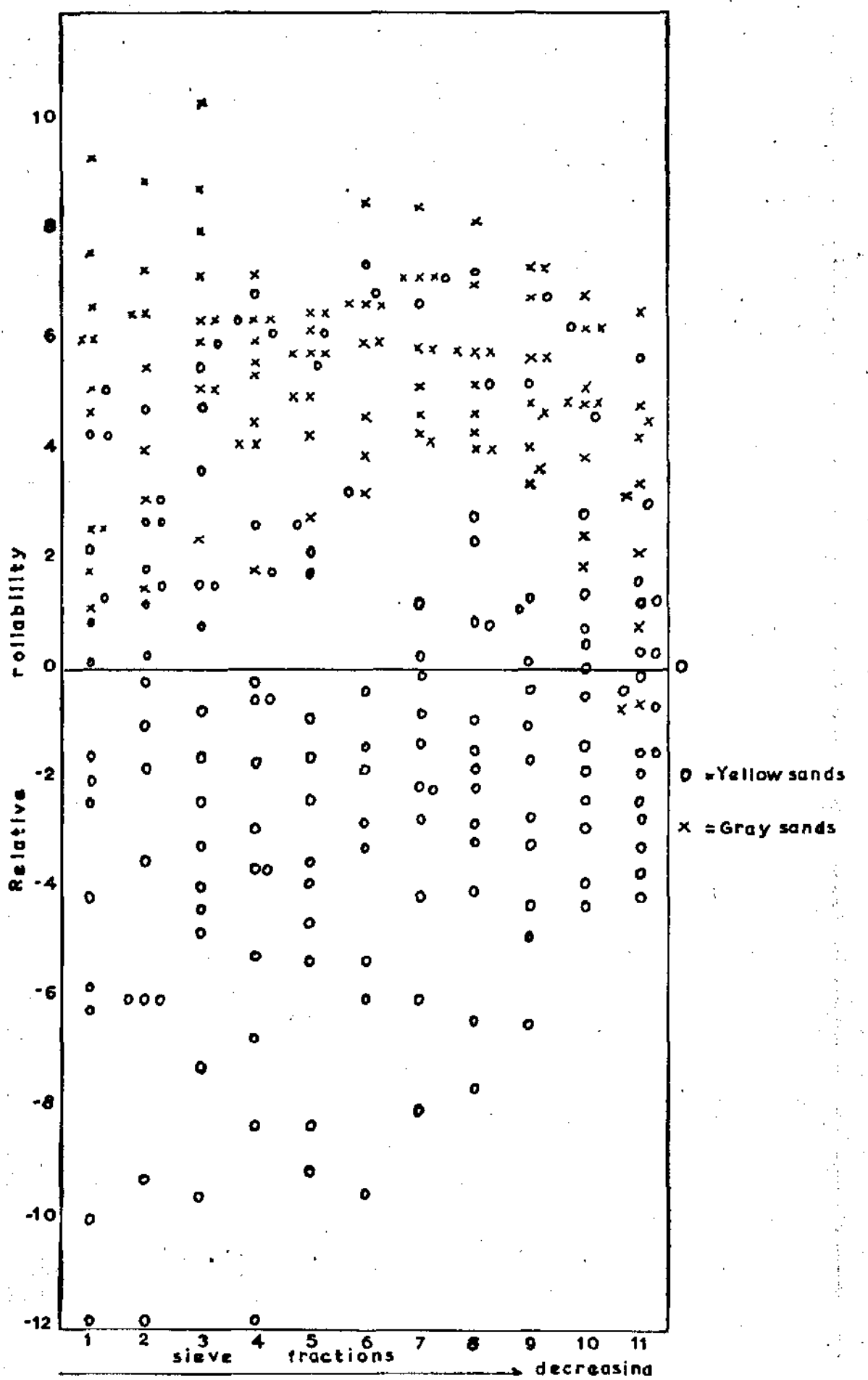


Fig. 6.6. A PLOT OF ROCK APRON SANDS AND GRAY SANDS I

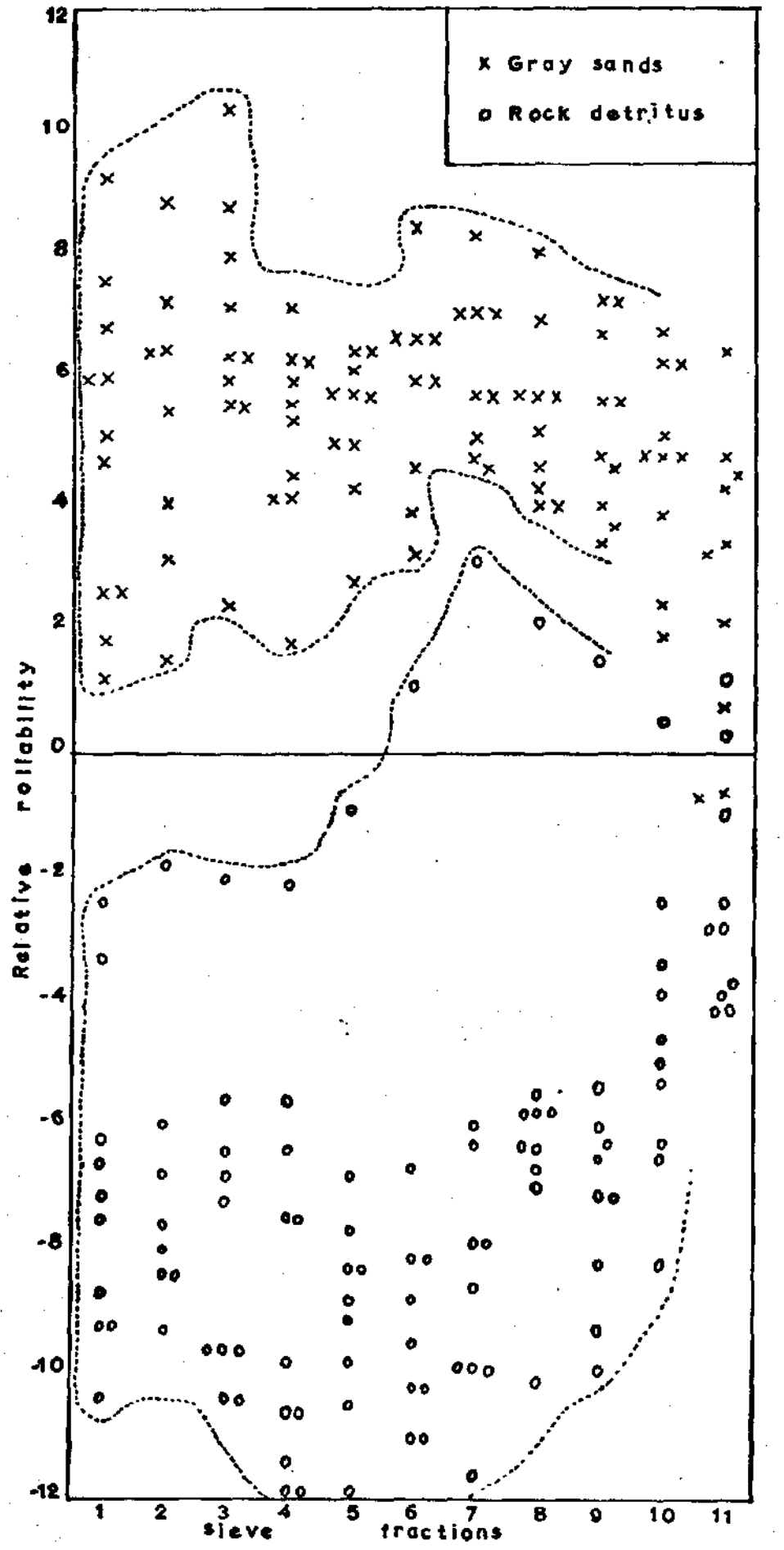


Fig. 6.7. A PLOT OF ROCK APRON SANDS AND GRAY SANDS II

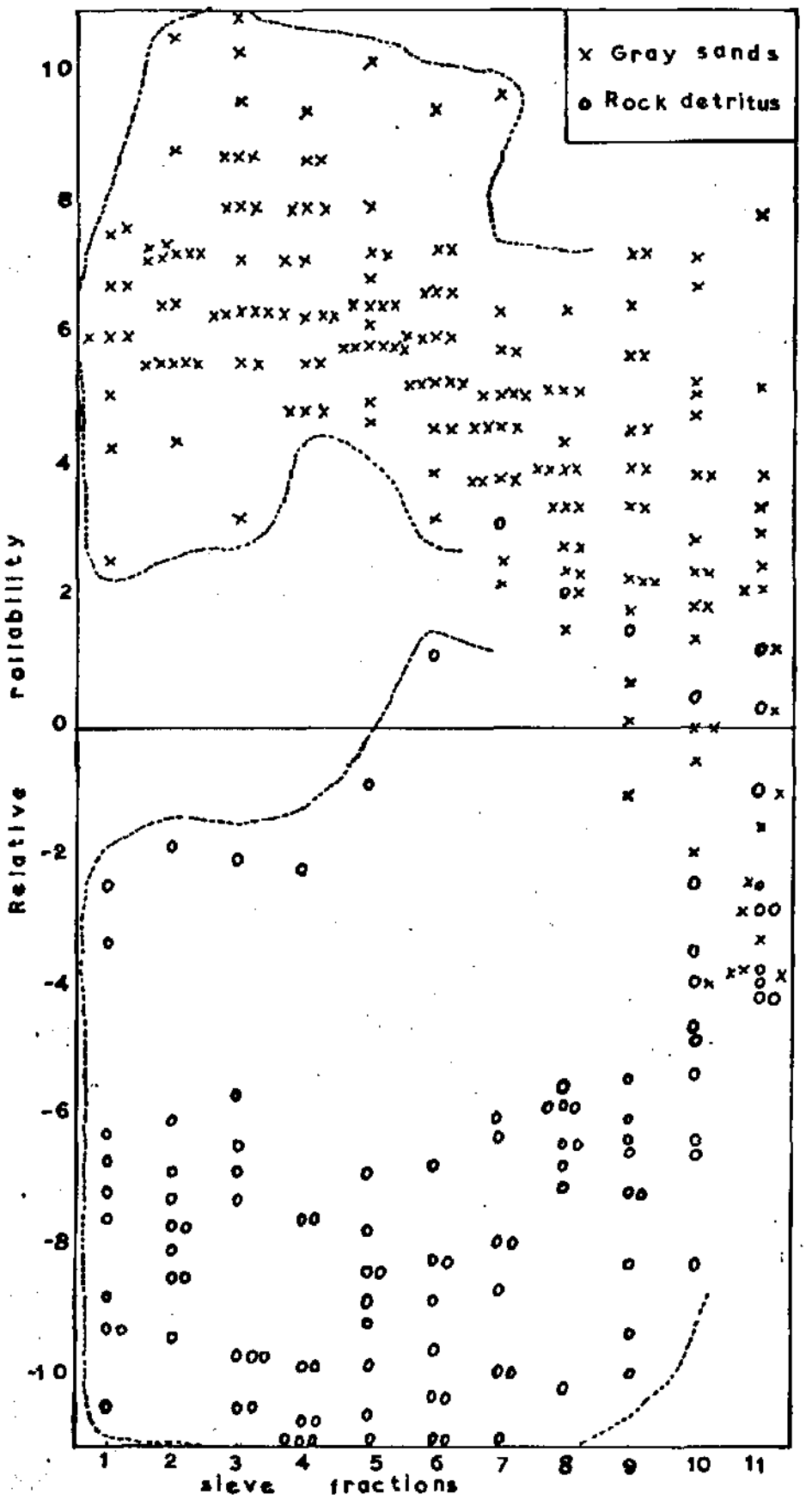


Fig. 6.8. A PLOT OF ROCK APRON SANDS AND YELLOW SAND.

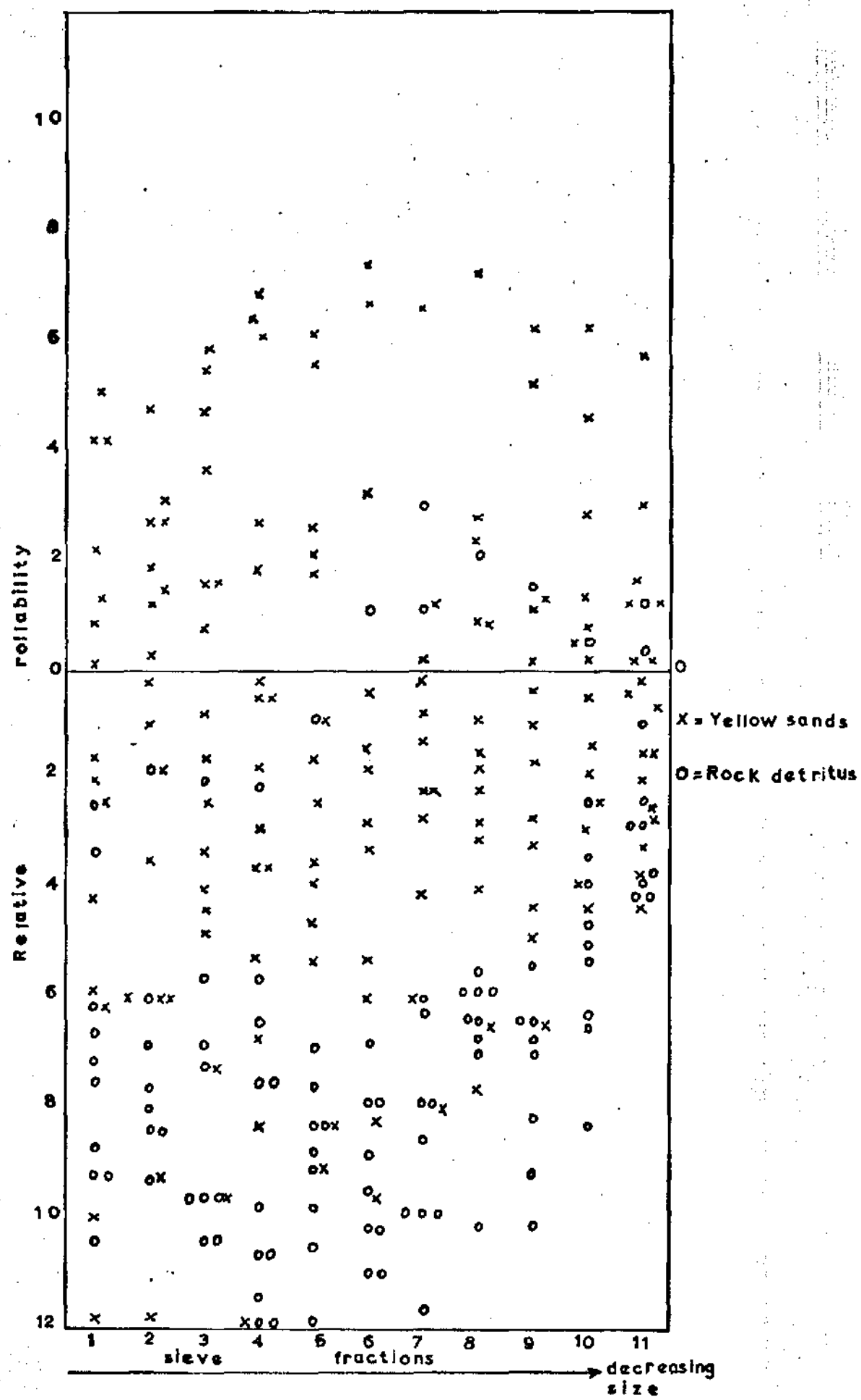


Figure 6.8 shows that a plot of yellow sands with rock apron sands does not completely separate the two. However, rock apron sands are generally more poorly rollable than yellow sands, and most of the values for the former fall between -6 and -10%.

It appears that differences in relative rollability between the various types of sands are greater in the coarser fractions.

Deposit-Repository Investigations*

Figure 6.9 shows two curves obtained by plotting the mean relative rollability value per sieve fraction for the first ten samples (upslope) of the yellow sand body and the last ten samples (downslope). These curves nearly overlap in the finer fractions but in the coarser fractions the curves are far apart. The relative rollability values for the coarser fractions show that samples from the downslope half of the sand body are much more rollable than those from the upslope half of the sand body. The curves produced from the means of the first three (upslope) samples and the last three samples demonstrate these differences more clearly (Fig. 6.10).

One may deduce from the above data that transport of sand has taken place downslope; that for the coarser sand grains shape selection took place during transport and the more rollable grains were transported in preference to the less rollable grains which dominate the upslope end of the sandbody. For the finer grains, the transporting mechanism was competent enough to transport grains regardless of shape.

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*A 'repository' is a concept introduced by Kuenen (1964) which is valuable for developing an understanding of shape-sorting. (See Chapter II - literature review)

Fig. 6.9.

COMPARISON OF THE ROLLABILITY VALUES OF THE FIRST TEN WITH THE LAST TEN SAMPLES OF THE YELLOW SAND SPILLWAY (Sp.2)

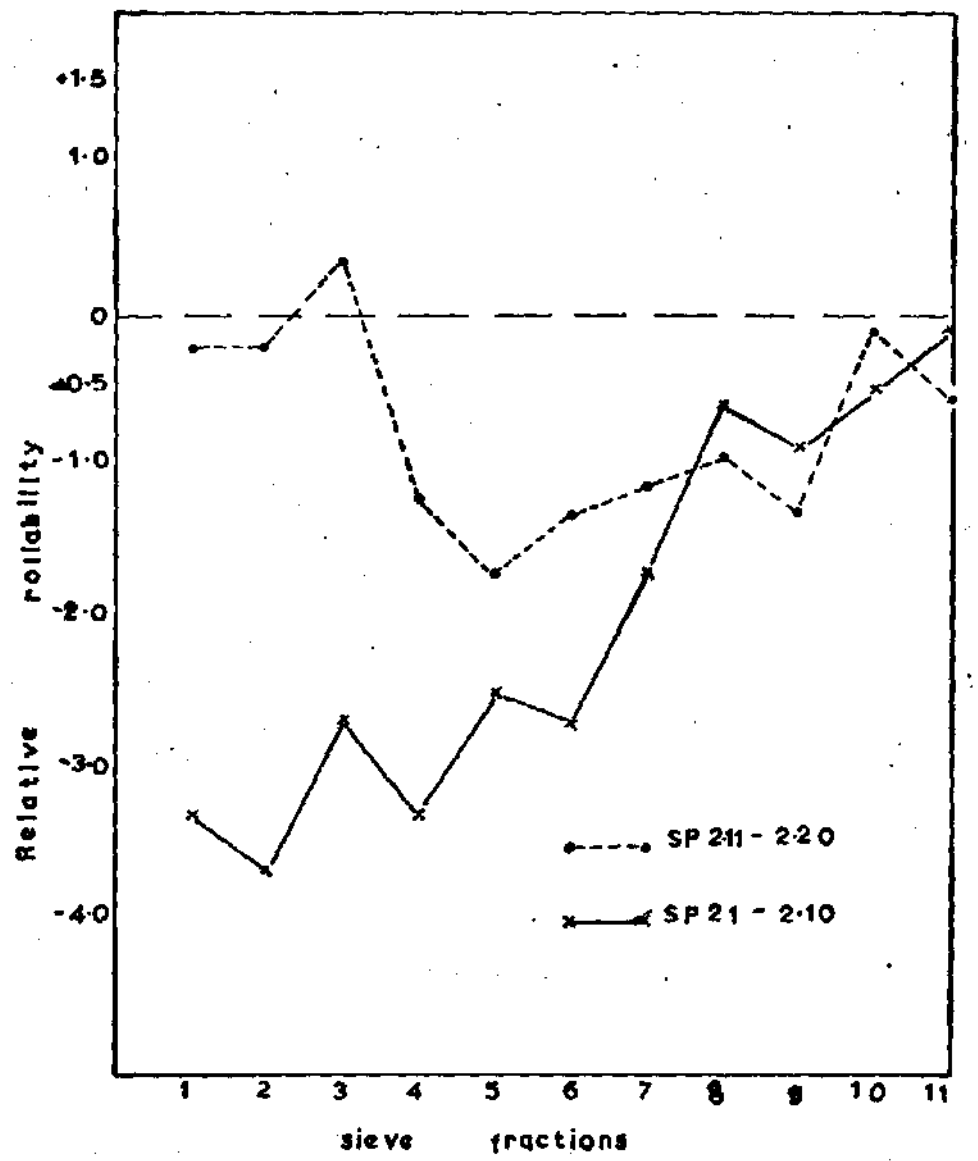
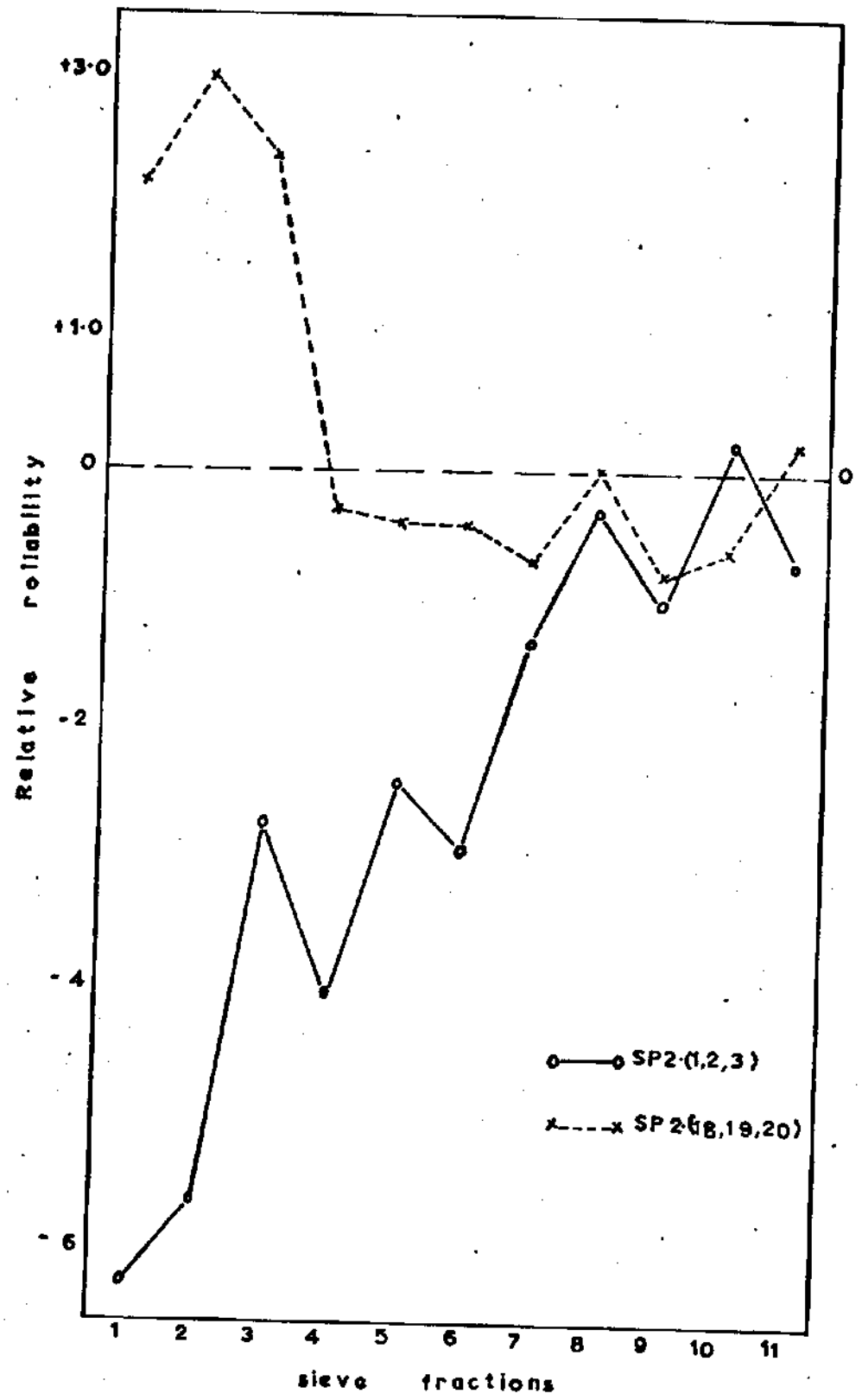


Fig. 6.10:

COMPARISON OF THE ROLLABILITY VALUES OF THE FIRST THREE WITH THE LAST THREE SAMPLES OF THE YELLOW SAND SPILLWAY.

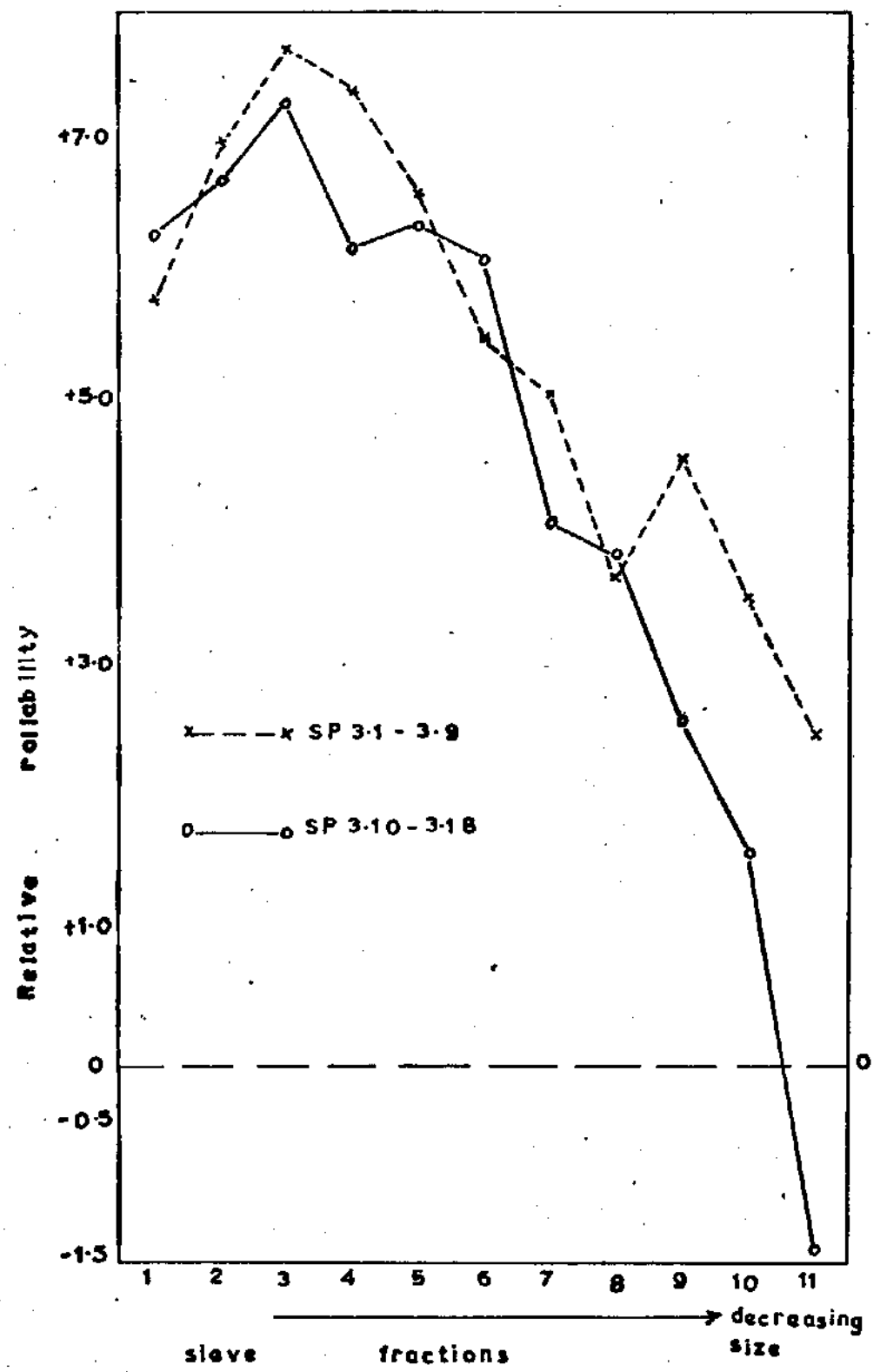


The plot of the mean relative rollability values for the first nine (upslope) samples of the gray sands and the last nine (Fig. 6.11) shows results opposite to those obtained for yellow sands. Here the curves almost overlap in the coarser fractions but are far apart for the fines. Similar results are obtained (Fig. 6.12, appendix 1) when the mean relative rollability for the first three (upslope) samples of gray sand body are plotted with the last three at the downslope end of the traverse. These results for gray sands indicate that, for the coarser sand grains, no significant change in rollability occurs with distance downslope. The finer sand grains of the upslope end are more rollable than those at the downslope end of the traverse. Hence, if these differences in rollability have been caused by shape selection during transport, this would mean that for the fines the less rollable grains have been transported downslope in preference to the more rounded. The coarser grains have probably not experienced any significant movement downslope since deposition, probably due to the low competence of the transport mechanism (running water) over highly porous sands.

The transport of rollable coarse grains in preference to less rollable coarse grains and the transport of less rollable fine grains in preference to rollable fine grains is generally in agreement with the views of Macarthy (1933), Lundahl and Pettijohn (1943). Winkelmolen (1974) in his 'working hypothesis for shape interpretation' indicated that "for the particles that are transported in suspension or in large saltations (fine sand grains) a good rollability will in general be unfavourable for transport, since their settling velocities are relatively high, which means more bottom contacts and therefore more chance to get trapped in the interstices of the coarser bottom sediment".

Fig. 6.11.

MEAN RELATIVE ROLLABILITY FOR THE FIRST NINE SAMPLES (UPSLOPE) OF THE GRAY SAND BODY COMPARED WITH THAT OF THE LAST NINE SAMPLES (DOWNSLOPE)



Rollability trend down the assumed direction of transport

Figures 6.13, 6.14, 6.15 and 6.16 show the rollability trends downslope of the yellow sand and gray sand bodies for the coarse and fine fractions. Here, averages for every three adjoining samples are used with a view to eliminating local irregularities. In this way, a clearer picture of the trend is obtained than when the more variable individual sample values are used (Winkelmolen 1974).

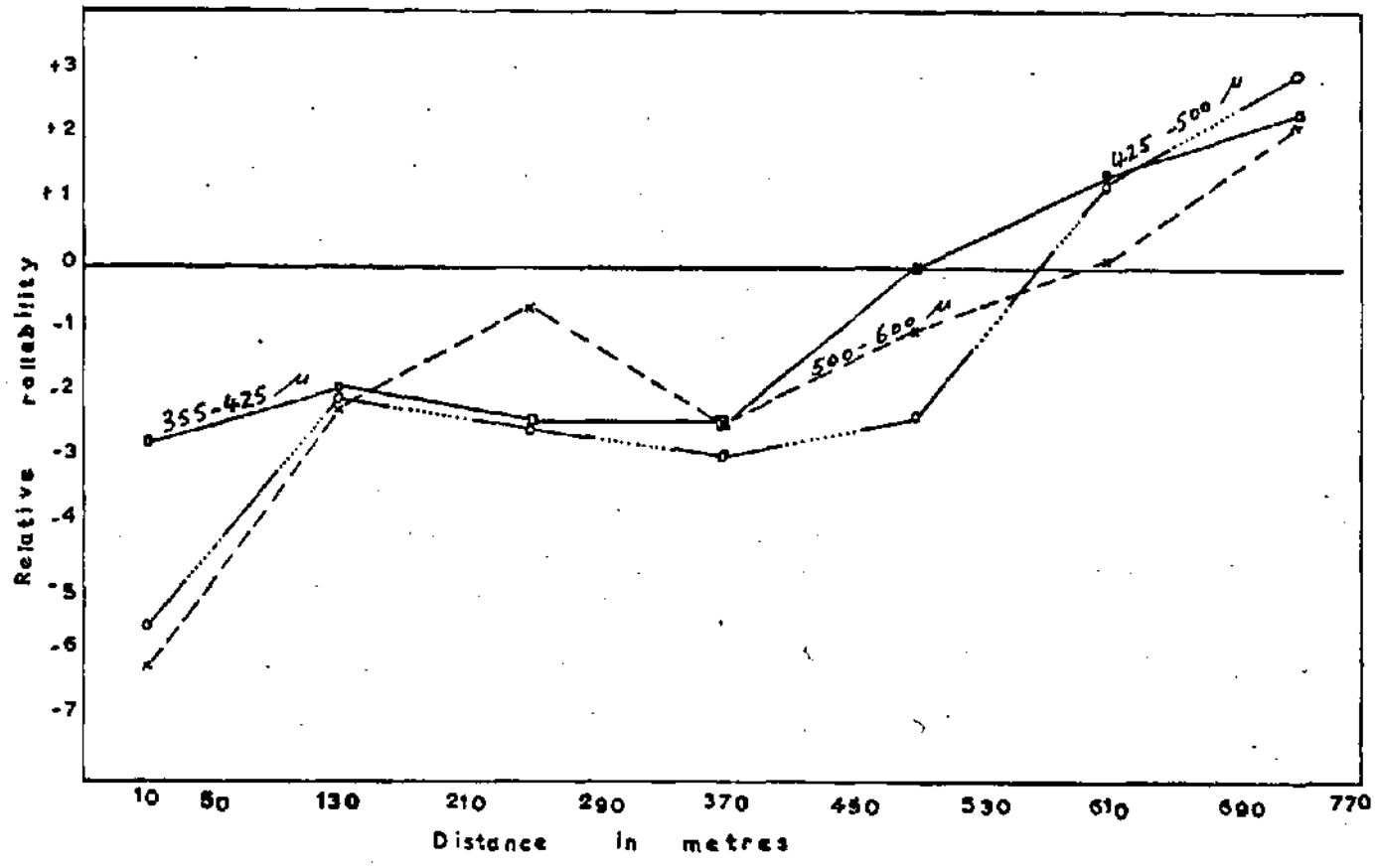
Figure 6.13 shows that for the coarse fractions of the yellow sands, rollability improves gradually with distance downslope. Rollability at the upslope end of the yellow sand body is poor, and negative (-6 to -2.7%) while that at the downslope end is relatively higher, and positive (+2.2 to +3%). For the fine fractions of the yellow sand (Fig. 6.14) no significant change in rollability occurs with distance downslope. The rollability values generally fall close to the zero line though there is a slight bias on the negative side.

Trend diagrams for the gray sands show almost the reverse of what is reported above for yellow sands. Figure 6.15 shows that for the coarse and modal sieve fractions for gray sands there is no systematic change in rollability downslope. All samples have high relative rollability values which range from +4.8 to +9.3%. For the fine fractions (150-90μ) of gray sands (Fig. 6.16) a gradual decrease in rollability with distance downslope is obtained. Relative rollability values for the fine sands at the upslope end of the gray sand body range from +3.4 to +6.1%, while values for the downslope end range from -0.5 to +2.8%.

Photomicrographs of successive time fractions

Figures 6.17(a) and (b) contain scanning electron photomicrographs of successive time fractions of the 300-355μ interval (magnification 67 times) of yellow and gray sand samples in order of emergence from

FIG. 6.13 ROLLABILITY TREND DOWN YELLOW SAND SPILLWAY (Sp.2) FOR THE COARSE SIEVE FRACTIONS (600–500μ, 500–425μ, 425–355μ), USING MEAN VALUES FOR EVERY THREE ADJOINING SAMPLES.



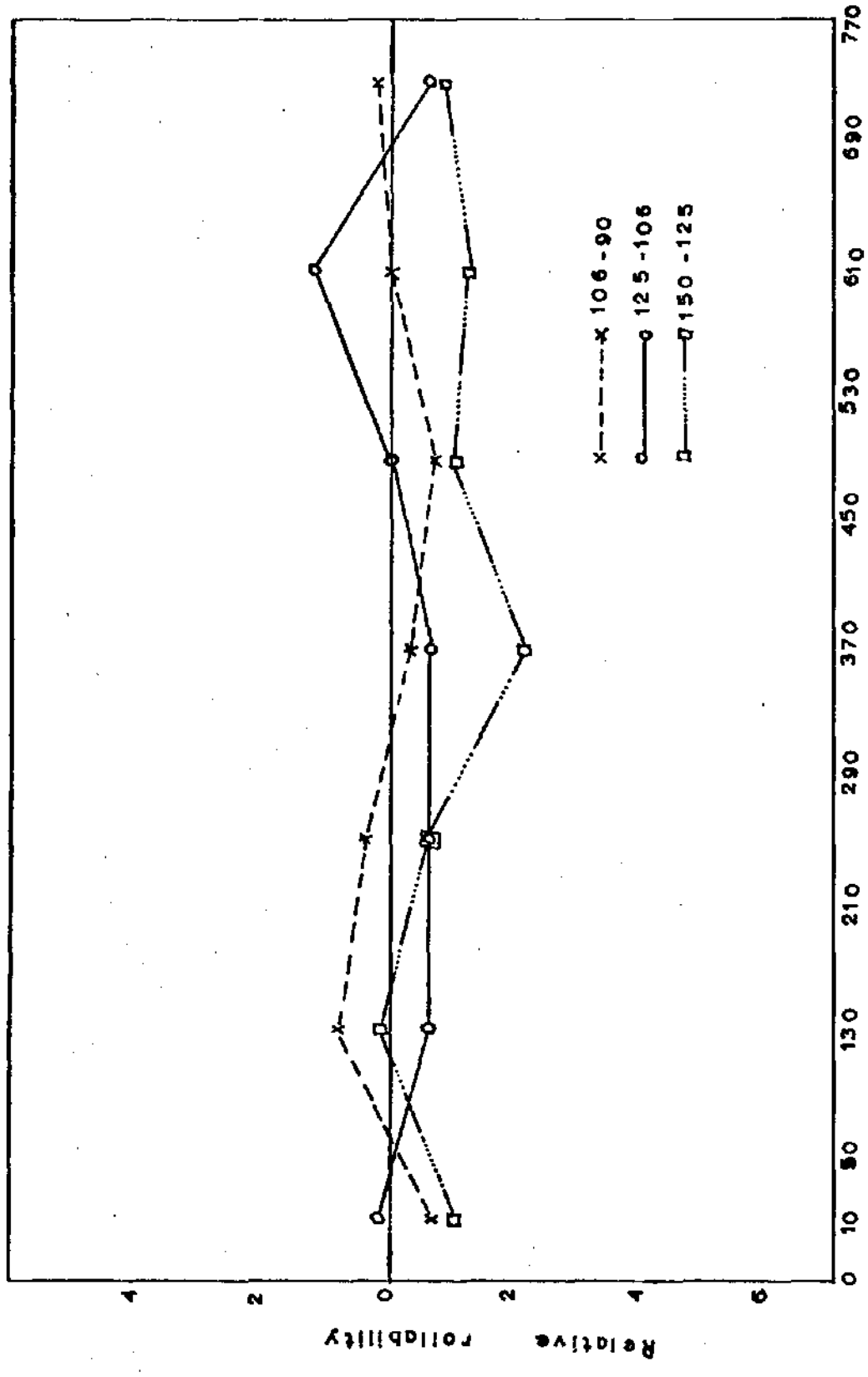


Fig. 6.14

ROLLABILITY TREND DOWN YELLOW SAND SPILLWAY (Sp.2) FOR THE FINE SIEVE FRACTIONS - USING MEAN VALUES FOR EVERY THREE ADJOINING SAMPLES

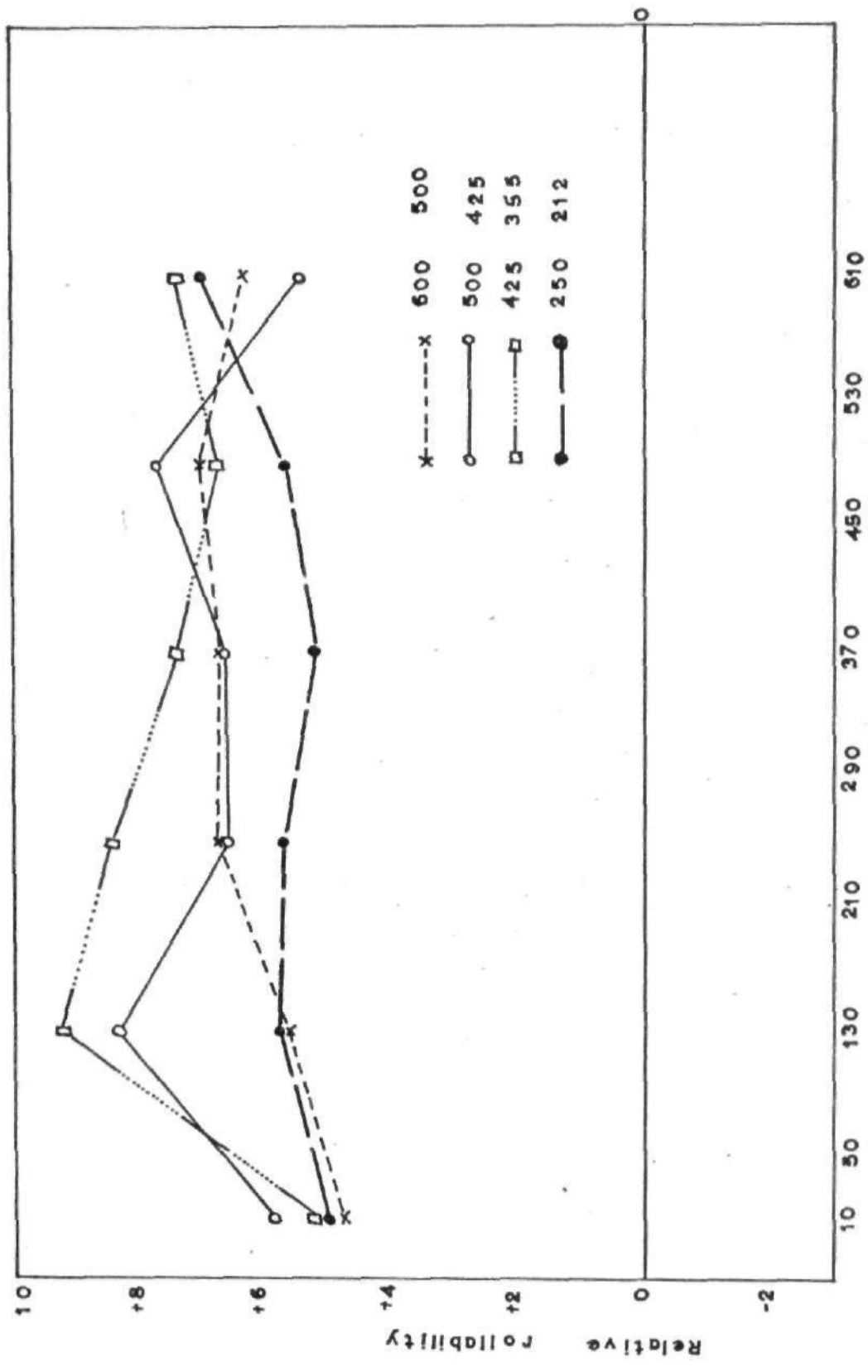
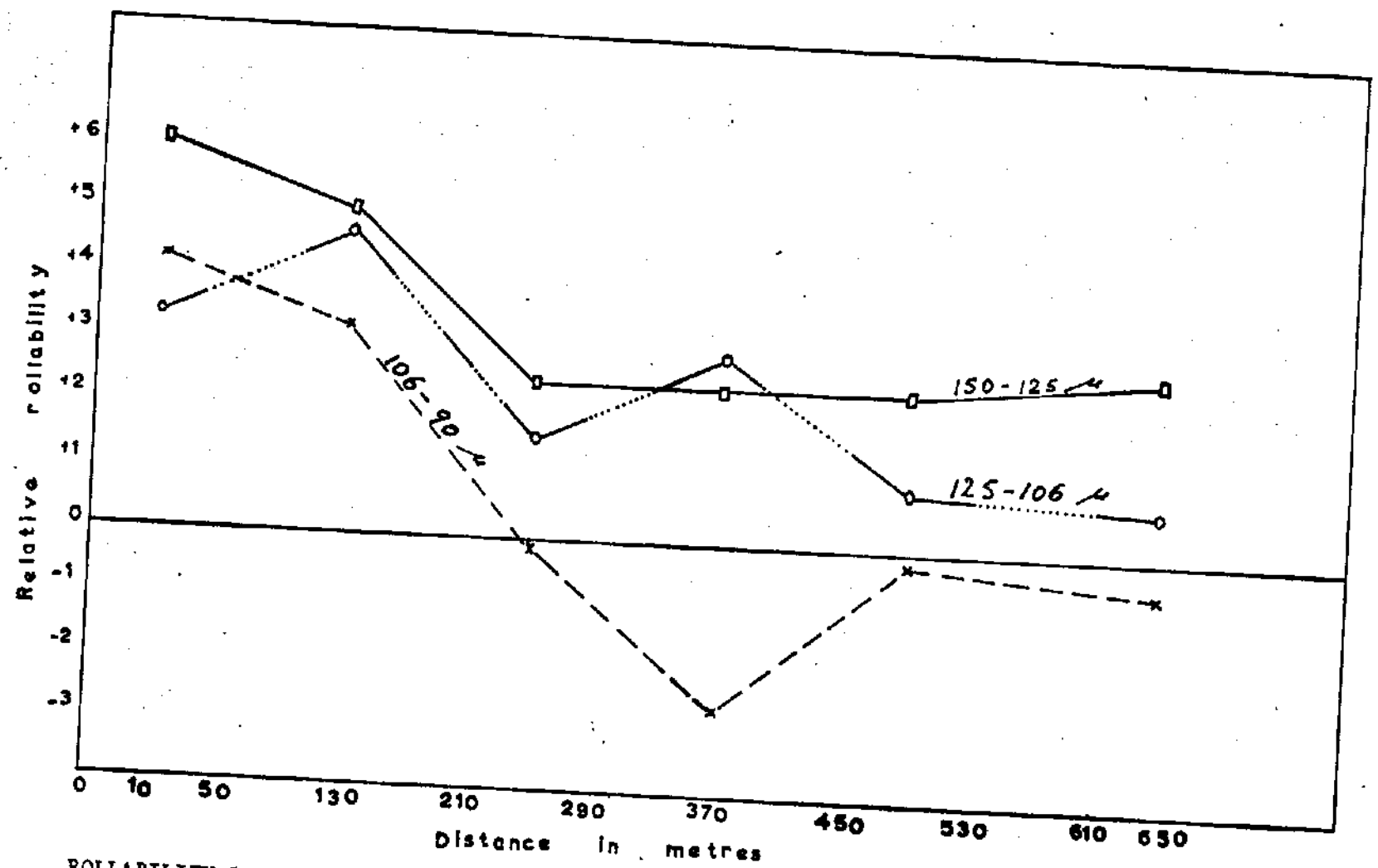


Fig. 6.15

ROLLABILITY TREND DOWN ECHIDNA/TAMMAR ROAD GREY SAND (Sp.3) FOR THE COARSE AND MODAL SIEVE FRACTIONS - USING MEAN VALUES FOR EVERY THREE ADJOINING SAMPLES.

Fig. 6.16



ROLLABILITY TREND DOWN ECHIDNA/TAMMAR ROAD GREY SAND (Sp.3) FOR THE FINE SIEVE FRACTIONS (150-125μ, 125-106μ, 106-90μ) USING MEAN VALUES FOR EVERY THREE ADJOINING SAMPLES.

Photomicrographs of successive time fractions of the 300-355 sieve interval.

FIGURE 6.17(a) Yellow Sands

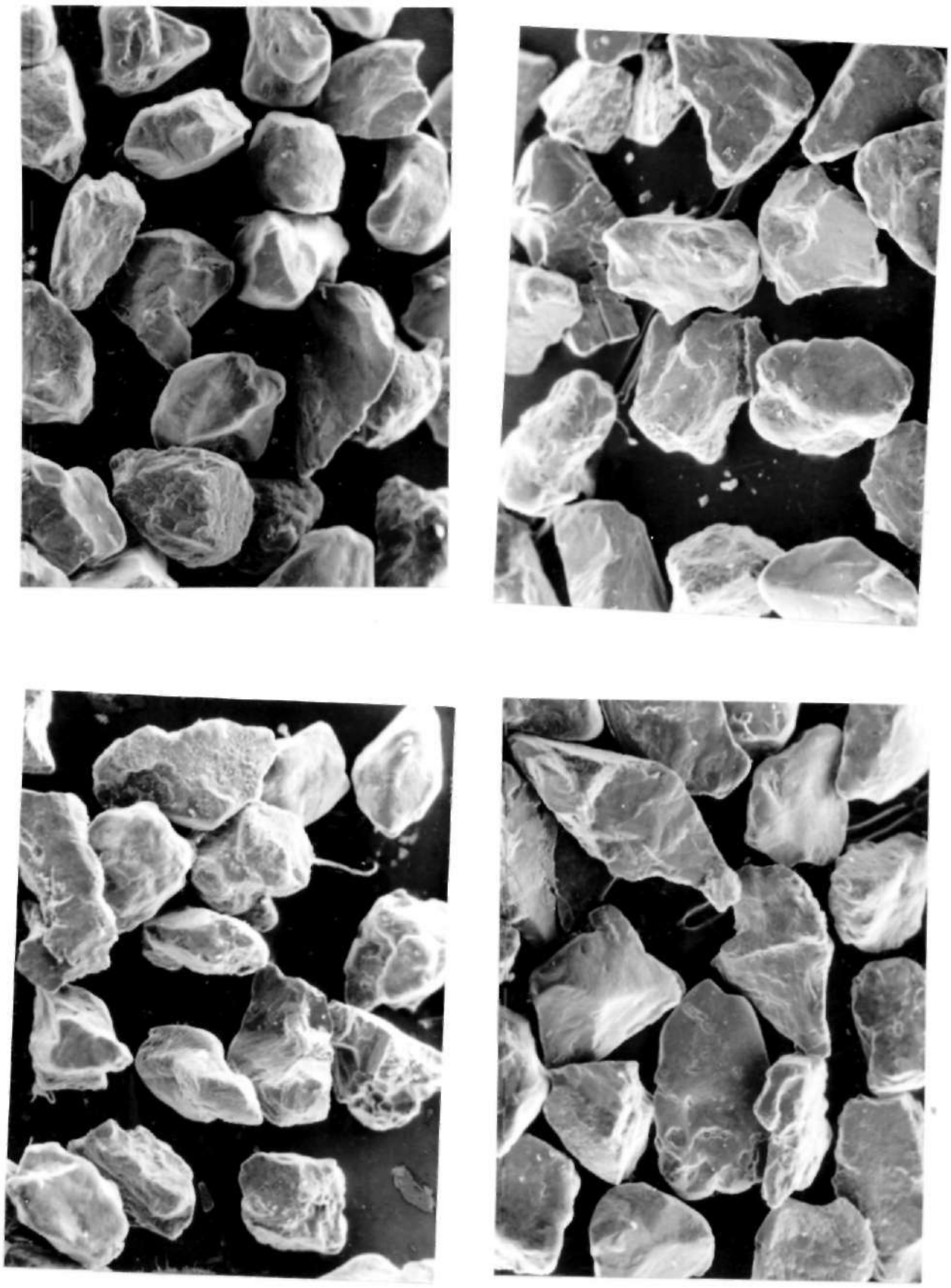
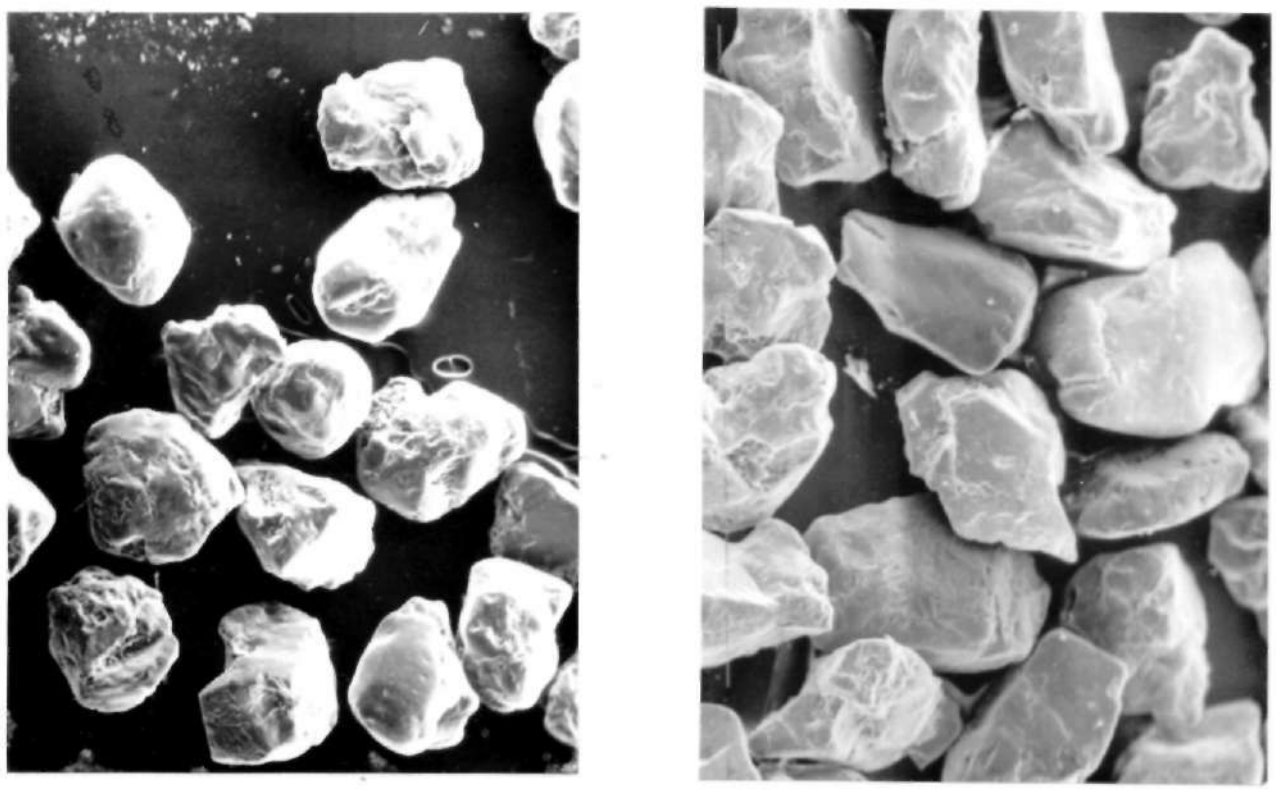


FIGURE 6.17(b) Gray Sands



the rollability apparatus. The photomicrographs demonstrate visually the effect of shape sorting. The most rounded grains in the sample travel fastest and emerge first from the rollability instrument.

More importantly, the photomicrographs show the high angularity of the yellow sand grains in contrast to those of the gray sands, which is consistent with the results of the rollability measurements. Time fractions 4 and 5 for yellow sands contain grains of low sphericity, some of which have long to short axis ratio of approximately 3:1. Most of the grains for the gray sand sample are sub-rounded with much lower long to short axis ratios than the yellow sands, though the former also have abundant surface features (pits, valleys, breakage lines, etc.) which were probably inherited from the mechanical fracture of the quartz crystals during sand formation.

Results of granulometric analyses

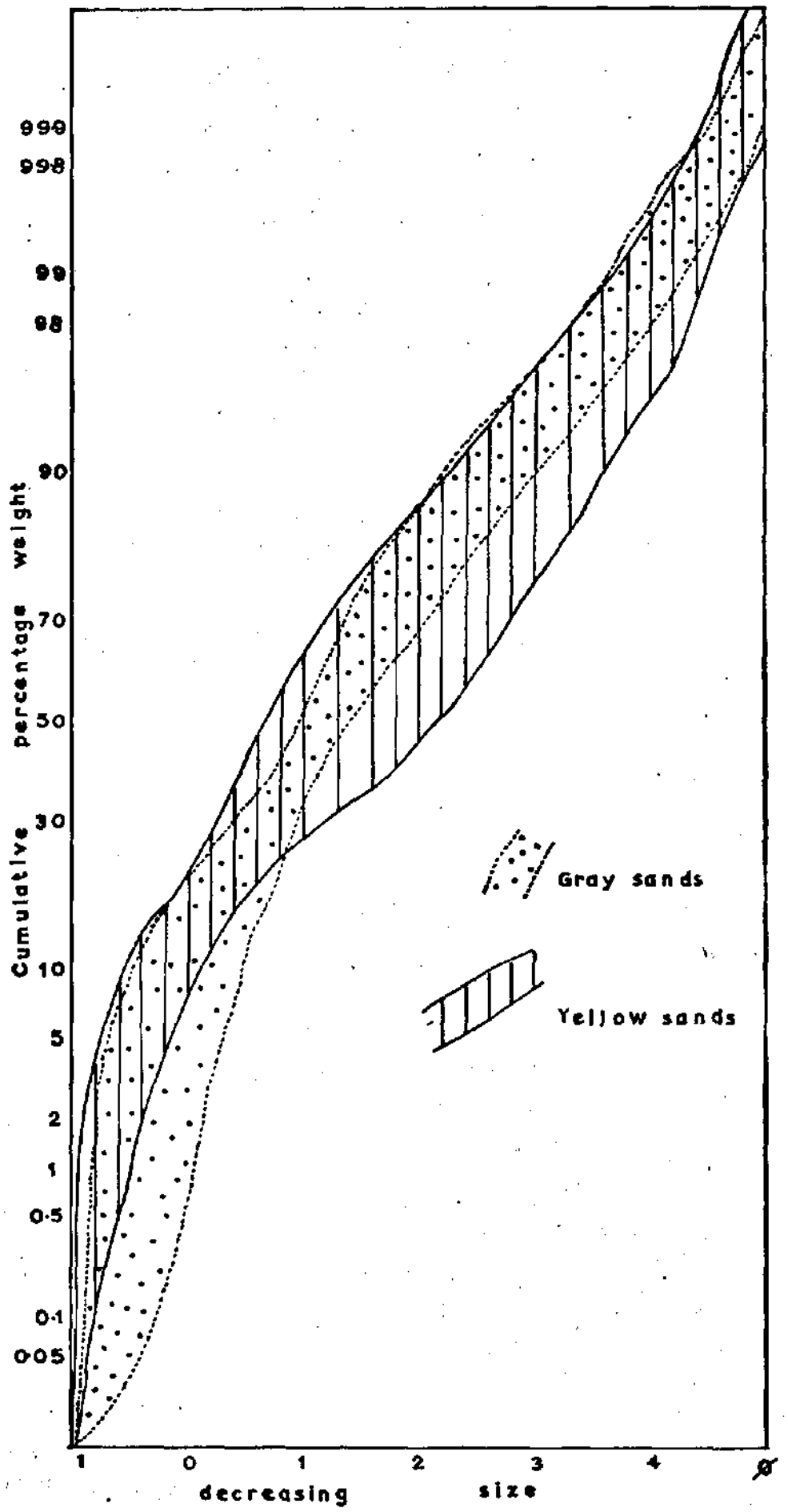
The methods used in arriving at and presenting the data below have already been treated in Chapters II and III (Literature Review and Methodology) where the grain-size parameters (mean, standard deviation, skewness, kurtosis) which are frequently referred to in this chapter are defined. The results of the analyses are presented in graphs (cumulative curves, frequency graphs, trend graphs, scatter graphs) and tables.

Cumulative Curves

The fields occupied by the cumulative curves of yellow sand samples and gray sand samples plotted on probability are shown in Fig. 6.18. None of the samples show normal particle distribution, i.e. *a normal sample would plot out as a straight line* (Inman 1952). The diagram also shows that the field occupied by the cumulative curves for yellow sands does not exactly overlap that for gray sands. The yellow sands tend to occupy a much greater field in the less than

Fig. 6.18

FIELDS OCCUPIED BY THE CUMULATIVE CURVES OF POSSUM YELLOW SANDS (20 SAMPLES) AND ECHIDNA GRAY SANDS (17 SAMPLES)



400μ section than the gray sands. The gray sands occupy a much wider field in the greater than 400μ section. None of the samples analysed showed a dearth of material in any of the sieve fractions (2000μ to <63μ).

Frequency distribution diagrams

Figure 6.19 shows the frequency distribution for the particle size parameters (mean, standard deviation (sorting), skewness and kurtosis) at the specified class intervals. The mean-size distribution for yellow sand samples occupies a wide field ranging from 0.6ϕ to 1.8ϕ with a 30% peak at 1.2 to 1.4ϕ. The mean size values for gray sands occupy a much narrower field with a prominent 70% peak at 1.2 - 1.4ϕ interval.

Standard deviation values show a 47% peak at 0.8 to 1.0ϕ interval for gray sands and a 50% peak at 1.0 to 1.2ϕ interval for yellow sands. Again it is the yellow sands that show a wider spread. Yellow sands have skewness values ranging from -0.2 to +0.3 with a 35% peak at +0.1 to +0.2 interval. Skewness values for gray sands are all positive with a prominent 71% peak at +0.2 to +0.3 interval.

The kurtosis diagram shows that most of the yellow sand samples have lower kurtosis values than the gray sands. The former has a 40% peak between K_G 0.9 and 1.0 and the latter a 50% peak between K_G 0.9 and 1.0 and the latter a 50% peak between K_G 1.1 and 1.2 and no values between K_G 0.9 and 1.0. Thus the yellow sand samples are either mesokurtic or platykurtic (Folk and Ward 1957) with the majority of the values below normal (unity). Most of the gray sand samples are leptokurtic with kurtosis values above normal. It is only in the kurtosis values that gray sands show a wider spread than yellow sands.

Fig. 6.19

FREQUENCY DISTRIBUTION FOR PARTICLE SIZE PARAMETERS FOR 20 YELLOW SAND SAMPLES AND 17 GRAY SAND SAMPLES (AFTER FOLK & WARD 1957)

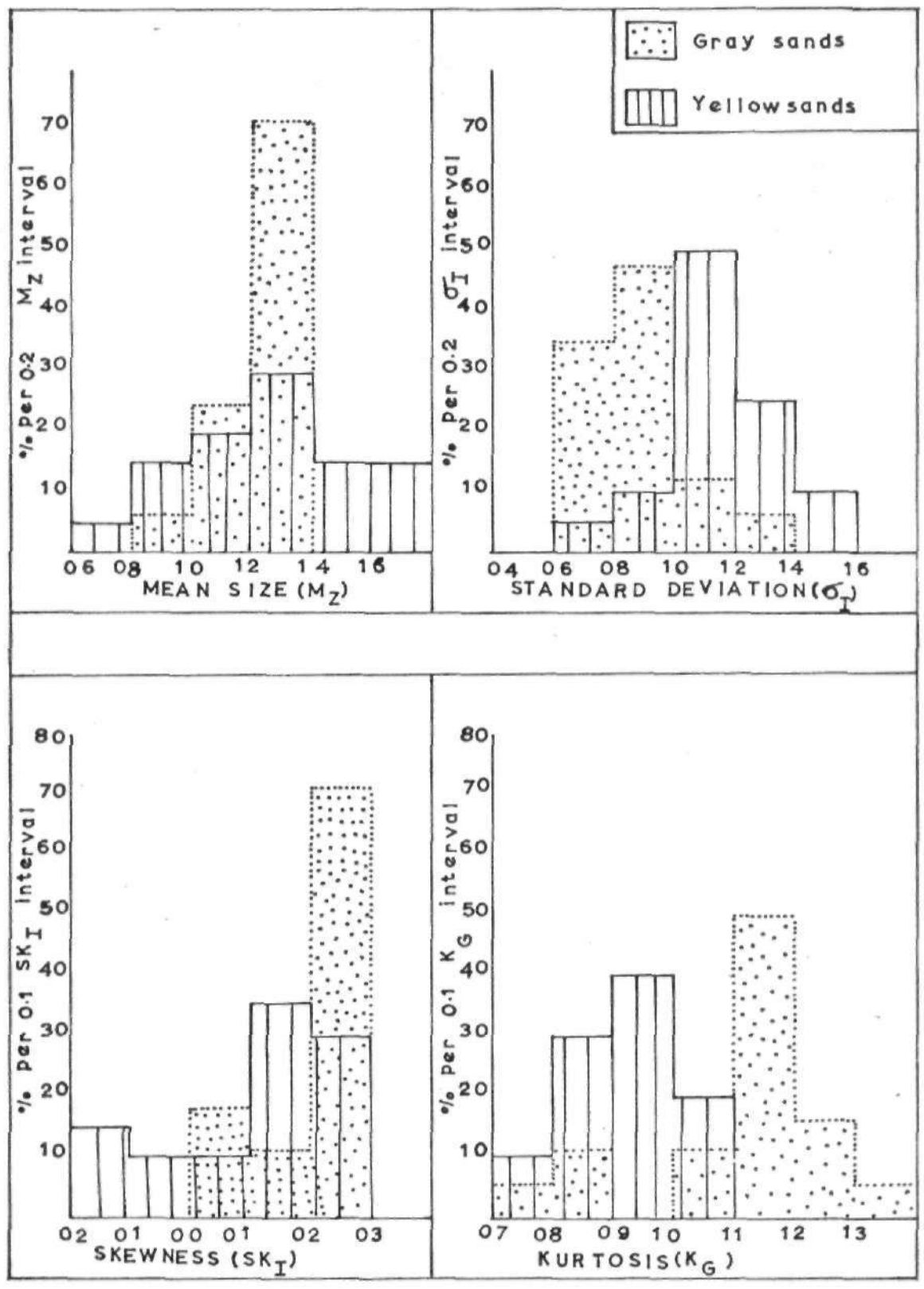


Figure 6.20 comprises frequency curves constructed from % weights of fraction (½ ϕ interval) for the samples at the upper end and the downslope end of the yellow and gray sand bodies respectively. The curves show the very poor sorting, lack of prominent peak and bi-modality associated with samples at the upslope end of both sand bodies and particularly the yellow sands. Samples near the lower end of both yellow sands and gray sands are much better sorted with modes in the 1000-710μ and 710-500μ ranges respectively, indicating that these sands are generally high in coarse grains (>400μ).

The frequency curves in Figure 6.21 represent samples taken at the specified distances downslope of the sand sheets. Here the yellow sand samples again display bi-modality. Both yellow sand and gray sand samples show better sorting and greater peakedness down-slope than upslope.

Scatter plots

Figure 6.22 is a plot of mean grain size (M_z) against standard deviation (σ_I) for yellow sands and gray sands together with sands of known provenance (rock apron sands). The rock apron sands are clear-ly segregated from both yellow sands and gray sands. Most of the gray sand samples occupy a small area of this plot (M_z 1.1 to 1.4 ϕ and σ_I 0.7 to 1.0 ϕ). The yellow sands on the other hand display marked lack of clustering and spread out along both the M_z and σ_I axes.

Figure 6.23 is a plot of mean grain size against skewness for yellow sands, gray sands and rock apron sands. The plot segregates rock apron sands from both gray sands and yellow sands. There is a greater overlap of gray sands with yellow sands than was the case in Figure 6.22 above. Again it is the yellow sand values that spread out the most.

Fig. 6.20

FREQUENCY CURVES FOR YELLOW SANDS AND GRAY SANDS DISPLAYING THE POOR SORTING AT THE UPSLOPE END AND THE HIGH PEAKS TOWARDS THE DOWNSLOPE END OF THE SAND SHEETS.

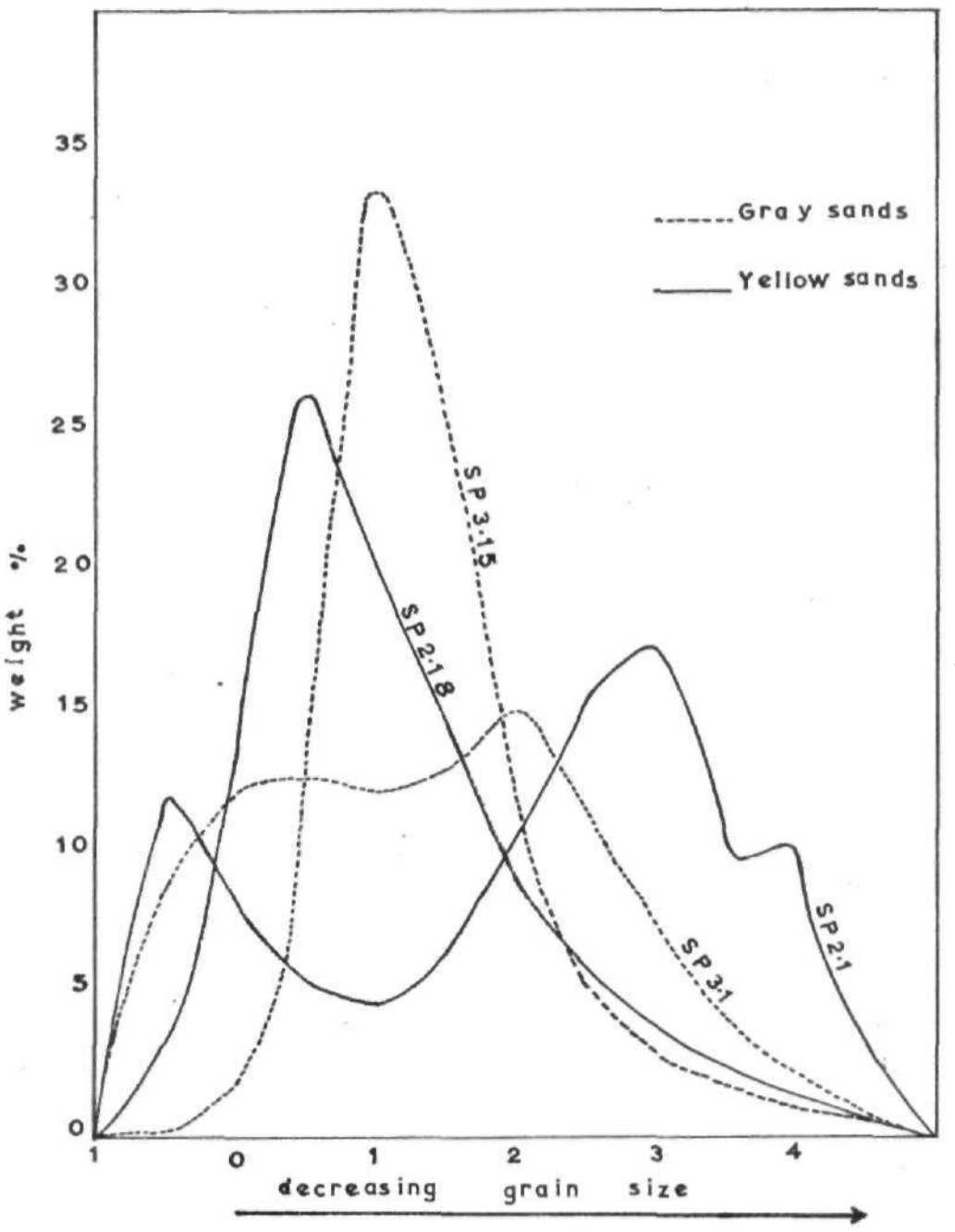


Fig. 6.22

A PLOT OF MEAN GRAIN SIZE (M_z) AGAINST STANDARD DEVIATION (σ_I) FOR YELLOW SANDS, GRAY SANDS AND ROCK DETRITUS.

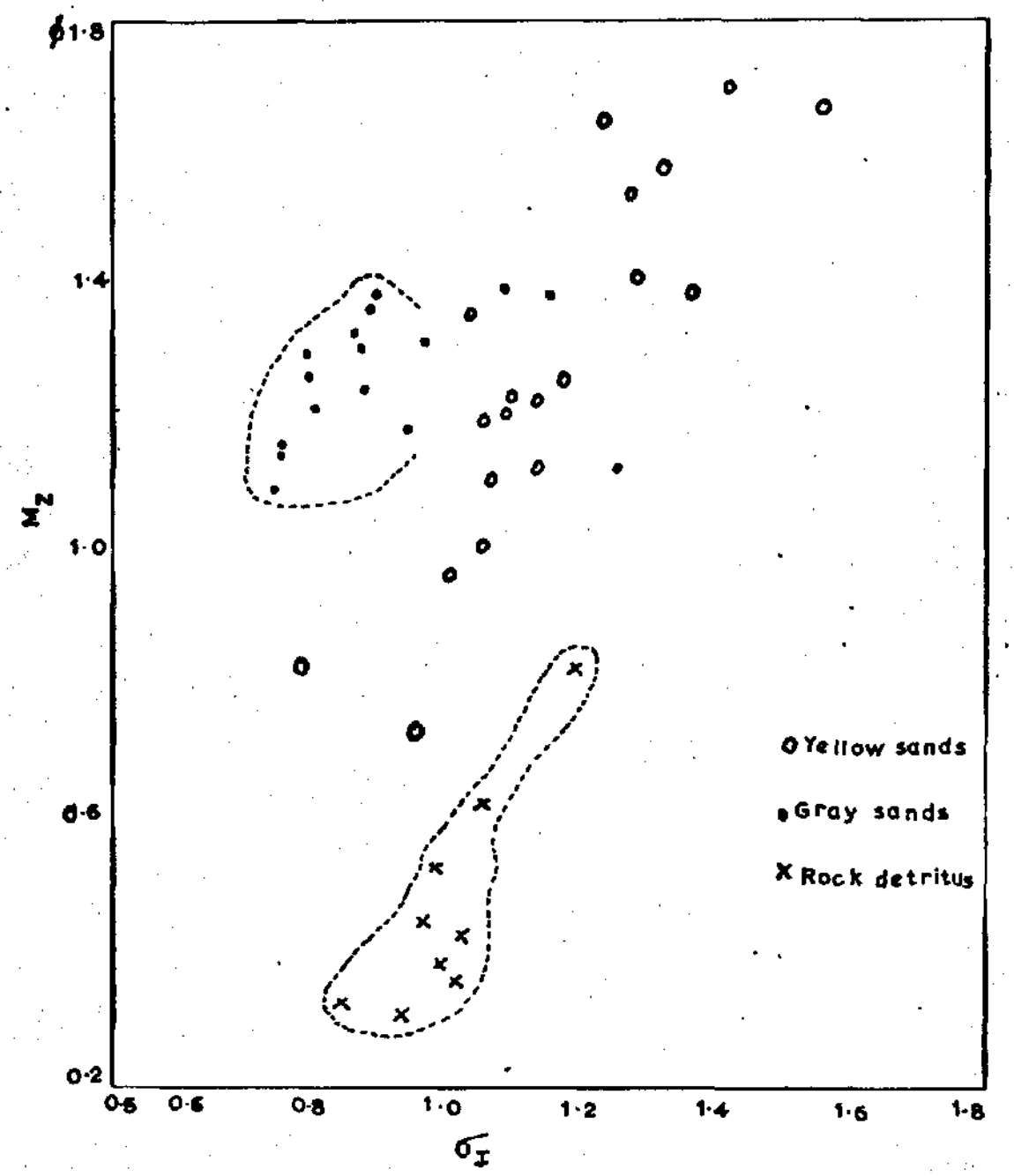


Fig. 6.23

A PLOT OF SKEWNESS (SK_I) AGAINST MEAN GRAIN SIZE (M_z) FOR YELLOW SANDS, GRAY SANDS AND ROCK DETRITUS.

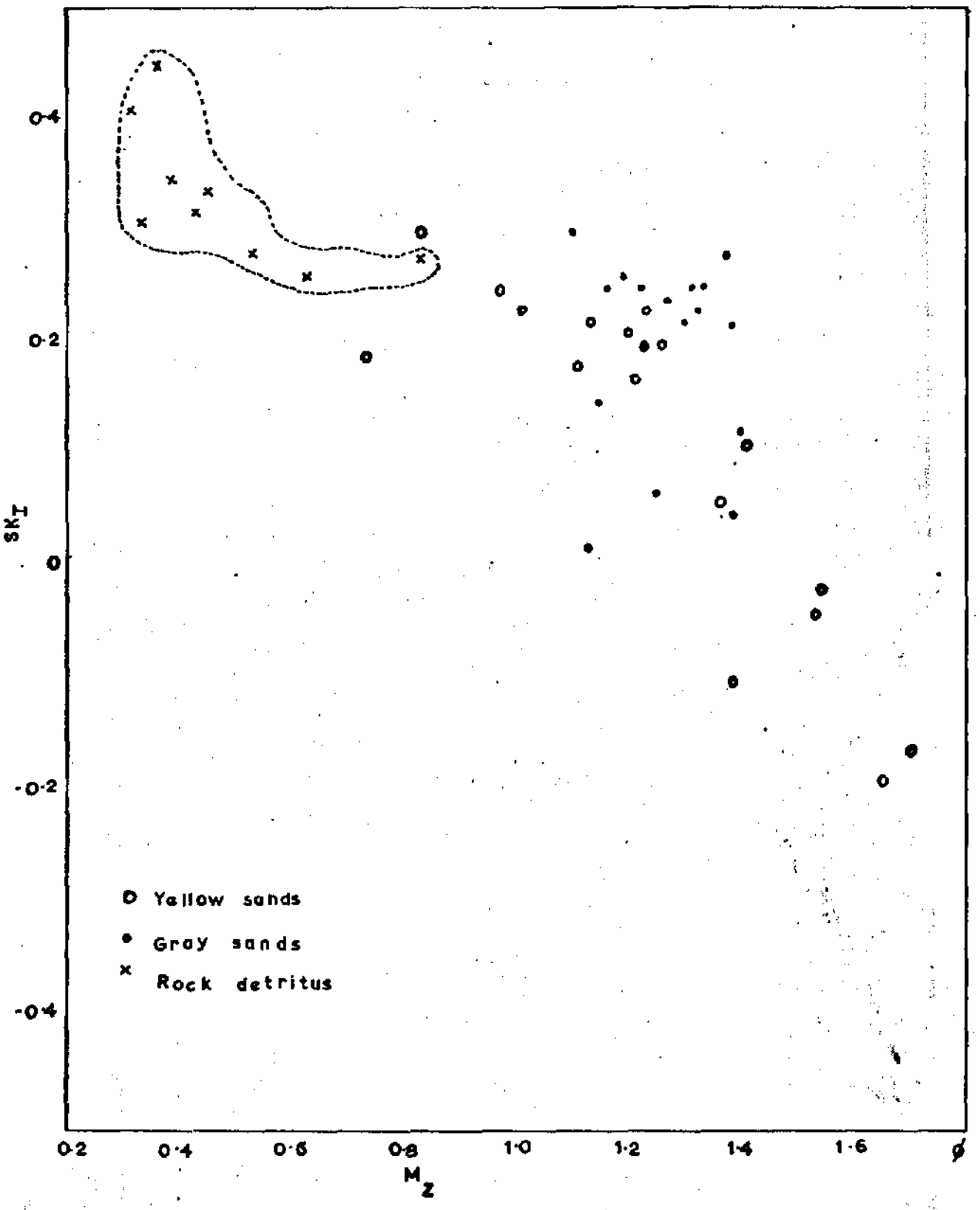


Figure 6.24 is a plot of mean grain size against kurtosis for the sands. As in the case above, a field made up exclusively of rock apron sands can be marked. Another field made up exclusively of yellow sands can also be marked, with gray sands falling on either side of this field.

Figure 6.25 (in appendix 2) is a plot of skewness against standard deviation which fails to segregate yellow sands from gray sands. The yellow sand values cover a wide territory, particularly along the SK_I axis.

In Figures 6.26 and 6.27 (in appendix 2) where standard deviation is plotted against kurtosis and skewness is plotted against kurtosis respectively, a field made up exclusively of yellow sands can be marked.

Trend diagrams

In Figure 6.28 standard deviation (sorting) values for yellow sands are plotted against their sample positions. Sorting tends to improve with distance downslope to 290 metres beyond which no systematic change in sorting occurs, most of the samples being poorly sorted (Folk 1966). The last two samples at the downslope end of the traverse are much more poorly sorted than the adjoining samples.

In Figure 6.29 mean grain size values for yellow sands are plotted against their sample positions. Mean grain size increases with distance downslope and reaches a maximum around 290 metres, beyond which it decreases with increasing distance. Such a change in the mean-size trend (at around 290 metres downslope) may sometimes coincide with a break of slope in the valley. However, there was no such break in this case.

Fig. 6.24

A PLOT OF MEAN GRAIN SIZE (M_z) AGAINST KURTOSIS (K_{GI}) FOR YELLOW SANDS, GRAY SANDS AND ROCK DETRITUS.

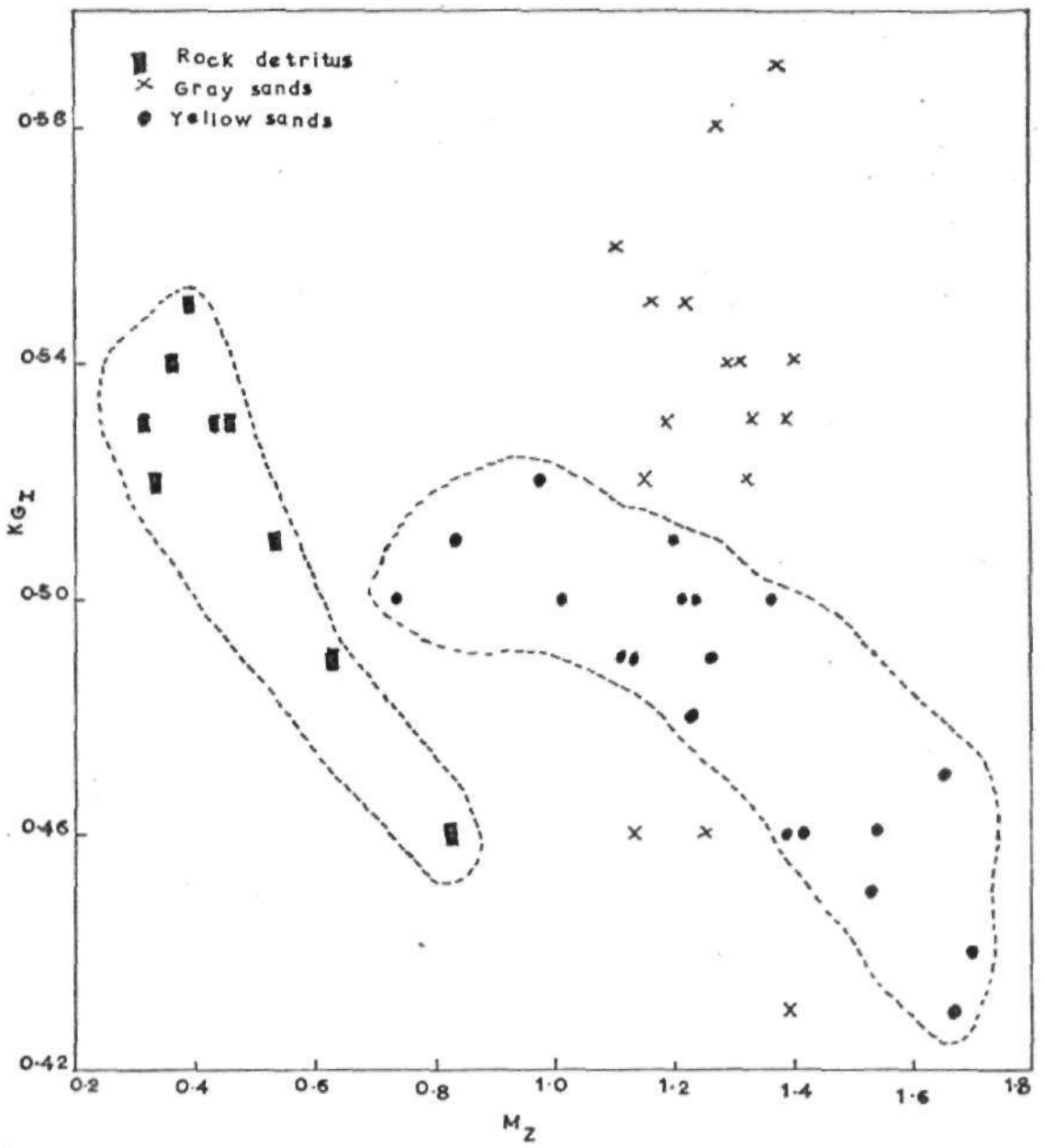
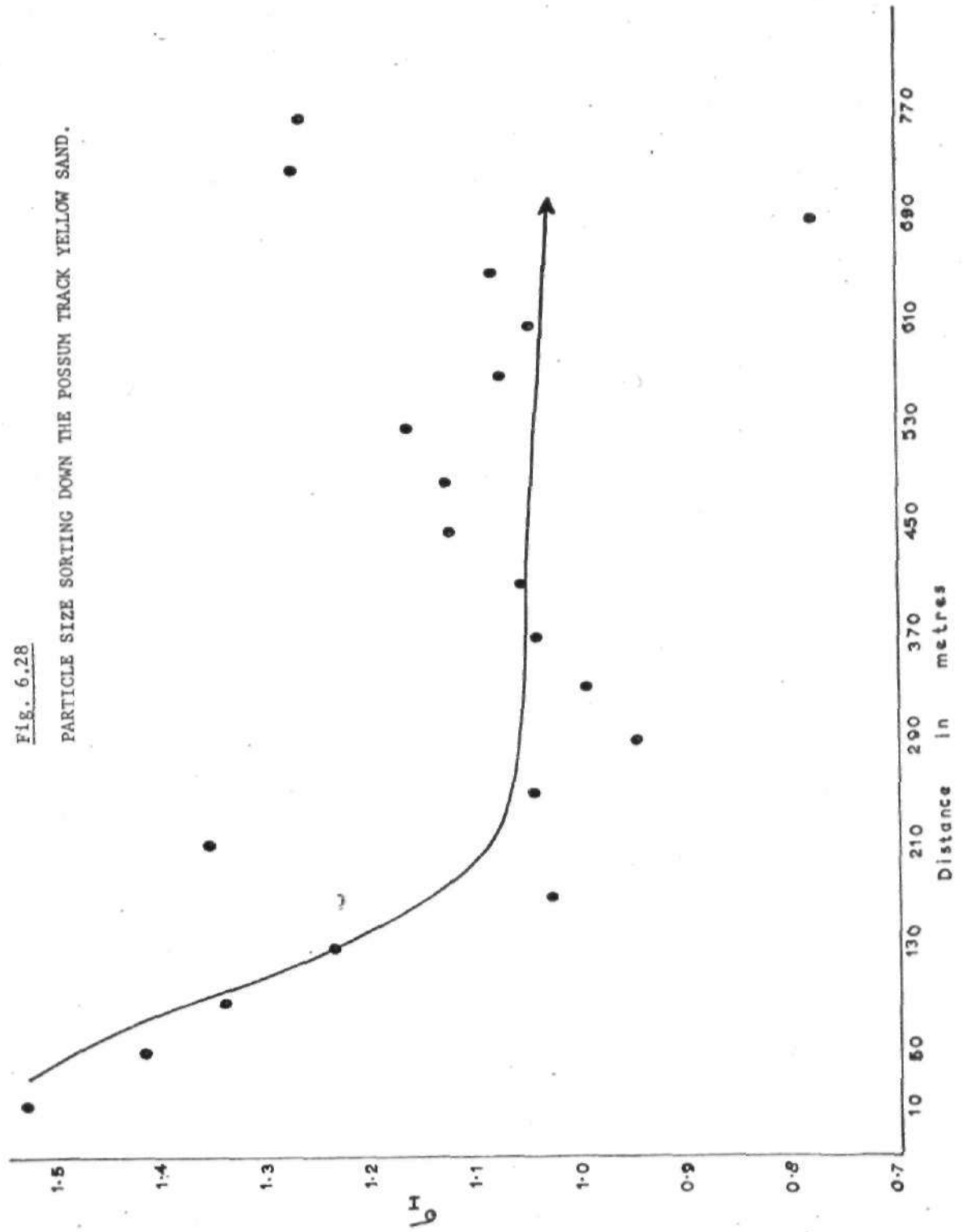


Fig. 6.28

PARTICLE SIZE SORTING DOWN THE POSSUM TRACK YELLOW SAND.



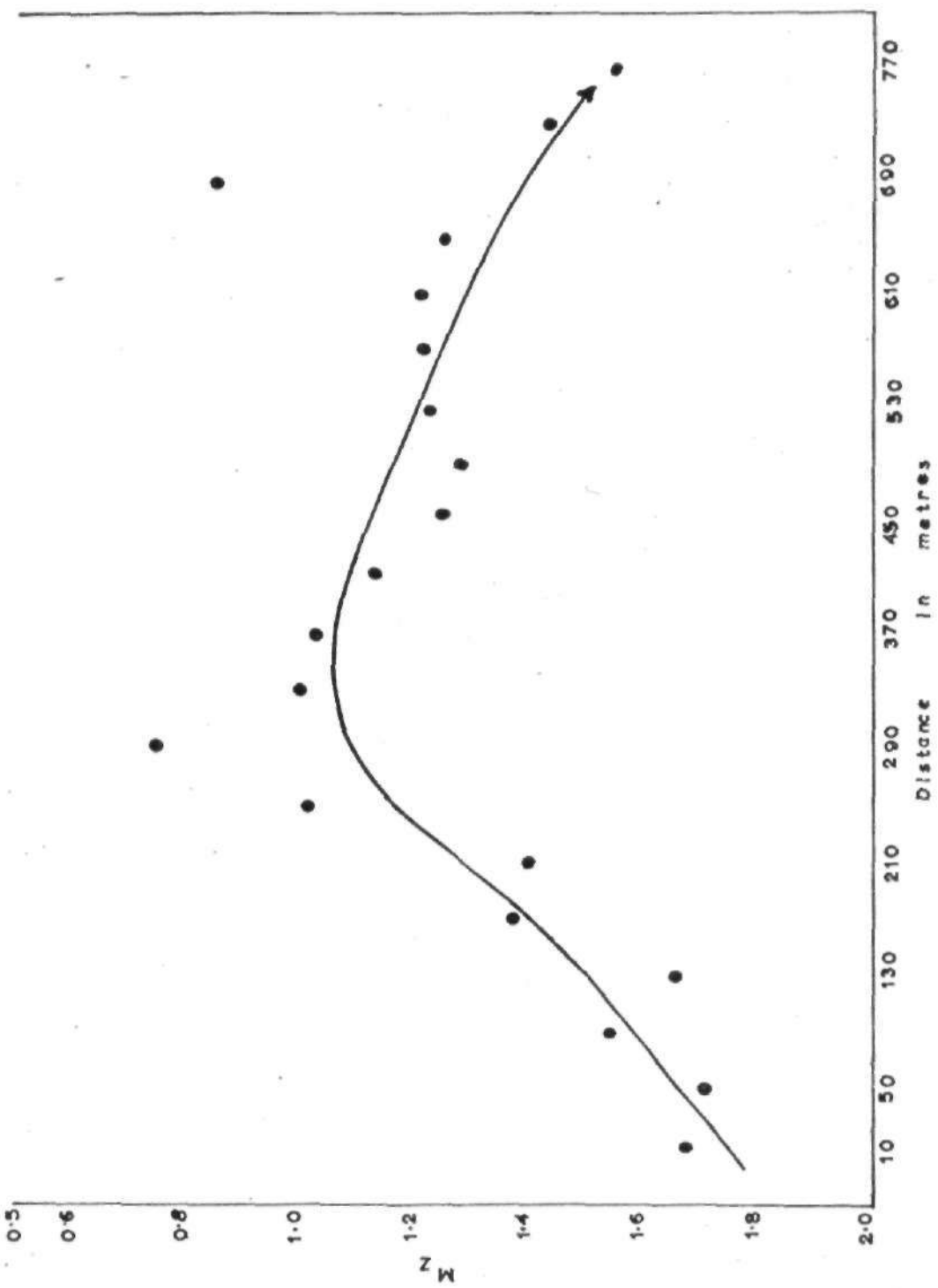


Fig. 6.29 MEAN GRAIN SIZE TREND DOWN THE POSSUM TRACK YELLOW SAND SPILLWAY.

In Figure 6.30 standard deviation (sorting) values for gray sands are plotted against their sample positions and show improved sorting with distance downslope. Figure 6.31 which is a plot of mean size for the gray sands against their sample positions indicates that there is no systematic change in mean size with distance downslope.

Feldspar content of the sands (feldspar/quartz peak height ratio)

A semi-quantitative determination of feldspar was carried out on the 90-106μ fraction of samples using the X-ray diffraction method (see Fitzpatrick 1971, p.83). The procedure followed has already been outlined in Chapter III. The quartz/feldspar ratio investigation is significant from the sedimentary point of view, as it indicates mineralogical maturity of the sediment concerned (Pettijohn 1957, p.508). Price *et al.* (1975) used quartz/feldspar ratio together with particle size distribution and field profile morphology to distinguish loess from the underlying residuum.

The results of the feldspar/quartz ratio investigation of Tuttanning sands are presented in Tables 6.2(a) and 6.2(b). These results show that, except for one sample (sp 5.12), all rock apron samples have high content of feldspar, the light fraction for the 90-106μ separation having 40% or more feldspar. The feldspar content for yellow sands and gray sands is much lower than that obtained for rock apron sands. Yellow sands generally show higher feldspar content than gray sands, though the values for the former are very erratic, e.g. the highest value obtained for the yellow sand samples is 29%, the lowest is 3.0% and the mean is 9%. Yellow sand samples 1,3, 1.4 and 1.5 with high feldspar values were obtained from the narrow depression north-east of the junction between Numbat and Jarrah tracks. Though the sides of this depression are mantled by duricrust and ironstone gravels, a few granitic rock outcrops are also present

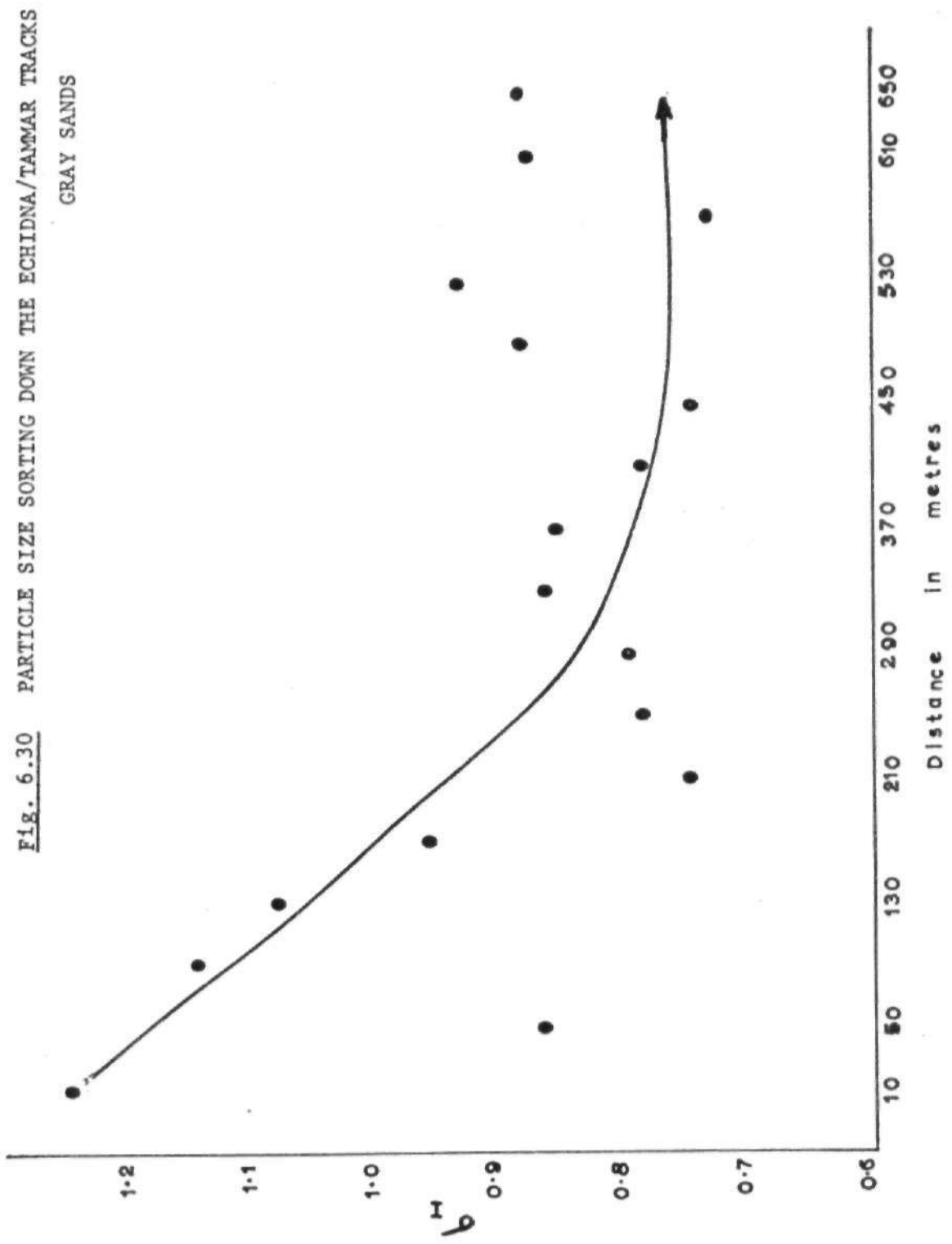


Fig. 6.30 PARTICLE SIZE SORTING DOWN THE ECHIDNA/TAMMAR TRACKS
GRAY SANDS

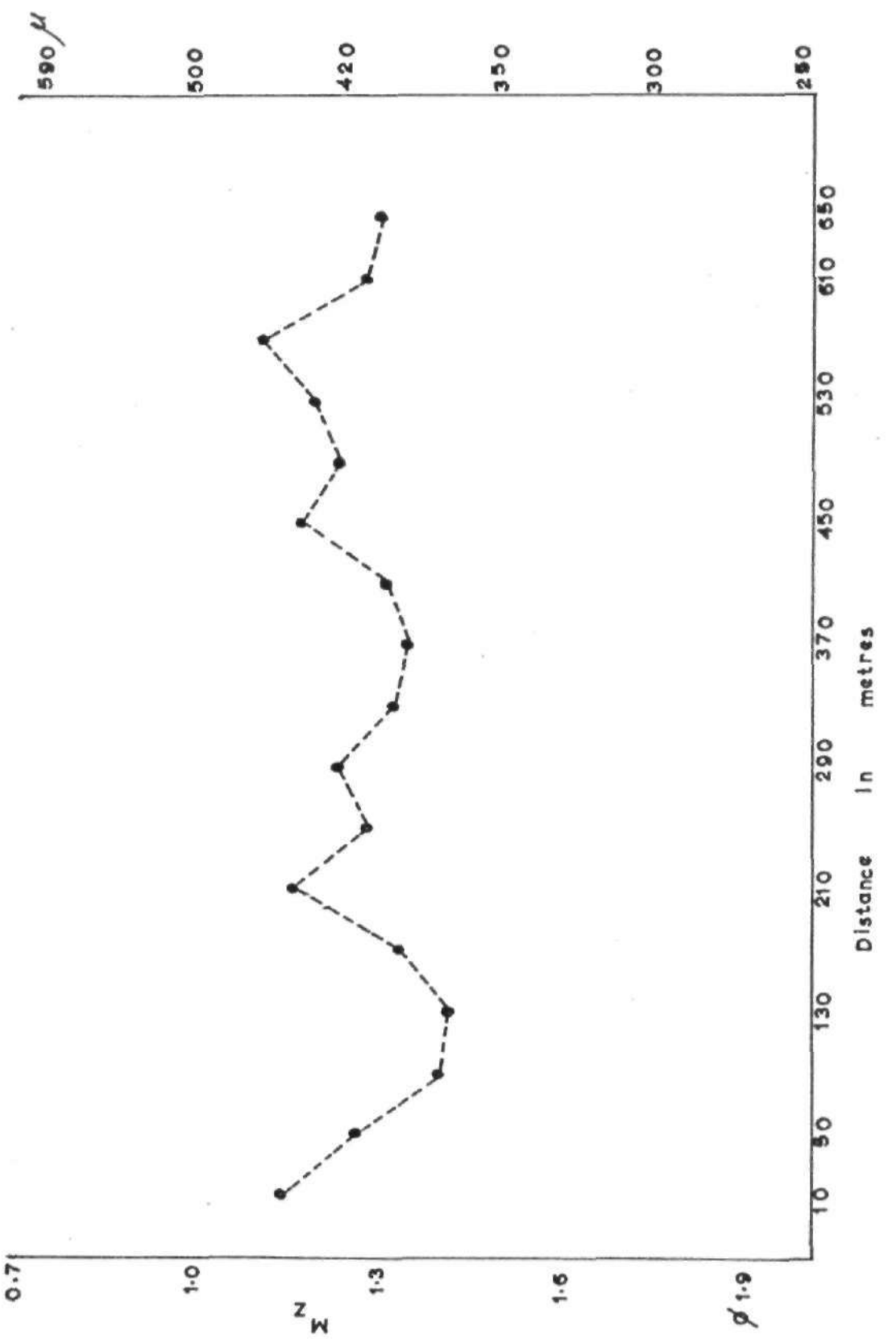


Fig. 6.31 MEAN GRAIN SIZE TREND DOWN THE ECHIDNA/TAMMAR TRACKS GRAY SANDS.

and could be contributing feldspar-rich detritus to the valley. The yellow sand samples (2.18 and 2.19) which also show relatively high feldspar values were collected at the lower end of the sand body where it appears sediment from the new plateau may also be feeding into the valley (see Fig. 6.1). The highest feldspar values obtained for gray sands is 6.0%, the lowest 1% and the mean is 4%.

The fact that feldspar values for yellow sands are not consistently higher than those for gray sands suggests that the feldspar content of the sands is a helpful but not very reliable criterion for differentiating yellow sands from gray sands. Also, since feldspars occur in various forms (e.g. microcline, orthoclase, oligoclase, plagioclase, labradorite, anorthite, albite, andesine, etc.), the figures in Tables 6.2(a) and 6.2(b) based on the strongest reflection for plagioclase can only give a rough estimate of the relative amount of feldspar present in the sands. When whole samples were analysed, yellow sands and gray sands showed only a trace (usually less than 2%) of feldspar while values for rock apron sands remained high (usually more than 20%).

TABLE 6.2(a)

Feldspar/quartz ratio and % feldspar content for the light fraction of the (90-106μ) sieve fraction for yellow sands and gray sands (2 sand bodies each) using the 31.0° feldspar peak and the 46.25° quartz peak; % feldspar values are read off from curves of standard binary mixtures.

SAMPLE	FELDSPAR		QUARTZ		F/Q	% F
	Peak height	RM*	Peak height	RM*		
Gray sands						
Sp 4.10	9.0	2×10^2	51.8	2×10^2	0.17	1
4.8	11.05	"	33.3	"	0.33	6
4.5	7.0	"	35.05	"	0.2	3
4.2	7.5	"	37.5	"	0.2	3
3.18	14.2	"	41	"	0.35	6
3.15	9.0	"	36.6	"	0.25	4
3.12	12.2	"	33.0	"	0.37	6
3.9	9.15	"	35.0	"	0.26	4
3.3	4.8	"	34.4	"	0.14	1
3.2	9.5	"	42.0	"	0.23	4
Yellow sands						
Sp 1.3	15	2×10^2	31.1	2×10^2	0.48	8
1.4	20.3	"	27.7	"	0.73	13
1.5	44	"	26.2	"	1.67	29
2.2	9.3	"	31.95	"	0.29	5
2.5	6.7	"	33.8	"	0.2	3
2.11	10.8	"	37.1	"	0.29	5
2.12	16.8	"	37.1	"	0.45	8
2.13	7.9	"	34.5	"	0.23	4
2.18	22.5	"	33.9	"	0.66	11
2.19	17.5	"	31.6	"	0.55	10

*RM = Rate meter setting

TABLE 6.2(b)

Feldspar/quartz ratio and percentage feldspar content for the concentrated fraction (90–106μ) for rock apron sands, using the $2\theta = 31.8^{o}$ feldspar peak and the 46.25^{o} quartz peak; % F values are read from standard curves.

SAMPLE	FELDSPAR		QUARTZ		F/Q	% F
	Peak height	RM*	Peak height	RM*		
Sp 5.12	36.6	2×10^2	42	2×10^2	0.87	15
5.13	44.2	4×10^2	13.8	"	3.2	50
5.14	36	"	15.5	"	2.3	47
5.15	38	"	13	"	2.9	49
5.16	33	"	12.6	"	2.6	48
5.17	42	"	15.7	"	2.68	48
5.18	58.8	"	13.2	"	4.45	>50
5.19	31	"	13.1	"	2.37	47
5.20	65.9	"	11.95	"	5.51	>50
5.21	35.0	"	12.0	"	2.9	49

*RM = Rate meter setting

Discussion

Heterogeneity in properties could well be diagnostic of yellow sands. Though shape distribution character curves for yellow sands are dominated by H- and R-curves, B-, D- and V-curves are also present. The relative rollability values for yellow sands range from below average through average to above average. The feldspar content is also very variable. Skewness values for yellow sands range from negative through near symmetry to positive. Some yellow sand samples are very poorly sorted and bimodal with an almost flattish spread (frequency curves for % sieve fraction weights) while others show a reasonable degree of peakedness and are unimodal. Gray sands on the other hand appear to have fairly homogeneous properties.

Photomicrographs of successive time fractions from the rollability apparatus obtained for yellow sands show that most of the grains are of low sphericity and very angular. In contrast the grains of gray sands are much more rounded and spherical although prominent surface textural features (e.g. pits, valleys, breakage lines, etc.) are abundant. Aeolian sand grains are generally well rounded, being much more rounded than grains of marine or fluvial sands (Bagnold 1941). Hence it is very unlikely that yellow and gray sand grains in particular are products of aeolian transport over long distances.

Both yellow and gray sands have high content of coarse and very coarse grains (Wentworth size classes). This is in sharp contrast to the observations of Winkelmolen and Veenstra (1974) which indicate that aeolian sands are generally deficient in coarse particles (i.e. >400μ) due to the limiting competence of the transporting mechanism. Sieve analyses for Tuttanning yellow sands show that quartz grains greater than 2 mm are present in nearly all samples.

Harris (1957) analysed samples from Egyptian dune sands and found that maximum grain size occurred between 450-1200μ. For Tuttanning yellow and gray sands, grains coarser than 1200μ are abundant in all samples as indicated by the frequency curves for sieve fractions.

Table 6.3 gives a comparison of three grain size parameter values for aeolian deposits in the landscape of the Central Orange River Basin, semi-arid South Africa (van Rooyen and duBurger 1974) and values for Tuttanning yellow and gray sands. Both investigations (granulometric analyses) were carried out using similar procedures. The comparison shows that Tuttanning sands have much coarser mean grain size, show poorer sorting and have much lower kurtosis values than the aeolian samples from the Orange River Basin.

Size distributions with very leptokurtic characteristics (Folk and Ward 1957) such as those indicated by the kurtosis values for the Orange River aeolian sands usually have high (35-45%) concentration of material in the modal sieve fraction.

TABLE 6.3

Comparison of mean grain size, sorting and kurtosis values for Tutanning sands and aeolian sands of the Central Orange River Basin, South Africa.

		M_z		σ_I		K_G	
		Max	Min	Max	Min	Max	Min
ORANGE RIVER BASIN sands	Red	2.04ϕ	2.80ϕ	0.65ϕ	1.24ϕ	2.41	0.62
	Yellow	2.29ϕ	2.76ϕ	0.64ϕ	0.97ϕ	2.94	1.02
TUTTANNING sands	Yellow	0.83ϕ	1.70ϕ	0.78ϕ	1.56ϕ	1.07	0.76
	Gray	1.10ϕ	1.40ϕ	0.74ϕ	1.25ϕ	1.42	0.74

Such high percentages for modal fractions have also been reported by Glassford (1976) who regards them as diagnostic of aeolian sands in south-western Australia. Tuttanning sands generally show low percentages for the modal fraction. The highest values for modal fractions for yellow sands and gray sands range between 25% to 28%. One gray sample however has a concentration of 33.6% material in the 710-500μ fraction.

The particle size and shape trends downslope of the yellow sand body may well be significant in understanding the provenance of these sands. Increase in rollability of coarser sand fractions and improved sorting downslope demonstrate the transported and depositional nature of the material (van Rooyen and duBurger 1974). In Figure 6.29 the increase in mean grain size with distance downslope to about 290 metres may mean that sand is fed into the valley from upslope and the relatively higher concentration of fines here could be due to the limited energy conditions of the often low intensity (drizzly) rainfall; the coarser grains being fed into the valley during heavier rainfall (e.g. flash floods associated with occasional summer thunder storms). Water moving downslope during heavy rains would transport sand and the fine fractions would tend to be affected most. However, the relative amount of fine sand that remains would tend to increase with increasing proximity to the 'source'. Downslope, with a gradual decrease in the gradient of the valley, deposition of material would result in a decrease in mean size with distance.

In the case of the gray sands, the fact that the mean size does not decrease with increasing distance downslope could point out that the sand did not migrate from an upslope situation to cover its present length and width. Movement of sand downslope for several metres, apart from occasional wind saltated grains, could have involved only

the fines, much of which may have been transported out of the sand body. The coarser grains have remained more or less in place after deposition. This conclusion is well supported by rollability data for gray sands which show that for the coarse fraction no change in rollability occurs with distance downslope, but rollability for the fines decreases with increasing distance downslope.

The presence of well developed duricrust below the gray sands and the much rounded nature of the grains in comparison with those of yellow sands may suggest that the gray sands are very old and probably much older than the yellow sands. The rounding of the gray sands is rather difficult to explain since the grains that are relatively most rounded are too coarse to have been transported by wind. Perhaps the gray sands could have been derived from the breakdown of sandstones similar to the pre-laterite conglomeratic sediments described by Taylor (1971), Finkl (1971), Churchward and Bettenay (1973) as Mesozoic or Cretaceous in age. In this case the more rounded characteristic of the gray sand grains could have been acquired (corrosion and attrition) by the deposition of the sandstone during the ancient past. Evidence in support of the above suggestion includes the presence of rounded quartz gravels in duricrusts adjacent to gray sand bodies, e.g. the duricrust to the north and north-east of Mopoke track, and the duricrust at the upslope end of the gray sands traversed by the Jarrah track.

It is also possible that, though extremely resistant to weathering at the sand size, quartz grains exposed to the atmosphere for many thousand years would tend to lose at least part of their angularity through

1) attrition during local surface creep and saltation within the sand body,

2) attrition between grains dislodged by rain drops and moving water during heavy stormy rainfall,

3) chemical weathering of the edges.

In the Tuttanning reserve, the presence of high breakaways would provide adequate obstacles for any saltating sand grains reaching the top of the upland residuals unless the grains were transported prior to breakaway formation. One may suggest that wind could have transported the sand upslope via the gaps or valleys but such a suggestion does not take into account the wind direction, for the sandy deposits occur mainly in valleys which radiate in all directions from the upland residuals of the Tuttanning drainage divide. Also, wind blowing yellow sands into the valleys of the upland residuals would have also deposited the sands on the new plateau below the breakaways. However, yellow sands, apart from the narrow zones relating to gravelly pediments and gravelly spurs, are almost completely absent on the new plateau, where grayish brown to brown gritty sands with fresh rock fragments are dominant.

General Conclusions

The soils of Tuttanning and, in fact, most of south-western Australia are generally extremely sandy being derived from quartzose parent materials. Hence, the yellow sandy deposits which are abundant in the landscape need not necessarily have been brought in from the drier country to the east. Colour is not diagnostic since iron oxides in degrading lateritic materials would provide yellow coatings on the local sandy deposits.

The fact that Tuttanning sands are generally coarse with the majority of the modal sieve fractions for samples in the greater than 400μ range suggests that these sands could not have been transported

over long distances by wind. This is particularly true of the yellow sands which contain very angular grains with elongate characteristics.

The Tuttanning yellow and gray sands may therefore be regarded as valley fills originating from local sources. The fact that yellow sands are consistently related to lateritic gravels points out that these sands could at least in part be derived from the breakdown of the duricrust. The breakdown released the sandy matrix which was eventually transported and deposited downslope. Also, the presence of relatively high amounts of feldspar in some of the yellow sand samples, together with the presence of a few fresh rock outcrops near this sand body, may suggest that material from fresh rock might also be present in some yellow sand deposits although such additions are virtually unidentifiable in the field.

The yellow sands seem to differ from the gray sands in several characteristics other than colour. The heterogeneity in the characteristics of yellow sands could well mean that these sands are much more complex deposits than the gray sands and that the latter is not a simple product of the leaching out of iron compounds and clay from the former.

The above conclusions have the following limitations:-

a) The particle shape and size analyses were restricted to surface (10-15 cm) samples. All that can be said of the deposits at depth is that they are reasonably rich in coarse (>400μ) grains.

b) Detailed investigation was restricted to one yellow sand body and one gray sand body.

c) The above conclusions may not be extended to cover the sand bodies found in other parts of south-western Australia due to the general complexity of the landscape.

CHAPTER VII

IRONSTONE GRAVELS

Gravels are defined by Northcote (1971) as particles between 77 mm and 2 mm in diameter and may comprise fragments of fresh rock or indurated lateritic materials (ironstone gravels). Ironstone gravels of various kinds are found either in the surface horizons or throughout the soil profile, or at some depth in the soil profile of some members of almost all the Tuttanning SMU's. The gravel content varies considerably from less than 10% to over 60%. Where the content of ironstone gravels amounts to 60% or more of the total mineral material, they are regarded as forming the bulk of the soil material (Northcote 1971).

Ironstone gravels dominate much of the soil profile of the Dutarning SMU and the A horizon of Marshall SMU (see Chapter VI, Soil Mapping Units). Such gravels could have formed *in situ* since they are always closely packed, increase in size with depth, are closely related to the fragmented mottled material below them, and the matrix material often brings out differences between acid, basic and quartzite parent materials. In addition some of the gravels at the surface (0-5 cm) of Dutarning SMU could be detrital derived from the breakdown of the overlying duricrust (Mulcahy and Hingston 1961). Such duricrust fragments are usually very angular and contain vesicules.

A thin layer of ironstone gravels usually occurs between the shallow surface sands of the Magpie SMU and the underlying mottled clay. This underlying mottled clay is usually sub-indurated and could well represent duricrust in the course of formation. A similar thin layer of ironstone gravels also occurs over the duricrust that underlies the gray sands of the Echidna SMU, which correspond with the

Eleanor sand described by Northcote (1946) as an intact fossil laterite. Such ironstone gravels could have developed at the sand-clay interface in the zone of intermittent waterlogging (Bloomfield 1951), in which case it would mean that at least some of the ironstone gravels mantling some present-day massive duricrusts could have developed in a similar way, on top of the duricrust, and may therefore not be products of the breakdown of the duricrust.

Ironstone gravels present in the B horizon of Tuttanning soils usually occur near the interface between the clay and the overlying sands, in the zone of intermittent waterlogging (mentioned earlier) where the ferruginous parts of the parent material act as foci for further deposition of iron oxide. On breaking, the gravels are seen to have several concentric skins of iron oxide around a coarser but still iron-rich matrix. With depth they become softer (concretions) until they are indistinguishable from the reddish mottlings below, indicating that the gravels have developed *in situ*. Such rounded gravels with concentric iron-rich bands are nearly always present where yellow sands (Possum SMU) overlie clayey material.

Detrital gravels associated with the A horizons of Rosella SMU's have already been described in Chapter V where gravelly and earthy pediments were related to breakaway morphology. The shapes and general appearance of these gravels show that they could have originated from at least three sources. The most abundant gravels are sub-rounded with thin skins of iron oxide but on breaking they are seen to be mottled yellow. Such gravels could probably have originated from the mottled zone of the breakaways. Some of the gravels are very angular and often vesicular, and could represent contributions from the mechanical breakdown of the duricrust at the free face. A small proportion of the gravels are grayish to grayish brown, angular with

rough surfaces and low in iron oxides (only a few faint mottles may be present). The blasting effect of raindrops has exposed quartz grains which sit in relief on the surfaces of these gravels. It is most likely that these pale-looking gravels are simply fragments of pallid zone material which have hardened.

A trace of ironstone gravels is usually present in the A horizon of Goanna, Chat, Bandicoot, Woiylie, Woyerling and Wambenger SMU's. These gravels are usually of different shapes and sizes, occur as discrete elements in the usually sandy materials and could have originated by one or more modes of genesis as follows:

a) detritus from the retreating breakaways,

b) detritus from degrading gravelly spurs and ridges,

c) fragments of weathering rock coated with iron oxides.

The occurrence of 'fragments of weathering rock coated with iron oxides' as gravels has already been reported by Mulcahy and Hingston (1961) for the Malebelling and Mobedine soils near York. In the Tuttanning reserve, this type of gravel has been identified in several profiles of the Woiylie, Bandicoot and Woyerling SMU's where rock fragments without iron oxide coatings are also present. A dense surface cover of ironstone gravels is present on a gentle rise by Gnow track close to the junction between Kangaroo and Mopoke tracks. In a hasty field investigation, this gravelly rise could be mistakenly grouped with soils of the Marshall SMU. Detailed examination of the situation, however, revealed that the gravels are restricted to the surface of the soil and are fragments of weathering rock coated with iron oxides. The soil on the gentle rise is a regosol with granitic fresh rock at 10-15 cm depth and therefore belongs to the Bandicoot SMU. Hence, since fresh rock outcrops are so widespread on the new plateau, a significant proportion of the ironstone gravels in the

A horizon of the soils on this plateau could have originated from fragments of weathering rock.

Deep ironstone gravels (Dutarning SMU) developed over basic rocks occur at the extreme north-east of the Tuttanning reserve near Wambenger track. These gravels are brownish to reddish brown and rounded. On breaking, they are seen to have an outer shell enclosing an inner iron-rich black to dark red material. Red soils of the Pingelly SMU usually contain a trace of fine rounded black ironstone gravels in the B horizon.

CHAPTER VIII

DESCRIPTION AND EXPLANATION OF SOIL LANDSCAPES

The relationship of the soils of south Western Australia with certain landscape elements has been indicated by earlier workers such as Mulcahy and Hingston (1961), Bettenay and Hingston (1964), Finkl (1971), Churchward and Batini (1975) (see Chapter II - Literature Review). In general, these workers related the erosional modification to changes of landscape stability responding at least in part to fluctuating climatic conditions.

In the discussion that follows, it will be shown that the complex pattern of soils and landforms at Tuttanning is related to the differential stripping of the mantle of weathering. Such natural erosion has released sediment from various elements of the weathering profile and from extensive exposures of country rock. This sediment, along with elements of the weathering profile *in situ*, forms the soil parent materials which range from light clays to sands, often with variable amounts of ironstone gravel.

For convenience, the landform elements of the Tuttanning reserve together with the soils occurring on them have been placed into one of two groups namely:

A the elements of the "old" plateau surface,

B the elements of the "new" plateau surface.

The old plateau surface

The old plateau surface generally occurs as remnants capping the mesas, buttes and other residuals and represent areas where erosional processes have not been sufficiently effective to remove the often deeply weathered laterite profile. Nevertheless, minor modifications

of this old surface have occurred and these together with some pre-laterite hollows have an important effect on the soil pattern. Four soil mapping units (SMU's) have been recognized on this surface. The Tuttanning SMU which is dominated by massive duricrust (lateritic pavement) occupies the highest positions on the old plateau surface and could represent the ferruginous zone of the laterite hardened after the removal of the overlying surface soil (Bettenay and Hingston 1964). The Dutarning SMU is dominated by deep lateritic gravels, occupies slightly lower levels than the Tuttanning SMU and is sometimes separated from the latter by an incipient but identifiable break of slope. This incipient break could well mark the extent of the destruction of the massive duricrust layer which often appears to be absent in Dutarning SMU. The presence of incipiently stripped zones on the surface of the upland residuals could mean that these residuals are undergoing destruction from two fronts - i.e. from the sides as expressed by the breakaways and from the top; the main difference between the two fronts of destruction being that of degree.

Mulcahy (1960, 1964), working in a similar landscape near York, reported that massive lateritic pavements are relatively rare, occurring near the breakaway edges or at the crests of slight rises. The rest of the surface of an upland residual he studied in detail was dominated by ironstone gravels and deep yellow sand. However, a greater variety of situations occur at Tuttanning where massive lateritic pavements (duricrust) cap entire surfaces of some of the mesas while others consist of landform elements associated with duricrust or ironstone gravels or sandy deposits.

The Possum and Echidna SMU's essentially comprise sandy deposits (yellow and gray respectively) which occupy depressions in the old plateau surface. From the material presented in Chapter IV, it could

well be that some of these depressions pre-date lateritization, though the deposits in them may not necessarily do so. For example, detritus derived from the erosional modification of the laterite landscape may fill pre-laterite hollows with yellow (Possum SMU) sands. According to Mulcahy and Hingston (1961), the depressions with gray sands (referred to by them as Kauring) were cut in the lateritized surface of the ancient plateau during an early stage of uplift and the pallid zone was exposed. The exposed pallid zone was then lateritized leaving gray sands as an eluvial horizon of the intact laterite profile. The opinions regarding the origins of yellow sands and gray sands have already been reviewed (Chapter VI) and are discussed at length in Chapter VI , where it was concluded that for the Tuttanning reserve, these sands are most likely valley-fills derived from nearby and possibly contrasting sources. Evidence from Tuttanning suggests that it may not be necessary to invoke different periods of lateritization to explain the presence of at least some of the gray sand bodies in the study area.

The new plateau surface

Complete stripping of the laterite profile has exposed fresh rocks on extensive parts of the new plateau surface. These fresh rocks have either been weathered *in situ* to give rise to parent materials for various soils, or have remained as massive rock outcrops which are being mechanically weathered to yield brownish to grayish brown gritty sandy deposits of the Woiylie SMU downslope. Where weathered country rock covers extensive areas, the soils are related to landscape elements produced by the dissection of such areas by incipient drainage lines and the deposits resulting from this. Hence, Goanna SMU's occupy well-drained flattish to very smoothly convex situations between widely spaced drainage floors while Woyerling and

Dailyerking SMU's occur on elements sloping towards the drainage floors. The Dailyerking SMU is usually confined to narrow zones particularly where there is a nick in the otherwise gently sloping surface. Here, it is most likely that stripping of the overlying loose sandy A horizon material has been complete, exposing the underlying clay.

The Wambenger SMU is confined to deposits on terrace-like flats adjacent to the main drainage floor of the Hotham drainage system. Where several drainage floors occur in close succession, as association of soils of the Goanna, Woyerling and Hotham SMU's may be found with the Goanna occupying the convex slopes of the interfluves; the Woyerling the flanking slopes and the Hotham the valley floors.

Where stripping of the laterite profile has not been complete, remnants of pallid or transitional zones and detritus derived from these give rise to distinctive types of soils. Such soils occur on spurs and ridges extending from the upland residuals, on concave pediment slopes cut below the breakaways and on slopes adjoining to these. The spurs and ridges are often capped with ironstone gravels and are associated with soils of the Marshall and Magpie SMU's. The relationship between the laterite of the spurs and that of the upland residuals is not well understood since the boundary between these is often transitional, but the deep pallid zone associated with the latter is absent beneath the spurs. Mulcahy and Hingston (1961) believed that laterite profiles on the spurs (referred to by them as Belmunging surface) could have developed independently at a later date than that of the upland residuals. Prider (1966) however indicated that lateritic materials on the spurs could merely represent dissected parts of the same laterite. The spurs and low ridges together with the associated soils seem to occupy an intermediate

position between the old plateau surface and the more classical new plateau form as represented by the pediments and the long gentle slopes below them. The main difference between the soils on the spurs and ridges on the one hand and those on the pediments on the other could well be that of the degree of stripping. The elements of the latter have been stripped of their weathered mantle much more than the former. Hence the transitional zone to fresh rock which occurs at shallow depth below sandy or gravelly A horizons of Rosella SMU's (acid pediments) is usually a feature of the deep sub-soil (often a metre or more) of Marshall and Magpie SMU's.

Magpie SMU's sometimes occur on the dip-slope of cuesta-like low ridges. Light grayish brown to gray sandy deposits of the Bungara SMU sometimes occur downslope of Magpie SMU and may extend into the nearby depression. Such sands could be detrital derived from the stripping of the gray sands that often occur as A horizon material of Magpie SMU. In such situations it is not uncommon to find a narrow zone of duricrust (usually at the shoulders of the ridge) separating the Magpie SMU from the Bungara SMU. Such duricrust is essentially the sub-indurated mottled B horizon of the Magpie which has hardened on exposure.

Marshall SMU's are often flanked by a narrow zone of deep yellowish brown sands similar to those belonging to the Possum SMU. Such yellow sands could be detrital, derived from the matrix in the ironstone gravels upslope.

The nature of the surface material of pediment soils (gravelly or earthy) appears to be closely related to breakaway morphology discussed below.

Gravelly and earthy pediments

Gravelly pediments seem to occur mainly below low breakaways and where the breakaway slope is convexo-concave (see Chapter IV - Geomorphology). Where the breakaway is low (2-5 metres) exposure of pallid zone in the scarp is limited or non-existent and the pedisediment comprises essentially ironstone gravels derived from the mottled zone, and fragments of duricrust. Where the breakaway slope is convexo-concave there is no duricrust (ferruginous zone) above the mottled and pallid zones (see Chapter IV and Figures 4.1(a) and 4.1(b)). The ironstone gravels that usually develop in the mottled zone are weathered from the matrix and transported downslope burying the pallid zone that may have been exposed in the scarp. The gravels also mantle the upper pediment slope. Such gravelly pediments often, but not always, have a narrow zone of yellow sandy deposits (Possum SMU) in the downslope situation.

Where the breakaway is high (8-15 metres) and capped by duricrust the gravels that usually develop in the mottled zone are effectively protected by the duricrust from erosion. Therefore much of the pedisediment is earthy, derived from the exposed pallid rock (Mulcahy and Hingston 1961). Usually, a few detrital ironstone gravels are also present, indicating contributions from the mottled (gravelly) and ferruginous (duricrust) zones. Downslope of earthy pediments, the pedisediment becomes progressively deeper and finer textured. Such lower pediment slopes constitute the Chat SMU.

Laterite deep weathering and the degree of stripping

Fresh rock exposed at different levels in the Tuttanning reserve indicate the highly variable basal surface of weathering present. This effect of the basal surface of weathering has reduced the

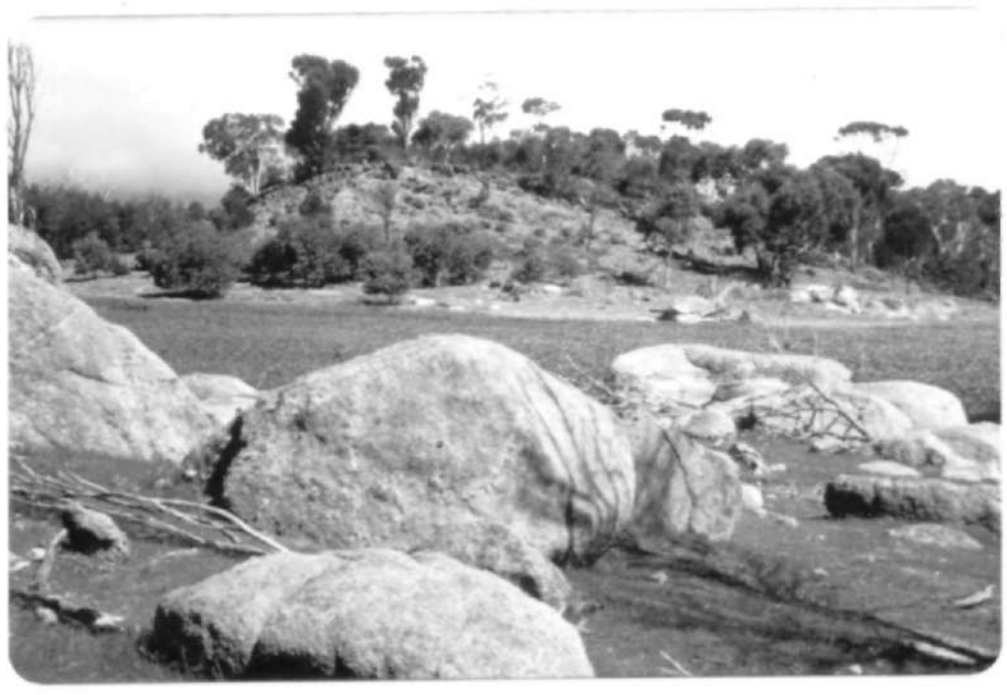
consistency of the correlation of soil units with landscape elements as described above and has demonstrated the gross inaccuracies that may be present on soil maps based on the interpretation of geomorphic elements and unaccompanied by detailed field investigation of the units. For example, though scattered rock outcrops often associated with a complex of soils (e.g. Bandicoot SMU) occur mainly on mid to lower slopes of the new plateau, they are not completely absent on pediment slopes, spurs, low ridges and drainage floors (see Photo 8.1). Such scattered rock outcrops are usually in the form of flats or boulders which are extremely difficult to identify by stereoscopic examination of aerial photographs alone. Shallow depressions cut into the surface of the old plateau and usually associated with yellow or gray sandy deposits (Possum or Echidna SMU respectively) occasionally reveal massive granitic rocks. Here, it is evident that the basal surface of weathering is only a few metres (two to three metres) below the duricrust layer, and a pallid zone might not have been present in the profile.

Parent materials and soil characteristics

Though the soils of the dissected laterite landscape of Tuttanning are related to landscape elements, the establishment of soil mapping units was refined by the recognition of rock types (Finkl 1971). Hence, the Pingelly SMU was separated from the Rosella SMU on the basis that the former is developed from basic rock and the latter from acid rock (see Photo 8.2). The separation of Mopoke from Bandicoot SMU followed similar considerations.

Tables 8.1(a) and 8.1(b) (in appendix 3) shows the differences in the chemistry of the most commonly occurring Tuttanning soils. Generally, soils derived from basic rocks (Pingelly SMU) have higher

PHOTO 8.1



Scattered granitic rock outcrops on pediment slope below a breakaway.

PHOTO 8.2



A sharp boundary between soils developed over basic and acid parent materials (north of Tuttanning Road and north-east of the reserve). Notice the red colour of the soils developed over basic rocks.

concentrations of Zn, Co, Mn, TiO_2, V, Cr than soils developed on weathered granite (e.g. Woiylie SMU) and on lateritic materials. Soils developed on fresh granites on the other hand show higher levels of K, Ca, Na_2O and Ba than the soils developed over lateritic materials. The levels of Ca, K, P, S in the lateritic materials are generally very low, particularly in the sands (e.g. Possum and Echidna SMU's).

Table 8.2 (in appendix 3) gives the semi-quantative clay mineralogy of the <5μ fraction for the most commonly occurring Tuttanning soils. It shows that kaolinite is the dominant clay mineral in these soils, often exceeding 80%, and occasionally it is exclusively present (e.g. Rosella SMU). Quartz occurs in the <5μ fraction in almost all of the soils and is particularly high in the gray sands (Echidna SMU). Small quantities of illite also occur associated mainly with fresh rock materials such as the Woiylie SMU (granite apron soil) and the Pingelly SMU (weathered basic rock). Oxides of iron and aluminium (goethite/hematite and gibbsite) occur associated with the lateritic materials such as the yellow sands (Possum SMU) and the Magpie SMU. Lateritic materials of the Marshall, Possum and Echidna SMU's show a trace of vermiculite. Small amounts of feldspar were encountered in the Echidna, Marshall and Woiylie SMU's. Feldspar content in the various types of sands at Tuttanning has already been treated in detail in Chapter VI where it was indicated that this mineral is usually present in substantial amounts in the fresh rock materials (e.g. Woiylie SMU) but in very small amounts in the lateritic materials.

The chemistry and mineralogy of the various soils of Western Australia have already been reported in detail by previous workers including Carroll (1944, 1970); Hingston and Mulcahy (1961); Turton

et al. (1962); Grubb (1966); Gilkes *et al.* (1973). The results presented above are largely consistent with the previous reports.

CHAPTER IX

THE RELATIONSHIP OF TUTTANNING SOILS TO VEGETATION

A The significance of vegetation to aerial photo patterns

The vegetation of the Tuttanning reserve occurs in "formations" (Gardner 1942) which are to a large extent related to the relief and to the soils. The nature and character of these vegetation formations together with the nature of the surface soil give rise to patterns represented by different photo tones and textures. The definition of these patterns was further enhanced by the use of coloured photos particularly since the colour of the surface soil occasionally showed up to advantage. Some of the patterns are shown on an annotated coloured aerial photograph of a portion of the Tuttanning reserve (see Figure 9.1).

Areas of heath vegetation usually appear in very light tones with fairly smooth texture and form sharp boundaries with the surrounding higher vegetation. The smoother textures of heath vegetation are in contrast with the wooded areas and appear to relate to the fairly dense cover of the heath plants. Heath communities in the Tuttanning reserve are characteristic of Magpie, Echidna and to a lesser degree, Possum SMU's. Echidna SMU's (gray sands) sometimes appear as distinct white patches. Possum SMU's (yellow sands) often have a yellowish hue together with the generally light tone, but this unit is usually not as consistently identifiable as the gray sands.

Dense sheoak (*Casuarina huegeliana*) thickets have little if any surface soil exposed and show up as very dark tones. Sometimes these areas may be related to zones of granite outcrops and associated gritty sandy deposits.

FIGURE 9.1



An annotated aerial photograph of part of the Tuttanning reserve showing the relationship between some of the soil mapping units and the vegetation.

a_1 Tuttanning Smu (Duricrust)
a_2 Dutarning Smu (Deep Gravels)
b_1 Possum Smu (Yellow sands)
b_2 Echidna Smu (Gray Sands)
f_1 Rock outcrop
c_{ii} Gravelly Pediment

Units with scattered wandoo *(Eucalyptus wandoo)* due to the pale colour of the surface soil appear as light tones with the widely scattered trees represented as dark spots. Such areas are usually representative of sands or loamy sands with a tendency to set hard over mottled clays (Goanna SMU) and occur on the gentle mid to lower slopes of the valleys. This "open wandoo woodland" also sometimes occurs on the lower apron to granitic rock outcrops and lower pediment slopes (Chat SMU).

The surfaces of the upland residuals are represented by tones intermediate between those for the heaths and those for areas of she-oak, particularly when the areas are dominated by dense bushes of *Dryanda* sp., *Isopogen* sp., *Melaleuca* sp. etc., and scattered powder bark wandoo trees on massive duricrust or deep lateritic gravels. The textures are generally smooth and the surfaces have a shiny appearance. Occasionally, brownish to greenish-brown colours may also be displayed due to the soil colour showing through the vegetation. The smoothness and sheen of lateritic surfaces are absent where the vegetation is either mallet or sheoak instead of bushes. Upland residual surfaces are often surrounded by pale narrow zones representative of the breakaways with their characteristic poorly vegetated pallid zone exposures. However, with the duricrust and upland deep gravelly soils (Tuttanning and Dutarning SMU's) it is the relief rather than the vegetation (as expressed in tone and texture) that is diagnostic.

The picture presented above is a great simplification of the situation in the Tuttanning reserve. Not only are some soils not represented by diagnostic aerial photo or vegetation patterns, but in some cases the vegetation is even misleading. For example, dense she-oak occurs on so many SMU's that its use in predicting soils is greatly reduced. In certain places the soils carry plant associations

which may comprise any one of the following:

1 Sheoak and jam,

2 Sheoak, York gum and wandoo,

3 Powder bark wandoo and sheoak,

4 Jam and wandoo.

These associations look very similar on aerial photographs and are of little help in mapping soils.

However, during the soil survey, vegetation patterns were used in conjunction with the relief in establishing analogous areas (Clarke and Beckett 1971) and predicting soils. It was noticed that, though there is a close relationship between the soils and the vegetation, several soil boundaries transgressed vegetation boundaries.

The vegetation of the soil mapping units

Tuttanning and Dutarning SMU's

Most examples of these units carry widely scattered powder bark wandoo (*E. accedens*) with fairly dense undergrowth of smaller plants comprising mainly *Dryandra* sp., *Isopogen* sp., *Melaleuca* sp., *Hakea* sp., *Xanthorrhoea preissii* and *Casuarina microstachya*. Some deep gravelly zones (Dutarning SMU) are covered almost exclusively by dense dryandra bush and scattered *X. preissii*. There are, however, some notable exceptions such as at the following sites:

1 On the duricrust of the upland residual between Bandicoot and Granite tracks the vegetation is exclusively powder bark wandoo with an almost complete absence of undergrowth.

2 The duricrust occurring near the junction between Honey Eater and Wattle tracks is covered with dense mallet (*E. astringens*) with no undergrowth.

3 Between Blackboy and Wambenger tracks duricrust is mantled by low dense thicket of *C. campestris*.

4 An association of powder bark wandoo and mallet was observed in a few places.

Possum and Echidna SMU's

These sands often carry heath vegetation comprising numerous plant species together with *X. preissii* and a few widely scattered trees. Tree species on Possum SMU's (yellow sands) are often restricted to sheoak, powder bark wandoo and small thickets of mallee-type of eucalyptus. Heath communities on the gray sands (Echidna SMU) occur together with *Banksia attenuata, B. prinotes,* sheoak, powder bark wandoo and Western Australian Christmas tree (*Nuytsia floribunda*). The gray sands traversed by the Jarrah track are underlain by massive duricrust and carry, apart from the already-named species, a few stands of jarrah *(E. marginata)* together with the heath. The heath vegetation of the Echidna-Tammer tracks' gray sands is replaced by dense sheoak with an undergrowth of heath plants as the sands occupy wetter sites close to the drainage line (see also Photos 9.1 and 9.2).

Magpie SMU

The soils of this unit usually have poor internal drainage and a sub-indurated B horizon at shallow depth. The heath communities that occur on this SMU are usually much more stunted than those on deep yellow sands or gray sands already described. This SMU has many prickly or thorny plants including stunted dryandra bushes. Trees are almost completely absent. The heath shrubs usually vary from 0.5-1 metre in height and possess very deep rooting systems. It is not uncommon to find shrubs less than 15 cm high with root systems extending to depths of over 60 cm. Even the *X. preissii* which grows

PHOTO 9.1



Heath vegetation on Echidna SMU (gray sands); note the scattered *Banksia* sp.

PHOTO 9.2



Heath community on yellow sands (Possum SMU) in a depression. Note the powder bark wandoo growing on higher ground (duricrust).

on these soils is stunted, while the contour of the heath vegetation remains more or less uniform. Occasional sheoak may occur standing like sentinels in areas of heath (Gardner 1942). See also Photo 9.3.

Rosella SMU

This unit occurs on pediment slopes that fringe the breakaways and carry dense mallet particularly where the pedisediment is earthy. Dense mallet areas usually have little or no undergrowth, though occasional box poison (*Oxylobium parviflorum*) and *Isopogen* sp. may be encountered. Mallet trees stranded some distance from the breakaways are good indications that here pinkish massive sandy clays similar to those of the upper pediments are close to the surface.

Where the pedisediment is very gravelly, powder bark wandoo and occasionally wandoo occur in association with the mallet or may completely replace it and carry shrubby undergrowth of *Dryandra* sp., *O. parviflorum*, *Isopogen* sp. and other smaller plants. Away from the upper pediment soils and with increasing depth of sand over saprolite (Chat SMU) wandoo and sheoak gradually take over.

Bandicoot, Woiylie and Mopoke SMU's.

Granitic rock outcrops and associated deposits dominate most of the valleys in the study area. The rock outcrops themselves are often quite devoid of soil and vegetation except for the small plants like ferns, lichens, pingrass and small flowering plants. However, the regosols and the deep gritty sands often carry dense sheoak almost to the total exclusion of other tree species. Away from the rock outcrops, wandoo and jam gradually come into association with sheoak. Much of the undergrowth is box poison shrubs. Eucalypts, particularly York gum, often become dominant in areas of basic rock outcrop.

PHOTO 9.3



Magpie SMU with heath community. Note the sharp boundary between the heath and the woodland.

Goanna, Woyerling, Dailyerking, Wambenger SMU's

Where the soils are developed on fresh rock saprolite or its detritus, the characteristics of the vegetation, particularly the density of the trees, relate largely to the physical properties of the soil, particularly to the moisture conditions. Where the surface horizons have the tendency to set hard (Goanna SMU), the trees are widely scattered with wandoo occurring as the dominant species in association with sheoak and jam. There is much exposure of bare ground. An open understorey is dominated by *X. preissii* and box poison. This vegetation has already been referred to in this chapter as "open wandoo woodland" and is best expressed in the study area on very gentle slopes east of Goanna track.

Elsewhere with moister soil conditions, the trees are more closely spaced and *X. preissii* more or less disappears, leaving box poison as the dominant undergrowth. The deep brownish to gray brown sands with shallow ground water often carry jam and sheoak and an undergrowth of water-loving plants. Close to the drainage lines the sheoak may occur in dense stands attaining heights of six to eight metres.

Quail SMU

The area affected by salinity is confined to a small narrow stretch along the Hotham drainage floor which is intersected by the Quail track. It carries dead sheoak and jam trees with an undergrowth of various sedges which are also dying and giving way to much bare ground. The presence of dead trees and grasses is indicative that the salinity is secondary, induced by the clearing of the surrounding country and the resultant rise in the saline underground water, the vegetation dying off as a result of the change in soil conditions (Prescott 1931; Teakle 1937, 1953; Hingston 1958; Dimmock *et al.* 1974).

General Comments

Powder bark wandoo and dryandra bush are particularly good, though not infallible, indicators of ironstone gravels in soils. Thus they tend to dominate the deep ironstone gravels of the uplands and the spurs and also the shallow detrital gravels of gravelly pediments. As ironstone gravel soils become more sandy and gritty, sheoak, jam and wandoo tend to come in; these three species together being especially characteristic of the soils developed from the weathering of fresh rock.

Sheoak appears to be most tolerant of soil conditions, appearing on almost all types of soils except where saline. The only occurrence of salmon gum is on red earths (Pingelly SMU) at the extreme west end of the Tuttanning reserve.

Lange (1960) regards all occurrences of jarrah and Western Australian Christmas tree east of the 20 inch isohyet as "disjunct" and associated with the high ground water effects of the "Monkopen deposits" (Mulcahy 1959), that such ground water effects simulate conditions of high rainfall in a low rainfall area; and that the species involved had continuous distributions over the area under rainfall and soil conditions preceding the most recent aridity.

Water repellent soils

The nature of water repellence in the soils of Australia and other countries has been reviewed in Chapter II. The association of this phenomenon with sandy soils has been indicated and it has been proposed that this condition is related to organic coatings produced by fungi particularly in association with specific plant species (Smith 1949, Bond 1968).

In the present study, field and laboratory tests have been carried out using the water drop penetration time (WDPT) method (Bond and Harris 1964). The results presented in Tables 9.1 and 9.2 show that this condition is well expressed by surface horizons of a number of soils from Tuttanning. In particular are those associated with a number of the eucalypts, namely powder bark wandoo, (*E. accedens*), wandoo (*E. wandoo*), mallet (*E. astringens*), salmon gum (*E. salmonophoia*). The surface horizon of these soils usually has WDPT in excess of one hour. In contrast, soil samples from beneath York gum (*E. loxophleba*) and jarrah (*E. marginata*) are only slightly water repellent and their WDPT ranges from only 6 to 30 seconds. Soils beneath non-eucalypts such as sheoak, jam, *Banksia* sp., and smaller plants like dryandra sp., box poison and heath shrubs have WDPT of less than 5 seconds for all samples analysed.

TABLE 9.1

Plant species and average water drop penetration time (WDPT) of the surface (0-5 cm) soil, under litter:

Plant species	Number of measurements	% clay content of soil	Average WDPT*
Mallet	15	5 - 10	70 minutes
Powder bark wandoo	15	<1 - 14	100 minutes
Salmon gum	5	10 - 15	85 minutes
Wandoo	10	3 - 5	65 minutes
York gum	5	10 - 15	5.5 seconds
Jarrah	5	<1	28 seconds
Sheoak	5	<1	1.0 seconds
Jam	5	1 - 3	2.0 seconds
Banksia sp.	5	1 - 3	1.0 seconds
Box poison	5	1 - 3	1.0 seconds
Heath shrubs	5	<1	1.0 seconds

*Mean WDPT values represent samples taken at different times of the year and with variable organic matter. Soils under powder bark wandoo are not necessarily the most water repellent.

TABLE 9.2

The relationship between water drop penetration time (WDPT) content of organic carbon in soil and plant species (texture, extremely sandy for all samples)

Plant species	Soil depth in cm	% organic carbon	WDPT
Powder bark wandoo	0 - 5	1.972	100 minutes
"	5 - 10	1.727	90 minutes
"	20 - 30	0.387	2 minutes
Jarrah	0 - 5	2.390	29 seconds
"	5 - 10	1.409	10 seconds
Sheoak	0 - 5	1.855	1 second

A link between water repellence and the quantity of soil organic matter similar to that reported by Holzhey (1968) was observed. For plant species like sheoak and jam that do not induce water repellence in soils, changes in the organic matter content of the associated soils do not affect the WDPT. The degree of water repellence in sandy soils under mallet and powder bark wandoo vegetation appears to vary directly with the organic matter content, hence it decreases with depth below the litter zone (see Table 9.2). The thickness of the litter and organic horizons determine the depth of the water repellent layer. For example, average WDPT of more than 2 minutes was recorded at a depth of 30 cm below thick powder bark wandoo litter on deep gray sands (Echidna SMU). An adjacent site with very little powder bark wandoo litter (and consequently very little organic matter in the soil) had WDPT of less than 5 seconds at 15 cm depth. Also it was demonstrated that less than 0.4% organic carbon can impart strong water repellence in sandy soil provided the organic material is hydrophobic.

Field investigations revealed that where the soil texture is heavy (e.g. Pingelly SMU with shallow A horizon) the water repellent layer is usually confined to the surface 5-10 cm. On Rosella SMU's with shallow pedisediment, the water repellent layer often terminates abruptly at the interface between the surface earthy material and the pinkish clays beneath, extending to greater depths only at points where tongues of A horizon are sandwiched between the clay.

Within an area of strong water repellence (e.g. soil under dense mallet vegetation) detailed examination of sites indicates very heterogenous distribution of WDPT values. The strongest repellence occurs with the zone closest to the tree trunk where WDPT in excess of six hours has been recorded, and then decreases radially away from it. The overlying partially decomposed organic matter (tree bark and leaves) is usually wettable and the water repellent layer lies a few centimetres (5-10 cm) below this. Pockets (less than 1 square metre) of wettable sites (i.e. WDPT <5 seconds) usually occur where there is no surface litter or where the litter is dominated by the undergrowth species like box poison or *Dryandra* sp. It is not uncommon to find a wettable site less than one metre away from an extremely repellent site. The presence of pockets of wettable soil within zones of extreme water repellence reveals that, though generally there is low infiltration and excessive run-off of rain water on these soils (Letey *et al.* 1962a), some of the moisture easily infiltrates the soil to wet-up the underlying layer. The effect of the capilliary rise of ground waters may also be important in this regard. Krammes & Osborn (1969) suggest that the presence of a moist layer under a wettable slightly hard layer that often underlies the water repellent layer, depends upon the presence of cracks or root channels which allow water penetration. However, field investigation of root channels in the Tuttanning

reserve show that they usually contain sands with strong water-repellent characteristics to depths of 50 cm or more and are therefore not the likely sites for water penetration except perhaps where the channels were formed by plants like sheoak that decompose to yield hydrophilic organic matter.

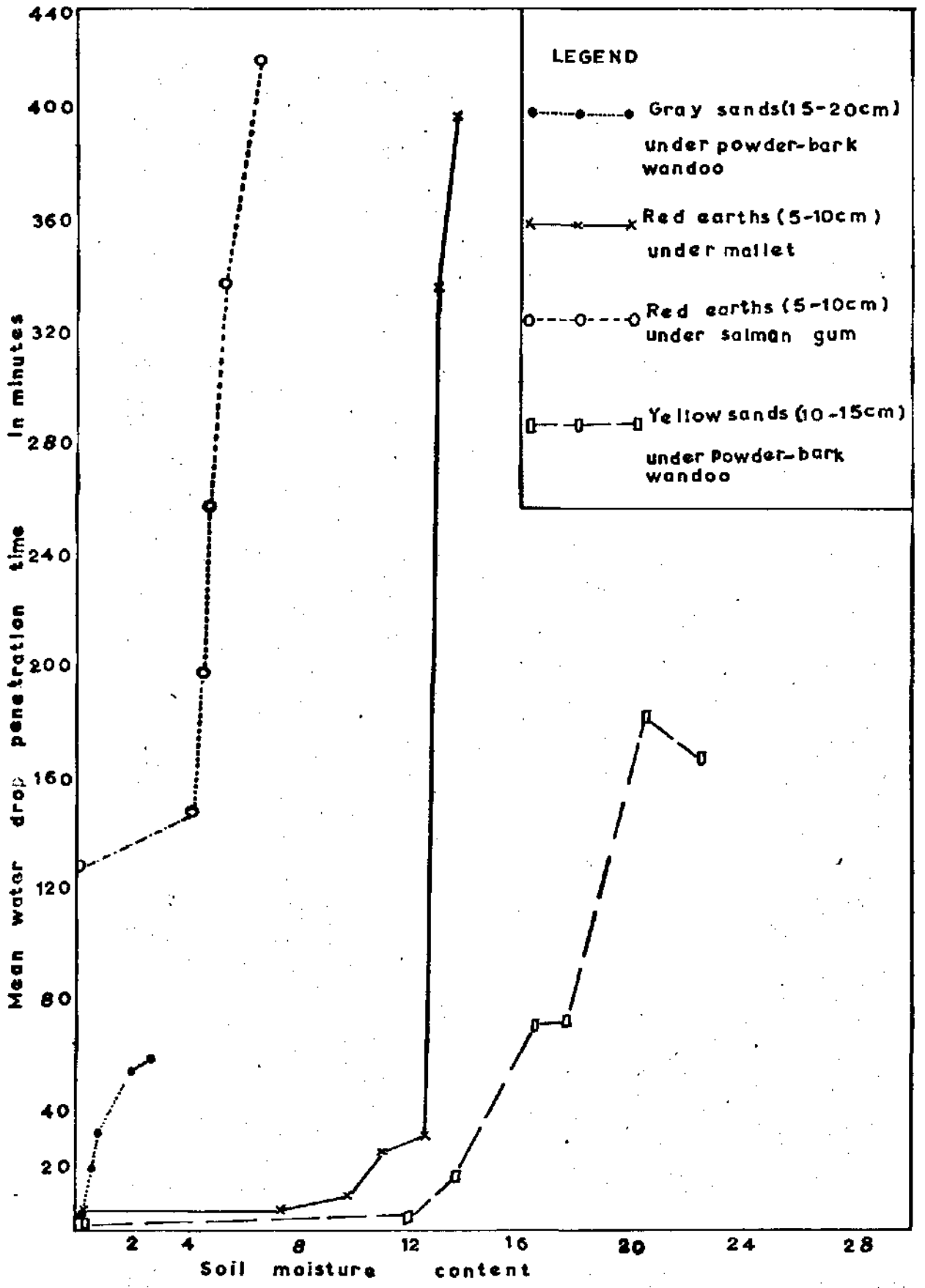
Water repellence and soil moisture content

Some water repellent samples were placed in ceramic pressure-plates at $^1/_3$ and 15 bar pressure of nitrogen and allowed to wet-up for several days; the WDPT and moisture content being determined at regular intervals (after Scholl 1971). The results presented in Figure 9.2 show that the degree of repellence increases with the increase in moisture. This increase appears to be gradual at first but is very dramatic after a certain amount of moisture is reached. Also the increase appears to be more pronounced on soil with heavier texture (i.e. red earths as against gray and yellow sands). Samples with WDPT up to one hour or more at air-dry condition sometimes become so repellent on taking up some moisture that it takes more than half a day for the water drop to disappear, particularly at low (less than 20°C) room temperatures. The disappearance of such water drops could be due to evaporation rather than absorption in the soil mass.

The finding that the degree of water repellence increases with the soil moisture content is at variance with the views of DeBano (1969) who indicated that, as moisture decreases in a non-wettable soil, the liquid-solid contact angle increases and WDPT under these conditions would be expected to increase. The finding is however in agreement with the observations of Bond (1969) that the soils become markedly more repellent after the first heavy falls of rain in the autumn period while the soil is still warm and during the period when

Fig. 9.2

THE DEGREE OF WATER REPELLENCE RELATED TO MOISTURE CONTENT OF SURFACE SOILS SAMPLED UNDER DIFFERENT VEGETATION SPECIES (INCREASE IN MOISTURE CONTENT OBTAINED FROM $\frac{1}{3}$ ATMOSPHERE PRESSURE PLATES, AFTER SCHOLL 1971.)



the soil fungi are in most active growth; that the repellence persists throughout the year though with much lower intensities during the dry summers than during the wet winters. The association of water repellent soils with soil fungi is still being investigated in several parts of the world including The University of Western Australia.

Distribution of water repellent soils

At Tuttanning extreme water repellence occurs in all soils examined under powder bark wandoo, mallet, salmon gum and wandoo litter regardless of the SMU. The only occurrence of salmon gum is at the extreme west end of the reserve, confined to the Pingelly SMU by Magpie track and therefore salmon gum does not significantly affect the distribution pattern of water repellent soils. Wandoo does not occur in dense stands, but is often widely scattered in association with sheoak and jam with undergrowth of box poison whose organic matter has hydrophilic properties. Therefore areas dominated by extreme water repellent soils are confined to the dense mallet and powder bark wandoo stands on the pediments and their extensions downslope into neighbouring soils with ironstone gravels. The relationship between ironstone gravels in soils and powder bark wandoo has already been treated in this chapter.

Map 2 (in map flap) shows the main areas dominated by water repellent soils and is based on the distribution of mallet and powder bark wandoo.

Water repellence and soil erosion

Letey *et al.* (1962a) Krammes and Osborn (1969) and others have emphasised the negligible infiltration rate resulting in excessive run-off on water repellent soils and how the surface run-off provides

the moving force for soil erosion. At Tuttanning, the occurrence of water repellent soils on fairly steep (4-7° declivity) pediment slopes (Rosella SMU) is ideal for maximum run-off. The increase in the degree of water repellence with the moistening up of the soil further aggravates the situation.

Erosion as expressed in rills and gullies is not evident on upper pediment soils. However, away from the upper pediments, channelled flow has carved out deep ravines, the bottoms of some of which lie about 3 metres below the surface. Pediment embayments (see Chapter IV - Geomorphology) are significant in this regard since they provide enough catchment for effective channelled flow. The ravines are recent, though most have been stabilised by vegetation, some still having fairly active heads, eating back into the regolith.

The dominance of sandy soils in the Tuttanning reserve and the low annual rainfall totals (around 17 inches) are ideal conditions for maximum infiltration of rain water. However, the presence of ravines suggests that extreme water repellence of the sands may be responsible for the channelled flow. Also, other factors that could at least in part be responsible for the formation of the ravines include:

1 The run-off from the granitic rock outcrops. A few of the ravines actually head from soaks below massive rock outcrops.

2 The presence of pre-weathered materials highly susceptible to water erosions. These materials include unconsolidated sediment and saprolite.

3 The effect of occasional summer thunder storms often associated with flash floods (see Chapter I - Climate).

CHAPTER X

SUMMARY

The Tuttanning reserve lies astride the divide between the Avon and the Hotham drainage systems. There is a good relationship between the orientation of the main first and second order elements of these drainage systems and the orientation of exposed features of geological structure such as basic dykes. The landscape is dominated by a number of laterite-capped residuals or mesas which represent remnants of the "old" plateau of Western Australia. Below these upland residuals is an undulating plateau, the "new" plateau, which contains features such as breakaways, pediments, spurs, low ridges and rock outcrops of variable shapes and sizes. It appears that the major elements of the present valley system were in existence prior to lateritization. Many of the present landforms are merely a consequence of erosional modification of an ancient landscape which had a general form rather similar to the present one.

There is a close, though complex, relationship between the soils and the topography. This complex pattern of soils and landforms is related to the differential stripping of the mantle of weathering. Such natural erosion has released sediment from various elements of the weathering profile and from extensive exposures of country rock. This sediment, along with elements of the *in situ* weathering profile, form the soil parent materials which range from light clays to sands, often with variable amounts of ironstone gravel.

The soils at Tuttanning are extremely sandy, derived from quartz-rich parent materials. Twenty two soil mapping units were recognised and mapped. Within these, the soils were insufficiently uniform for the units to be regarded either as types or series.

Therefore a relatively non-specific term, the soil mapping unit, was used and frequently abbreviated to SMU.

Ironstone gravels in the soils could have originated from any one of the following ways:

1 *In situ*, near the interface between the clay and the overlying sand in the zone of intermittent waterlogging.

2 *In situ*, as fragments of the mottled zone which were subsequently indurated.

3 Detrital from erosial activity on gravelly spurs, ridges and breakaways.

4 Fragments of fresh rock, partially weathered and coated with iron oxide.

Two main types of sand plain occur at Tuttanning, namely those dominated by yellow sands and those dominated by gray sands, referred to in this thesis as the Possum and Echidna SMU's respectively. In addition, coarse sandy materials forming aprons to the granite outcrops are another important component of surficial materials.

Particle size and shape analysis and quartz-feldspar ratio investigations revealed that yellow sands at Tuttanning are very heterogenous in properties. For example, the relative rollability values for yellow sands range from below average through average to above average. The feldspar content is also very variable. Skewness values for yellow sands range from negative through near symmetry to positive. Some yellow sand samples are very poorly sorted and bimodal with an almost flattish spread while others show a reasonable degree of peakedness and are unimodal. Gray sands, on the other hand, appear

to have fairly homogenous properties and are generally much more rounded and spherical than yellow sands. Increased rollability of coarser sand fractions and improved sorting downslope of the Possum track yellow sand body demonstrate the transported and depositional nature of the material.

The fact that Tuttanning sands are generally coarse with the majority of the modal sieve fractions for samples greater than 400μ suggests that these sands could not have been transported over long distances by wind. This is particularly true of the yellow sands which contain very angular grains with elongate characteristics. The Tuttanning yellow and gray sands may therefore be regarded as valley fills originating from local sources. The fact that yellow sands are consistently related to lateritic gravels points out that these sands could at least in part be derived from the breakdown of the duricrust. The breakdown released the sandy matrix which was eventually transported and deposited downslope.

Aeolian activity may not have been responsible for rounding the gray sands since the grains that are relatively most rounded are too coarse to have been transported by wind. Perhaps the gray sands could have been derived from the breakdown of sandstones similar to the pre-laterite conglomeratic sediments described by earlier workers as Mesozoic or Cretaceous in age. In this case, the gray sands could have been rounded during the deposition of the sandstone in the ancient past. It is also possible that, though extremely resistant to weathering at the sand size, quartz grains exposed to the atmosphere for many thousand years would tend to lose at least part of their angularity through

1 attrition during local surface creep and saltation within the sand body,

2 attrition between grains dislodged by rain drops and moving water during heavy stormy rainfall,

3 chemical weathering of the edges.

The vegetation of the Tuttanning reserve occurs in formations which are to a large extent related to the relief and to the soils. The nature and character of these vegetation formations, together with the nature of the surface soil, give rise to patterns represented by different photo tones and textures. It was noticed that though there was a close relationship between the soils and the vegetation, several soil boundaries transgressed vegetation boundaries.

Water repellency is well expressed by surface horizons of a number of soils from Tuttanning. In particular, those soils associated with a number of the eucalypts namely powder bark wandoo, wandoo, mallet and salmon gum show strong water repellence. Within an area of strong water repellence, detailed examination of sites indicated very heterogenous distribution of "water drop penetration time" values. Pockets of wettable sites usually occur where there is no surface litter or where the litter is dominated by the undergrowth species like box poison legumes. The degree of water repellence increases with the increase in soil moisture. This increase appears to be more pronounced on soil with heavier texture. At Tuttanning the occurrence of water repellent soils on fairly steep (4-7^{o} declivity) pediment slopes is ideal for maximum run-off. Hence deep ravines heading in pediment embayments are not uncommon.

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Fig. 6.12. MEAN RELATIVE ROLLABILITY FOR THE FIRST THREE SAMPLES OF THE TAMMER-ECHIDNA ROAD GRAY SANDS (Sp.3) COMPARED WITH THAT OF THE LAST THREE SAMPLES.

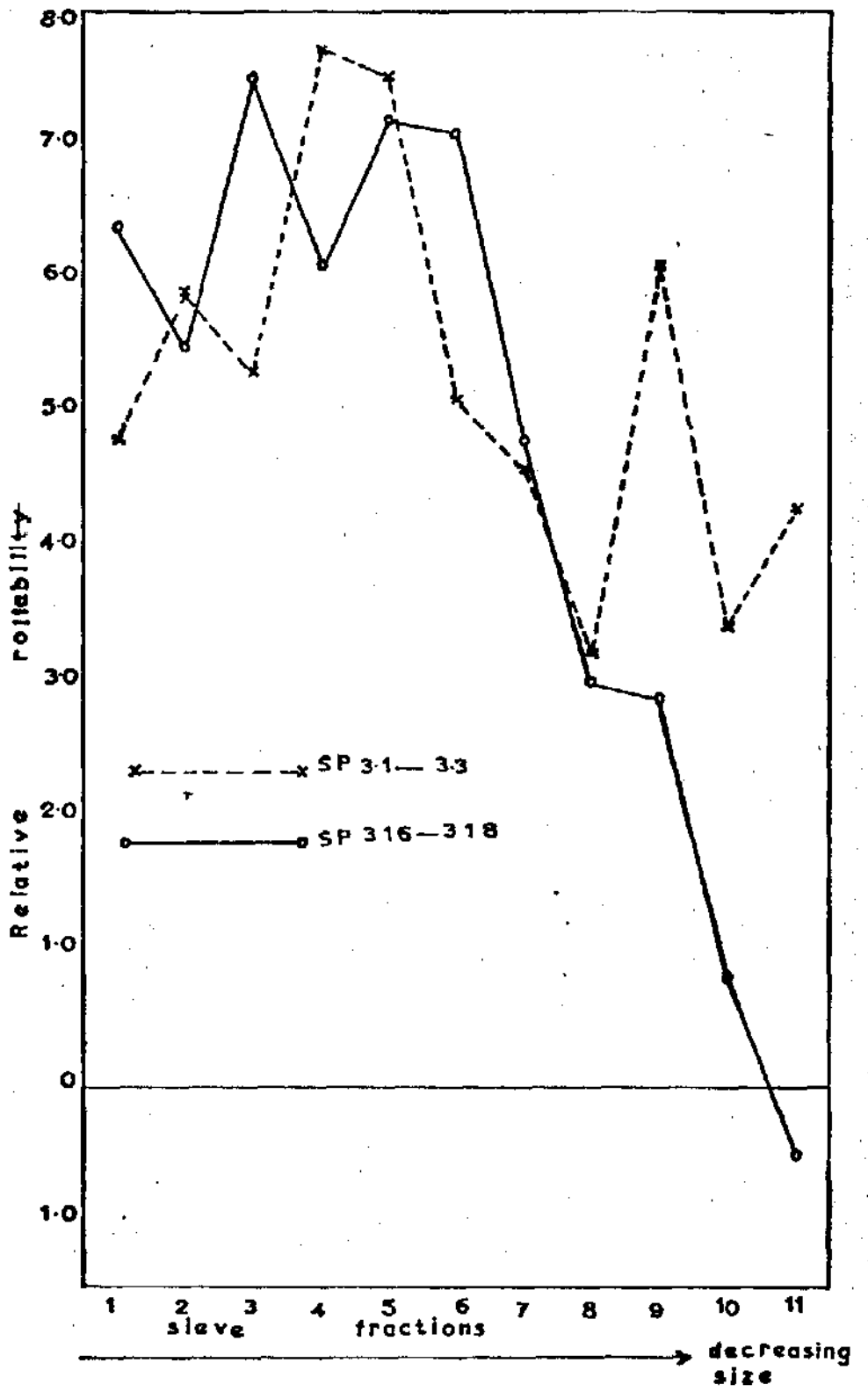


Fig. 6.25.

A PLOT OF SKEWNESS AGAINST STANDARD DEVIATION (σ_I) FOR YELLOW SANDS AND GRAY SANDS.

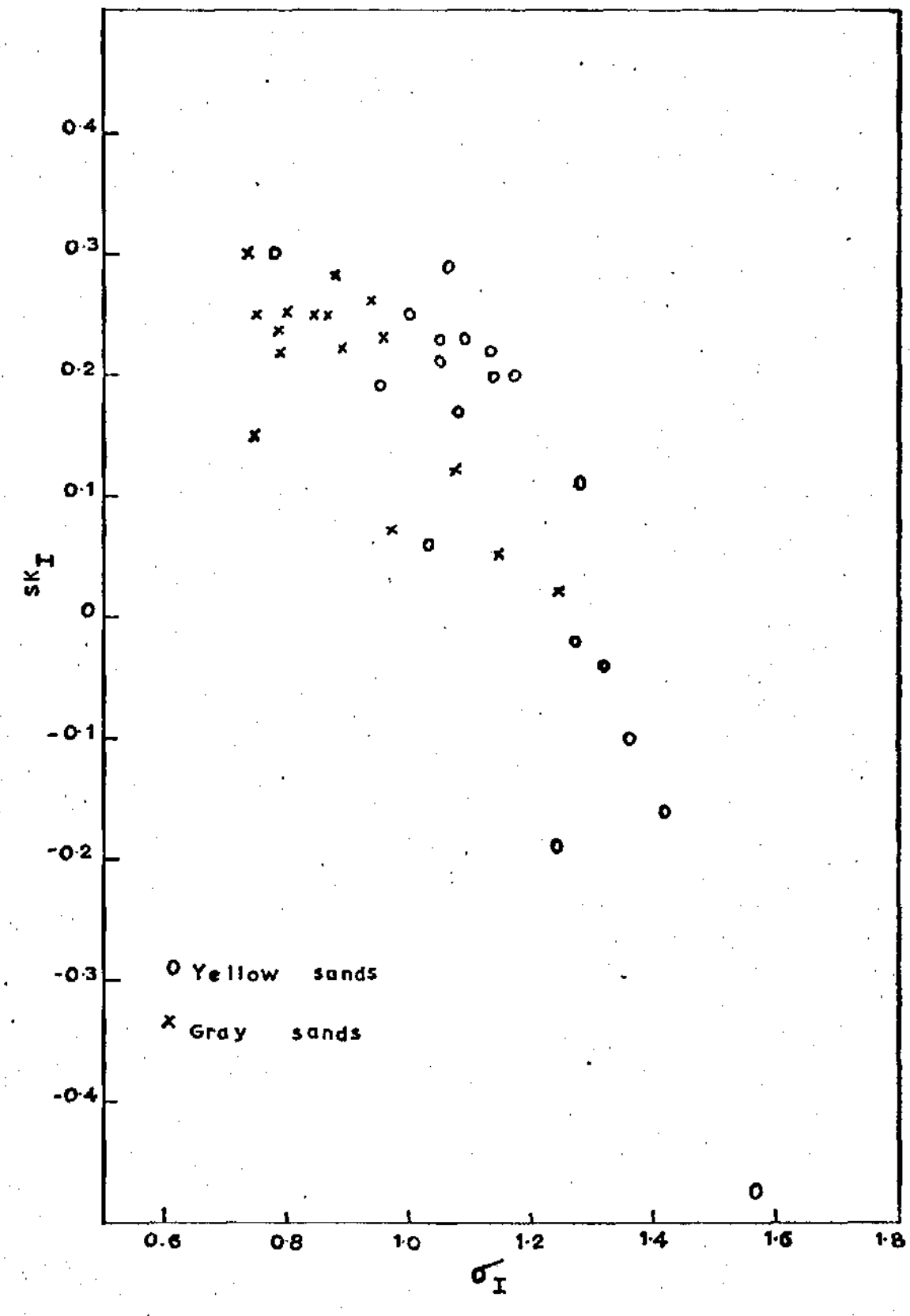


Fig. 6.26.

A PLOT OF SORTING (σ_I) AGAINST KURTOSIS (K_{GI}) FOR YELLOW SANDS AND GRAY SANDS.

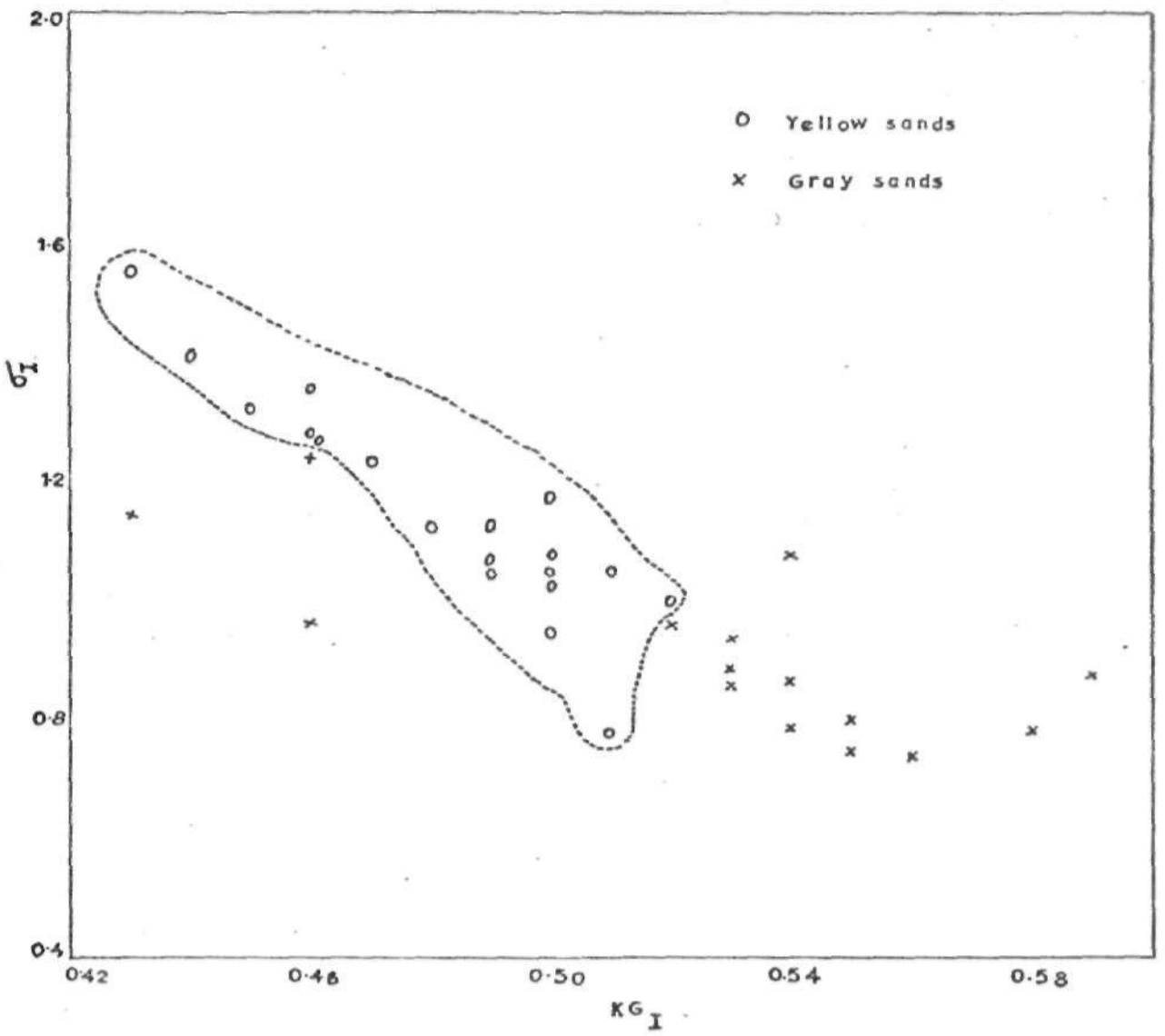


Fig. 6.27.

A PLOT OF SKEWNESS (SK_I) AGAINST KURTOSIS (K_{GI}) FOR YELLOW SANDS AND GRAY SANDS.

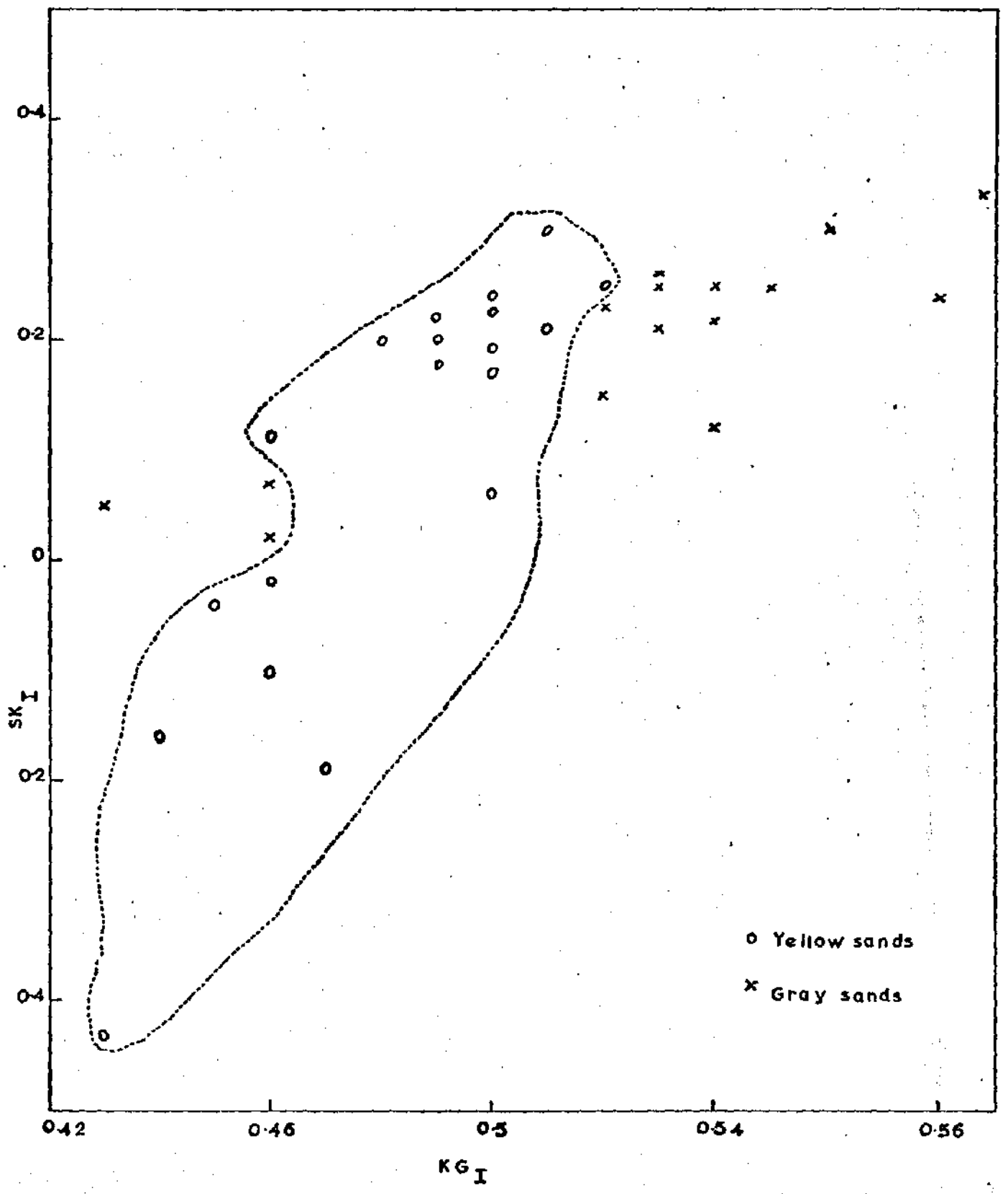
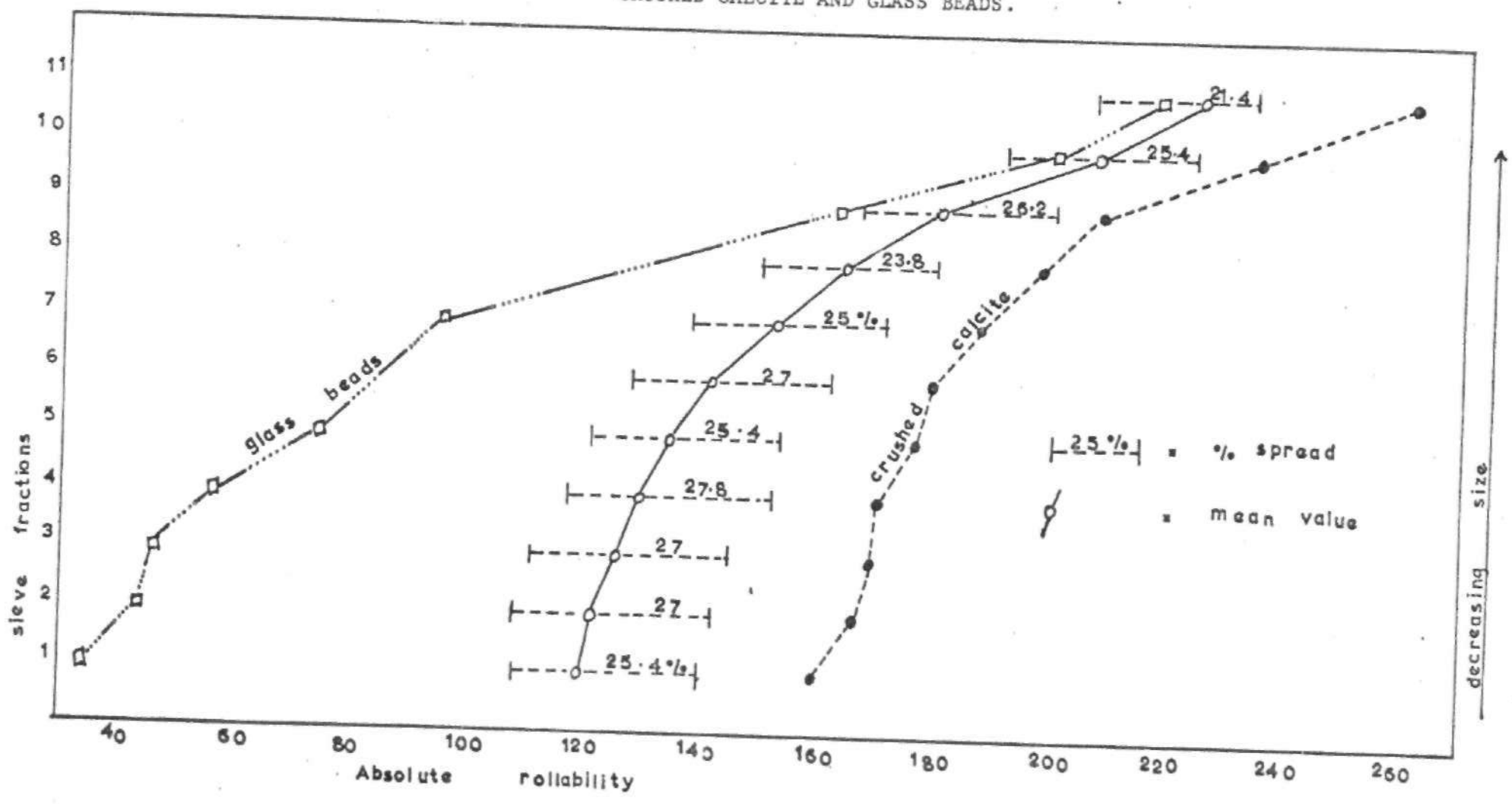


Fig. 6.3. RANGE OF ROLLABILITY VALUES PER SIEVE FRACTION FOR 100 SAMPLES OF TUTTANNING SANDS CONTRASTED WITH CRUSHED CALCITE AND GLASS BEADS.



APPENDIX I

TABLE 3.1

Absolute rollability values for sands before and after HCl treatment (in seconds)

Sample No.	Size Range	Roll before HCl treatment	Roll after HCl treatment
sp 2.1	180 - 212 μ	142.5	143
sp 2.3	180 - 212	165	167
sp 2.4	180 - 212	157	155.5
sp 2.6	300 - 355 μ	140	142
sp 2.7	300 - 355	129.5	128
sp 2.8	300 - 355 μ	134	135
sp 2.9	300 - 355	136	137.5
sp 2.12	125 - 150 μ	181	179
sp 2.14	125 - 150	182	180.5
sp 2.16	125 - 150 μ	186	186

APPENDIX I

TABLE 6.1(a)

Repeatability of Rollability measurements (in seconds)

Mesh size (microns)	90-106	106-125	125-150	150-180	180-212	212-250	250-300	300-355	355-425	425-500	500-600
Calcite											
1	261	233	204	198	188	180	176	170	169	168	160
2	261	238	212	197	186	179	177	170	169	164	159
Mean	261	235.5	208	197.5	187	179.5	176.5	170	169	166	159.5

Calcite	
10 runs	174
	175
	169.5
	173
	173
	173
	174
	169
	174
	177

APPENDIX I

TABLE 6.1(b)

Repeatability of Rollability measurements (in seconds).

Mesh size (microns)	91-107	107-124	124-176	176-249	249-318	318-418	418-452	452-520	520-690
Glass beads									
1	203	199	163	90	74	56	46.5	*u3*	33
2	214	201	170	90	75	56	45	43	35
Mean	208.5	200	166.5	90	74.5	56	45.75	43	34

Glass beads	
10 runs	76
	73
	75
	75
	74
	75
	76
	75
	75
	74

00

APPENDIX I

Absolute Rollability (sees)

Mesh size (microns)	90-106	106-125	125-150	150-180	180-212	212 250	250-300	300-355	355-425	425-500	500-600
(a) Yellow sand											
sp 1.1	226	217	193	177.5	165	152	145	138.5	129	128	123.5
sp 1.2	232	218	193	175	163	153	148	146	139	132	131
sp 1.3	232	217	194	178	165	162	149	141	141	138	140
sp 1.4	234	218	195	179	167	160	151	148	145	140	137
sp 1.5	233	218	200	178	170	161	153	152	143	142	138
sp 1.6	231	213	184	169	160	148	139	132	121	118	117
sp 1.7	221	200	172	154	146	134	127	123	118	117.5	117
sp 1.8	230	210.	183	170	160	146	141	136	127	122	117
sp 1.9	231.5	210	188	168	160.5	148	144.5	138.5	131	127	124
sp 1.10	230	218	189	167	157.5	147	135	126	121	116.5	113
(b) Gray sand											
sp 3.1	207	193	167	160	149	134	121	121	120	114	H6
sp 3.2	216	199	168.5	155	143	132	126	120	117	114	HO
SP 3.3	222	208	172	159.5	145	137	127	117	117	113	H4
SP 3-4	213	196.5	167	159	144	133	126	118	Hi	i12	113

APPENDIX I

Absolute Rollability (secs)

Mesh size (microns)	90-106	106-125	125-150	150-180	180-212	212-250	250-300	300-355	355-425	425-500	500-600
(b) Gray sand (cont.)											
sp 3.5	219	196	170	158	138	131	127	118	113	112	112
sp 3.6	220	199	176	153	147	136	126	123	116	108	112
sp 3.7	218	202	174	158	145	131	128	119	114	114	111
sp 3.8	224	202	173	157	145	134	125	120	114	112	110
sp 3.9	233	207	180	157	149.5	135	127	121	115	112	112
sp 3.10	232	203	177	157	147	134	127	121	118	112	111
sp 3.11	233	207	176	159	147	134	128.5	123	114	114	111
sp 3.12	227	192	174	155	147	134	127	119	115	112	111
sp 3.13	207	211	179	157	146	133	127	122	117	110	109
sp 3.14	230	201	176	156	146	132	126	119	115	112	111
sp 3.15	228	203	172	158	144	135	125	123	117	112	112
sp 3.16	233	215	173	159.5	146	133	125	121	112	113	110
sp 3.17	230	204	182	155	146	128	126.5	122	112	114	115
sp 3.18	220	197	170	161	145	133	124	121	118	113.5	109.5
sp 4.1	215	196.5	167	156.5	145.5	137	131	127	122	119	117
sp 4.2	217	203	171.5	150	142	135	126	122.5	118	114	116
sp 4.3	223	199	174	154	145	132	127	121.5	117	116	113.5

APPENDIX I

Absolute Rollability (secs)

Mesh size (microns)	90-106	106-125	125-150	150-180	180-212	212-250	250-300	300-355	355-425	425-500	500-600
(b) Gray sand (cont.)											
sp 4.4	214	202	170	152	142	132	126.5	121	115	117	116
sp 4.5	220	195	173	154	142	132	128	123.5	118	112	112
sp 4.6	226	197	172	157	140	129.5	126	124	117	115	113
sp 4.7	214	193	173.5	157	142	133	127	121	116	112	110
sp 4.8	210	197	168	156	144	133	129	120	112	110	111
sp 4.9	217.5	194	167	155	146	136	128	124	114	113	108
sp 4.10	226	197	170	154	144	132	127	122	117.5	113	112
(c) Rock detritus											
sp 5.1	230	207	177	165	150	143	136	127	122	122.5	117.5
sp 5.2	222	199	175	163	151	140.5	135	129	126	122	117
sp 5.3	234	215	191	177	167	155	149	140	133.5	131.5	128
sp 5.4	232	213	187	168	156	144	137	132	127	126	125
sp 5.5	227	206	176	161	149	138	133.5	128	124	118	120.5
sp 5.6	228	211	180	166.5	153	141	133	127	123.5	122	122
sp 5.7	220	205	176	159.5	151.5	138	132	126	124	117	119
sp 5.8	216	201	178	159	148	139	135	129	123.5	118	117

APPENDIX I

Absolute Rollability (secs)

Mesh size (microns)	90-106	106-125	125-150	150-180	180-212	212-250	250-300	300-355	355-425	425-500	500-600
(c) Rock Detritus (cont)											
sp 5.9	222	213	174.5	166	152	143	134	129	126.5	123	121
sp 5.10	222.5	206	176.5	157	161	140	135	130	126	122	121
sp 5.11	222	199	172	160	151	139	134	132	121	123	120.5
sp 5.12	222	206	177.5	160	148	140	136	132	127.5	123	122
sp 5.13	233.5	218	192	174.5	170.5	157	145	142	134	131	130
sp 5.14	231	216.5	191	173	168	157	149	145	138	132	129.5
sp 5.15	224	214	193	172.5	165	154	147	139	133.5	130.5	128
sp 5.16	233	217	191.5	173	162.5	156	146	143	137	130	126.5
sp 5.17	230	215	190	173	165	151	146.5	145	137	129.5	127
sp 5.18	234	221	198	180	168	156	151	144	138	130	131.5
sp 5.19	227	221.5	193	174	162	155	146	143	137	131	130
sp 5.20	234	213	197	174	166	153	148	139	133	128	127.5
sp 5.21	231	224	195	175	168	153	144	142	132	129	123
sp 5.22	228	216	194	172	162	150	144	136	131	126	122

APPENDIX I

Absolute Rollability (secs)

Mesh size (microns)	90-106	106-125	125-150	150-180	180-212	212-250	250-300	300-355	355-425	425-500	500-600
(d) Stream channel sands											
sp 6.1		208.5	182	169	152	138	137	127	123	124	118
sp 6.2			181	163	157	141	136	129	122	121	120
sp 6.3			176	163	151	141	133	129	122	122	117
sp 6.4		208	172	160	150	139	130	125	125	121	117
sp 6.5	218	210	181	162	150	136.5	133	127	123	121	118
sp 6.6			178	162	153	137	133	126	121	119	119.5
sp 6.7	218	208	178	162	152	137	131	128	122	119	118
sp 6.8	222	204	178	162	152	138	133	126	122	118	114
sp 6.9	225	209.5	177	162	151	139	133	129	124	120	117
sp 6.10	226	210	178	161	154	142	133	128	124	122.5	117
sp 6.11		212	183	167	150	141	135	128	122	119	118
sp 6.12			179	160	149	136	131	132	120	121	114
sp 6.13			176	162	150	141	132	128	122	121	118
sp 6.14			175	163	150	140	132	128	122	119	115
sp 6.15	220	208	185	167	151	138	133	128	124	120.5	118
sp 6.16			186	166	153	137	135	123	121	118	118
sp 6.17	219	204	180	162	152	139	131	126	121	119.5	115

APPENDIX I

Absolute Rollability (secs)

Mesh size (microns)	90-106	106-125	125-150	150-180	180-212	212-250	250-300	300-355	355-425	425-500	500-600
(d) Stream channel sands											
sp 6.18	226	204	181	162	151.5	136	133	127	122	117.5	116
sp 6.19		207	177	161	148	140	132.5	128	121.5	120	117
sp 6.20	221	200	173	162.5	148.5	140	132	128	122	120	118
(e) Yellow sands (spillway analysed)											
sp 2.1	221	197	170	151	142.5	132	127	120.5	117.5	117.5	116.5
sp 2.2	226	210	184	165	157	150	141	138	130.5	128	126.5
sp 2.3	232	213	192	176	165	155	146	145	137	137	136.5
sp 2.4	224	216	183	168	157	146	139.5	134	130	121	121
sp 2.5	212	194	168	155	142	131	126	121	118	117	113
sp 2.6	233	215	189	174	162	151	147	140	134	132	131
sp 2.7	222	207	181	159	156	144	136	129.5	127	118.5	114
sp 2.8	221	206	178	162	157	145	138	134	128	125	124
sp 2.9	228	213	185	168.5	156	149	138	136	129	128	121.5
sp 2.10	229	211	188	167	159	149	142	138	131	128	126
sp 2.11	225.5	205	183	166.5	155	143.5	140	130	127	123	122
sp 2.12	224	208	181	165	154	143	137	130	126	122	118

APPENDIX I

Absolute Rollability (secs)

Mesh size (microns)	90-106	106-125	125-150	150-180	180-212	212-250	250-300	300-355	355-425	425-500	500-600
(e) Yellow sands (spillway analysed)											
sp 2.13	221	204	180	162	151	143	136	127	120.5	120.5	119
sp 2.14	224	209	182	170	157	145	138	133	127	125	120
sp 2.15	234	209	186	166	157	146	139	131.5	127.5	125	122
sp 2.16	228	207	186	166	153	142	137	135	128	122	124
sp 2.17	228	205	183	164	156	144	138	133	123	121	119
sp 2.18	218	201	179	159.5	156	137	132	126	119	115	114
sp 2.19	225	211	182	166	152.5	146	138	132	124	119	118
sp 2.20	230	213	185	165	153	143	136	131	123	117.5	117.5

APPENDIX I

Relative Rollability as % deviation ± from the mean

Mesh size (microns)	90-106	106-125	125-150	150-180	180-212	212-250	250-300	300-355	355-425	425-500	500-600
sp 2.1	+1.6	+4.8	+5.7	+7.6	+6.7	+6.7	+5.8	+6.8	+6.0	+2.7	+2.2
sp 2.2	-0.6	-1.4	-2.1	-0.9	-2.7	-6.0	-4.6	-6.7	-4.4	-6.0	-6.2
sp 2.3	-3.2	-2.9	-6.5	-7.6	-8.0	-9.5	-8.3	-12.1	-9.6	-13.4	-14.6
sp 2.4	+0.3	-4.3	-1.6	-2.8	-2.7	-3.2	-3.5	-3.6	-4.0	-0.2	-1.6
sp 2.5	+5.7	+6.3	+6.8	+5.2	+7.1	+7.4	+6.2	+6.4	+5.6	+3.1	+5.1
sp 2.6	-3.7	-3.9	-4.9	-6.4	-6.0	-6.7	-9.1	-8.3	-7.2	-9.3	-10.0
sp 2.7	+1.2	0	-0.4	+2.8	-2.1	-1.8	-0.9	-0.2	-1.6	+1.9	+4.3
sp 2.8	+1.6	+0.5	+1.2	+0.9	-2.7	-2.8	-2.4	-3.6	-2.4	-3.5	-4.1
sp 2.9	-1.5	-2.4	-2.7	-3.1	-2.1	-5.3	-2.4	-5.2	-3.2	-6.0	-2.0
sp 2.10	-1.9	-1.9	-4.3	-2.1	-4.1	-5.3	-5.3	-6.7	-4.8	-6.0	-5.8
sp 2.11	-0.4	+0.7	-1.6	-1.8	-1.4	-1.4	-3.9	-0.5	-1.6	-1.8	-2.4
sp 2.12	+0.3	-0.5	-0.4	-0.9	-0.8	-1.1	-1.6	-0.5	-0.8	-1.0	+0.9
sp 2.13	+1.6	+1.4	+0.1	+0.9	+1.2	-1.1	-0.9	+1.8	+3.6	+0.2	+0.1
sp 2.14	+0.3	-0.7	-1.0	-4.0	-2.7	-2.8	-2.4	-2.9	-1.6	-3.5	-0.8
sp 2.15	-4.1	-0.7	-3.2	-1.5	-2.7	-3.2	-3.1	-1.7	-2.0	-3.5	-2.4
sp 2.16	-1.5	0	-3.2	-1.5	-0.1	-0.4	-1.6	-4.4	-2.4	-1.0	-4.1
sp 2.17	-1.5	+0.7	-1.6	-0.3	-2.1	-1.8	-2.4	-2.9	+1.6	-0.2	+0.1
sp 2.18	+3.0	+2.9	+1.2	+2.4	-2.1	+3.2	+2.1	+2.6	+4.8	+4.8	+4.3
sp 2.19	-0.1	-1.9	-1.0	-1.5	+0.2	-3.2	-2.4	-2.1	+0.8	+1.5	+0.9
sp 2.20	-2.4	-2.9	-2.7	-0.9	-0.1	-1.1	-0.9	-1.3	+1.6	+2.7	+1.3
sp 5.12	+1.2	+0.5	+1.5	+2.1	+3.1	+1.1	-0.9	-2.1	-2.0	-1.8	-2.4
sp 5.13	-3.9	-5.3	-6.5	-6.7	-11.6	-11.0	-7.7	-9.8	-7.2	-8.4	-9.2
sp 5.14	-2.8	-4.6	-6.0	-5.8	-9.9	-11.0	-10.5	-12.1	-10.4	-9.3	-8.7
sp 5.15	+0.3	-3.4	-7.1	-5.5	-7.9	-8.8	-9.1	-7.5	-6.8	-8.0	-7.5
sp 5.16	-3.7	-4.8	-6.3	-5.8	-6.3	-10.2	-8.3	-10.6	-9.6	-7.6	-6.2
sp 5.17	-2.4	-3.9	-5.4	-5.8	-7.9	-6.7	-8.8	-12.1	-9.6	-7.2	-6.6
sp 5.18	-4.1	-6.3	-9.9	-10.1	-9.9	-10.2	-12.0	-11.4	-10.4	-7.6	-10.4
sp 5.19	-1.0	-6.5	-7.1	-6.4	-6.0	-9.5	-8.3	-10.6	-9.6	-8.4	-9.2
sp 5.20	-4.1	-2.4	-9.3	-6.4	-8.6	-8.1	-9.8	-7.5	-6.4	-6.0	-7.1
sp 5.21	-2.8	-8.2	-8.2	-7.0	-9.9	-8.1	-6.8	-9.8	-5.6	-6.8	-3.3

Relative Rollability as % deviation ± from the mean (Cont)

Mesh size (microns)	90-106	106-125	125-150	150-180	180-212	212-250	250-300	300-355	355-425	425-500	500-600
sp 3.1	+7.9	+6.8	+7.3	+2.1	+2.5	+5.3	+10.2	+6.4	+3.2	+5.6	+2.6
sp 3.2	+3.9	+3.9	+6.5	+5.2	+6.4	+6.7	+6.5	+7.2	+6.4	+5.6	+7.6
sp 3.3	+1.2	-0.5	+4.6	+2.4	+5.1	+3.2	+5.9	+9.5	+6.4	+6.5	+4.3
sp 3.4	+5.2	+5.1	+7.3	+2.8	+5.8	+6.0	+6.5	+8.7	+11.2	+7.3	+5.1
sp 3.5	+2.5	+5.3	+5.7	+3.4	+9.7	+7.4	+5.9	+8.7	+9.6	+7.3	+6.0
sp 3.6	+2.1	+3.9	+2.3	+6.4	+3.8	+3.9	+6.5	+4.9	+7.2	+10.6	+6.0
sp 3.7	+3.0	+2.4	+3.4	+3.4	+5.1	+7.4	+5.0	+8.0	+8.8	+5.6	+6.8
sp 3.8	+0.3	+2.4	+4.0	+4.0	+5.1	+5.3	+6.9	+7.2	+8.8	+7.3	+7.6
sp 3.9	-3.7	0	_0.1	+4.0	+2.2	+4.6	+5.9	+6.4	+8.0	+7.3	+6.0
sp 3.10	-3.2	+1.9	+1.8	+4.0	+3.8	+5.3	+5.9	+6.4	+5.6	+7.3	+6.8
sp 3.11	-3.7	0	+2.3	+2.8	+3.8	+5.3	+4.7	+4.9	+8.8	+5.6	+6.8
sp 3.12	-1.0	-7.2	+3.4	+5.2	+3.8	+5.3	+5.9	+8.0	+8.0	+7.3	+6.8
sp 3.13	+3.4	-1.9	+0.7	+4.0	+4.6	+6.0	+5.9	+5.6	+6.4	+8.9	+8.5
sp 3.14	-2.4	+2.9	+2.3	+4.6	+4.6	+6.7	+6.5	+8.0	+8.0	+7.3	+6.8
sp 3.15	-1.5	+1.9	+4.6	+3.4	+5.8	+4.6	+7.3	+4.9	+6.4	+7.3	+6.0
sp 3.16	-3.7	-3.9	+4.0	+2.4	+4.6	+6.0	+7.3	+6.4	+10.4	+6.5	+7.6
sp 3.17	-2.8	+1.4	-1.0	+5.2	+4.6	+9.5	+6.2	+5.6	+6.4	+5.6	+3.4
sp 3.18	+2.1	+4.8	+5.7	+1.5	+5.1	+6.0	+8.0	+6.4	+5.6	+4.4	+8.1
sp 4.1	+4.3	+5.1	+7.3	+4.3	+4.8	+3.2	+2.8	+1.8	+2.4	+1.5	+1.8
sp 4.2	+3.4	+1.9	+4.8	+8.1	+7.1	+4.6	+6.5	+5.3	+5.6	+5.6	+2.6
sp 4.3	+0.8	+3.9	+3.4	+5.8	+5.1	+6.7	+5.8	+6.0	+6.4	+4.0	+4.7
sp 4.4	+4.8	+2.4	+5.7	+7.0	+7.1	+6.7	+6.2	+6.4	+8.0	+3.1	+2.6
sp 4.5	+2.1	+6.3	+4.0	+5.8	+7.1	+6.7	+5.0	+4.5	+5.6	+7.3	+6.0
sp 4.6	-0.6	+4.8	+4.6	+4.0	+8.4	+8.5	+6.5	+4.1	+6.4	+4.8	+5.1
sp 4.7	+4.8	+6.8	+3.6	+4.0	+7.1	+6.0	+5.8	+6.4	+7.2	+7.3	+7.6
sp 4.8	+6.5	+4.8	+6.8	+4.6	+5.8	+6.0	+4.3	+7.2	+10.4	+8.9	+6.8
sp 4.9	+3.2	+6.3	+7.3	+5.2	+4.6	+3.9	+5.0	+4.1	+8.8	+6.5	+9.3
sp 4.10	-0.6	+4.8	+5.7	+5.8	+5.8	+6.7	+5.8	+5.6	+6.0	+6.5	+6.0

Mean Relative Rollability values for 3 adjoining samples - sp 2

Mesh size (microns)	90-106	106-125	125-150	150-180	180-212	212-250	250-300	300-355	355-425	425-500	500-600
1,2,3	-0.7	+0.2	-1.0	-0.3	-1.3	-2.9	-2.4	-4.0	-2.7	-5.6	-6.2
4,5,6	+0.8	-0.6	+0.1	-1.3	-0.5	-0.8	-2.1	-1.8	-1.9	-2.1	-2.2
7,8,9	+0.4	-0.6	-0.6	+0.2	-2.3	-3.3	-1.9	-3.0	-2.4	-2.5	-0.6
10,11,12	-0.3	-0.6	-2.1	-1.6	-2.1	-2.6	-3.6	-2.6	-2.4	-2.9	-2.4
13,14,15	-0.7	0	-1.0	-1.5	-1.4	-2.4	-2.1	-0.9	0	-2.3	-1.0
16,17,18	0	+1.2	-1.2	+0.2	-1.4	+0.3	-0.6	-1.7	+1.3	+1.2	+0.1
18,19,20	+0.2	-0.6	-0.8	0	-0.7	-0.4	-0.4	-0.3	+2.4	+3.0	+2.2

Mean Relative Rollability values for 3 adjoining samples - sp 3

Mesh size (microns)	90-106	106-125	125-150	150-180	180-212	212-250	250-300	300-355	355-425	425-500	500-600
1,2,3	+4.3	+3.4	+6.1	+3.2	+4.6	+5.1	+7.5	+7.7	+5.3	+5.9	+4.8
4,5,6	+3.3	+4.8	+5.1	+4.2	+6.4	+5.8	+6.3	+7.4	+9.3	+8.4	+5.7
7,8,9	-0.1	+1.6	+2.5	+3.8	+4.1	+5.8	+5.9	+7.2	+8.5	+6.7	+6.8
10,11,12	+2.6	+3.0	+2.5	+4.0	+3.8	+5.3	+5.5	+6.4	+7.5	+6.7	+6.8
13,14,15	-0.2	+1.0	+2.5	+4.0	+5.0	+5.8	+6.6	+6.2	+6.9	+7.8	+7.1
16,17,18	-0.5	+0.8	+2.9	+3.0	+4.8	+7.1	+7.2	+6.1	+7.5	+5.5	+6.4

Deposit - Repository calculations - First nine vs last nine samples (sp 3)

Mesh size (microns)	90-106	106-125	125-150	150-180	180-212	212-250	250-300	300-355	355-425	425-500	500-600
sp 3.1-3.9	+2.5	+3.3	+4.6	+3.7	+5.1	+5.5	+6.6	+7.4	+7.7	+7.0	+5.8
sp 3.10-3.18	-1.4	+1.6	+2.6	+3.8	+4.1	+6.1	+6.4	+6.2	+7.3	+6.7	+6.8

Deposit - Repository calculations - First ten vs last ten samples (sp 2)

Mesh size (microns)	90-106	106-125	125-150	150-180	180-212	212-250	250-300	300-355	355-425	425-500	500-600
sp 2.1-2.10	-0.1	-0.5	-0.9	-0.6	-1.7	-2.7	-2.5	-3.3	-2.7	-3.7	-3.3
sp 2.11-2.20	-0.5	-0.1	-1.3	-0.9	-1.1	-1.3	-1.7	-1.2	+0.4	-0.2	-0.2

APPENDIX I

Maximum, minimum and mean rollability values for each sieve fraction, all specimens included (in seconds)

Sieve fraction	Maximum	Minimum	Difference	Mean
90-106μ	234	207	27	224.7
106-125μ	224	192	32	207.0
125-150μ	200	167	33	180.2
150-180μ	180	150	30	163.5
180-212μ	170.5	138	31.5	141.5
250-300μ	153	121	32	134.8
300-355μ	152	117	35	129.3
355-425μ	145	111	34	125
425-500μ	142	108	34	120.7
500-600μ	140	108	32	119

APPENDIX I

Relative Rollability values (deviations) for yellow sands (sp 2)

Mesh size (microns)	90-106	106-125	125-150	150-180	180-212	212-250	250-300	300-355	355-425	425-500	500-600
sp 2.1	+ 3.7	+10	_10.2	+12.5	+10.3	+ 9.5	+ 7.8	+ 8.8	+ 7.5	+ 3.3	+ 2.6
sp 2.2	- 1.3	- 3	- 3.8	- 1.5	- 4.2	- 8.5	- 6.2	- 8.7	- 5.5	- 7.2	- 7.4
sp 2.3	- 7.3	- 6	-11.8	-12.5	-12.2	-13.5	-11.2	-15.7	-12.0	-16.2	-17.4
sp 2.4	+ 0.7	- 9	- 2.8	- 4.5	- 4.2	- 4.5	- 4.7	- 4.7	- 5.0	- 0.2	- 1.9
sp 2.5	+12.7	+13	+12.2	+ 8.5	+10.8	+10.5	+ 8.8	+ 8.3	+ 7.0	+ 3.8	+ 6.1
sp 2.6	- 8.3	- 8	- 8.8	-10.5	- 9.2	- 9.5	-12.2	-10.7	- 9.0	-11.2	-11.9
sp 2.7	+ 2.7	0	- 0.8	+ 4.5	- 3.2	- 2.5	- 1.2	- 0.2	- 2.0	+ 2.3	+ 5.1
sp 2.8	+ 3.7	+ 1	+ 2.2	+ 1.5	- 4.2	- 3.5	- 3.2	- 4.7	- 3.0	- 4.2	- 4.9
sp 2.9	- 3.3	- 5.0	- 4.8	- 5.0	- 3.2	- 7.5	- 3.2	- 6.7	- 4.0	- 7.2	- 2.4
sp 2.10	- 4.3	- 4	- 7.8	- 3.5	- 6.2	- 7.5	- 7.2	- 8.7	- 6.0	- 7.2	- 6.9
sp 2.11	- 0.8	+ 2	- 2.8	- 3.0	- 2.2	- 2.0	- 5.2	- 0.7	- 2.0	- 2.2	- 2.9
sp 2.12	+ 0.7	- 1	- 0.8	- 1.5	- 1.2	- 1.5	- 2.2	- 0.7	- 1.0	- 1.2	+ 1.1
sp 2.13	+ 3.7	+ 3	+ 0.2	+ 1.5	+ 1.8	- 1.5	- 1.2	+ 2.3	+ 4.5	+ 0.3	+ 0.1
sp 2.14	+ 0.7	- 2	- 1.8	- 6.5	- 4.2	- 3.5	- 3.2	- 3.7	- 2.0	- 4.2	- 0.9
sp 2.15	- 9.3	- 2	- 5.8	- 2.5	- 4.2	- 4.5	- 4.2	- 2.2	- 2.5	- 4.2	- 2.9
sp 2.16	- 3.3	0	- 5.8	- 2.5	- 0.2	- 0.5	- 2.2	- 5.7	- 3.0	- 1.2	- 4.9
sp 2.17	- 3.3	+ 2	- 2.8	- 0.5	- 3.2	- 2.5	- 3.2	- 3.7	+ 2.0	- 0.2	+ 0.1
sp 2.18	+ 6.7	+ 6	+ 2.2	+ 4.0	- 3.2	+ 4.5	+ 2.8	+ 3.3	+ 6.0	+ 5.8	+ 5.1
sp 2.19	- 0.3	- 4	- 1.8	- 2.5	+ 0.3	- 4.5	- 3.2	- 2.7	+ 1.0	+ 1.8	+ 1.1
sp 2.20	- 5.3	- 6	- 4.8	- 1.5	- 0.2	- 1.5	- 1.2	- 1.7	+ 2.0	+ 3.3	+ 1.6

APPENDIX I

Relative Rollability values (deviations) for sp 5 (rock detritus), sp 5 (12-21)

Mesh size (microns)	90-106	106-125	125-150	150-180	180-212	212-250	250-300	300-355	355-425	425-500	500-600
sp 5.12	+ 2.7	+ 1.0	+ 2.7	+ 3.5	+ 4.8	+ 1.5	- 1.2	- 2.7	- 2.5	- 2.2	- 2.9
sp 5.13	- 8.8	-11.0	-11.8	-11.0	-17.7	-15.5	-10.2	-12.7	- 9.0	-10.2	-10.9
sp 5.14	- 6.3	- 9.5	-10.8	- 9.5	-15.2	-15.5	-14.2	-15.7	-13.0	-11.2	-10.4
sp 5.15	+ 0.7	- 7.0	-12.8	- 9.0	-12.2	-12.5	-12.2	- 9.7	- 8.5	- 9.7	- 8.9
sp 5.16	- 8.3	-10.0	-11.3	- 9.5	- 9.7	-14.5	-11.2	-13.7	-12.0	- 9.2	- 7.4
sp 5.17	- 5.3	- 8.0	- 9.8	- 9.5	-12.2	- 9.5	-11.7	-15.7	-12.0	- 8.7	- 7.9
sp 5.18	- 9.3	-13.0	-17.8	-16.5	-15.2	-14.5	-16.2	-14.7	-13.0	- 9.2	-12.4
sp 5.19	- 2.3	-13.5	-12.8	-10.5	- 9.2	-13.5	-11.2	-13.7	-12.0	-10.2	-10.9
sp 5.20	- 9.3	- 5.0	-16.8	-10.5	-13.2	-11.5	-13.2	- 9.7	- 8.0	- 7.2	- 8.4
sp 5.21	- 6.3	-17.0	-14.8	-11.5	-15.2	-11.5	- 9.2	-12.7	- 7.0	- 8.2	- 3.9

APPENDIX I

Relative Rollability values (deviations) for sp 3 (Giant Gray sands)

Mesh size (microns)	90-106	106-125	125-150	150-180	180-212	212-250	250-300	300-355	355-425	425-500	500-600
sp 3.1	+17.7	+14.0	+13.2	+ 3.5	+ 3.8	+ 7.5	+13.8	+ 8.3	+ 4	+ 6.8	+ 3.1
sp 3.2	+ 8.7	+ 8.0	+11.7	+ 8.5	+ 9.8	+ 9.5	+ 8.8	+ 9.3	+ 8	+ 6.8	+ 9.1
sp 3.3	+ 2.7	- 1.0	+ 8.2	+ 4.0	+ 7.8	+ 4.5	+ 7.8	+12.3	+ 8	+ 7.8	+ 5.1
sp 3.4	+11.7	+10.5	+13.2	+ 4.5	+ 8.8	+ 8.5	+ 8.8	+11.3	+14	+ 8.8	+ 6.1
sp 3.5	+ 5.7	+11.0	+10.2	+ 5.5	+14.8	+10.5	+ 7.8	+11.3	+12	+ 8.8	+ 7.1
sp 3.6	+ 4.7	+ 8.0	+ 4.2	+10.5	+ 5.8	+ 5.5	+ 8.8	+ 6.3	+ 9	+12.8	+ 7.1
sp 3.7	+ 6.7	+ 5.0	+ 6.2	+ 5.5	+ 7.8	+10.5	+ 6.8	+10.3	+11	+ 6.8	+ 8.1
sp 3.8	+ 0.7	+ 5.0	+ 7.2	+ 6.5	+ 7.8	+ 7.5	+ 9.3	+ 9.3	+11	+ 8.8	+ 9.1
sp 3.9	- 8.3	0	+ 0.2	+ 6.5	+ 3.3	+ 6.5	+ 7.8	+ 8.3	+10	+ 8.8	+ 7.1
sp 3.10	- 7.3	+ 4.0	+ 3.2	+ 6.5	+ 5.8	+ 7.5	+ 7.8	+ 8.3	+ 7	+ 8.8	+ 8.1
sp 3.11	- 8.3	0	+ 4.2	+ 4.5	+ 5.8	+ 7.5	+ 6.3	+ 6.3	+11	+ 6.8	+ 8.1
sp 3.12	- 2.3	+15.0	+ 6.2	+ 8.5	+ 5.8	+ 7.5	+ 7.8	+10.3	+10	+ 8.8	+ 8.1
sp 3.13	+ 7.7	- 4.0	+ 1.2	+ 6.5	+ 6.8	+ 8.5	+ 7.8	+ 7.3	+ 8	+10.8	+10.1
sp 3.14	- 5.3	+ 6.0	+ 4.2	+ 7.5	+ 6.8	+ 9.5	+ 8.8	+10.3	+10	+ 8.8	+ 8.1
sp 3.15	- 3.3	+ 4.0	+ 8.2	+ 5.5	+ 8.8	+ 6.5	+ 9.8	+ 6.3	+ 8	+ 8.8	+ 7.1
sp 3.16	- 8.3	- 8.0	+ 7.2	+ 4.0	+ 6.8	+ 8.5	+ 9.8	+ 8.3	+13	+ 7.8	+ 9.1
sp 3.17	- 6.3	+ 3.0	- 1.8	+ 8.5	+ 6.8	+13.5	+ 8.3	+ 7.3	+ 8	+ 6.8	+ 4.1
sp 3.18	+ 4.7	+10.0	+10.2	+ 2.5	+ 7.8	+ 8.5	+10.8	+ 8.3	+ 7	+ 7.3	+ 9.6

APPENDIX I

Relative Rollability values (deviations) for sp 4 (Jarrah Gray sands)

Mesh size (microns)	90-106	106-125	125-150	150-180	180-212	212-250	250-300	300-355	355-425	425-500	500-600
sp 4.1	+ 9.7	+10.5	+13.2	+ 7.0	+ 7.3	+ 4.5	+ 3.8	+ 2.3	+ 3.0	+ 1.8	+ 2.1
sp 4.2	+ 7.7	+ 4.0	+ 8.7	+13.5	+10.8	+ 6.5	+ 8.8	+ 6.8	+ 7.0	+ 6.8	+ 3.1
sp 4.3	+ 1.7	+ 8.0	+ 6.2	+ 9.5	+ 7.8	+ 9.5	+ 7.8	+ 7.8	+ 8.0	+ 4.8	+ 5.6
sp 4.4	+10.7	+ 5.0	+10.2	+11.5	+10.8	+ 9.5	+ 8.3	+ 8.3	+10.0	+ 3.8	+ 3.1
sp 4.5	+ 4.7	+13.0	+ 7.2	+ 9.5	+10.8	+ 9.5	+ 6.8	+ 5.8	+ 7.0	+ 8.8	+ 7.1
sp 4.6	- 1.3	+10.0	+ 8.2	+ 6.5	+12.8	+12.0	+ 8.8	+ 5.3	+ 8.0	+ 5.8	+ 6.1
sp 4.7	+10.7	+14.0	+ 6.5	+ 6.5	+10.8	+ 8.5	+ 7.8	+ 8.3	+ 9.0	+ 8.8	+ 9.1
sp 4.8	+14.7	+10.0	+12.2	+ 7.5	+ 8.8	+ 8.5	+ 5.8	+ 9.3	+13.0	+10.8	+ 8.1
sp 4.9	+ 7.2	+13.0	+13.2	+ 8.5	+ 6.8	+ 5.5	+ 6.8	+ 5.3	+11.0	+ 7.8	+11.1
sp 4.10	= 1.3	+10.0	+10.2	+ 9.5	+ 8.8	+ 9.5	+ 7.8	+ 7.3	+ 7.5	+ 7.8	+ 7.1

APPENDIX I

Relative Rollability values (deviations) for sp 6 (Stream sands)

Mesh size (microns)	90-106	106-125	125-150	150-180	180-212	212-250	250-300	300-355	355-425	425-500	500-600
sp 6.1		- 1.5	- 1.8	- 5.5	+ 0.8	+ 3.5	- 2.2	+ 2.3	+ 2.0	- 3.2	+ 1.1
sp 6.2			- 0.8	+ 0.5	- 4.2	+ 0.5	- 1.2	+ 0.3	+ 3.0	- 0.2	- 0.9
sp 6.3			+ 4.2	+ 0.5	+ 1.8	+ 0.5	+ 1.8	+ 0.3	+ 3.0	- 1.2	+ 2.1
sp 6.4		- 1.0	+ 8.2	+ 3.5	+ 2.8	+ 2.5	+ 4.8	+ 4.3	0	- 0.2	+ 2.1
sp 6.5	+ 6.7	- 3.0	- 0.8	+ 1.5	+ 2.8	+ 5.0	+ 1.8	+ 2.3	+ 2.0	- 0.2	+ 1.1
sp 6.6			+ 2.2	+ 1.5	- 0.2	+ 4.5	+ 1.8	+ 3.3	+ 4.0	+ 1.8	- 0.4
sp 6.7	+ 6.7	- 1.0	+ 2.2	+ 1.5	+ 0.8	+ 4.5	+ 3.8	+ 1.3	+ 3.0	+ 1.8	+ 1.1
sp 6.8	+ 2.7	+ 3.0	+ 2.2	+ 1.5	+ 0.8	+ 3.5	+ 1.8	+ 3.3	+ 3.0	+ 2.8	+ 5.1
sp 6.9	- 0.3	- 2.5	+ 3.2	+ 1.5	+ 1.8	+ 2.5	+ 1.8	+ 0.3	+ 1.0	+ 0.8	+ 2.1
sp 6.10	- 1.3	- 3.0	+ 2.3	+ 2.5	- 1.2	+ 1.5	+ 1.8	+ 1.3	+ 1.0	- 1.7	+ 2.1

APPENDIX 2

Granulometric analysis - Yellow sand sp 2

	Graphic Readings									
Sample	$\phi 5$	$\phi 16$	$\phi 25$	$\phi 50$	$\phi 75$	$\phi 84$	$\phi 95$	SKI	Kg	Kg^1
sp 2.1	-0.77	-0.30	0.4	2.1	2.85	3.2	3.8	-0.47	0.76	0.43
sp 2.2	-0.55	+0.1	0.55	1.9	2.80	3.1	3.85	-0.16	0.80	0.44
sp 2.3	-0.48	0.1	0.45	1.6	2.53	2.9	3.64	-0.04	0.81	0.45
sp 2.4	-0.4	0.23	0.75	1.88	2.55	2.83	3.52	-0.19	0.89	0.47
sp 2.5	-0.2	0.35	0.65	1.34	2.05	2.4	3.2	+0.06	1.00	0.50
sp 2.6	-0.7	-0.1	0.3	1.53	2.4	2.73	3.58	-0.10	0.84	0.46
sp 2.7	-0.47	-0.08	0.25	1.01	1.70	2.07	2.90	-0.01	0.95	0.49
sp 2.8	-0.45	-0.04	0.2	0.77	1.5	1.87	2.70	+0.19	0.99	0.50
sp 2.9	-0.27	+0.05	0.26	0.86	1.55	2.0	3.10	+0.25	1.07	0.52
sp 2.10	-0.3	+0.02	0.25	0.90	1.70	2.1	3.2	+0.23	0.99	0.50
sp 2.11	-0.32	0.10	0.35	1.02	1.85	2.2	3.18	+0.18	0.96	0.49
sp 2.12	-0.35	0.05	0.32	1.00	1.90	2.35	3.34	+0.22	0.96	0.49
sp 2.13	-0.25	0.13	0.40	1.12	2.03	2.45	3.40	+0.20	0.92	0.48
sp 2.14	-0.31	0.13	0.40	1.19	2.05	2.46	3.60	+0.20	0.97	0.49
sp 2.15	-0.28	0.19	0.45	1.12	1.90	2.31	3.34	+0.17	1.02	0.50
sp 2.16	-0.20	0.22	0.48	1.09	1.85	2.28	3.31	+0.21	1.05	0.51
sp 2.17	-0.19	0.20	0.43	1.10	1.92	2.38	3.40	+0.23	0.99	0.50

APPENDIX 2

Granulometric analysis - Yellow sand sp 2 (cont)

	Graphic Readings								
Sample	ϕ5	ϕ16	ϕ25	ϕ50	ϕ75	ϕ84	ϕ95	MZ	σI
sp 2.12	-0.35	0.05	0.32	1.00	1.90	2.35	3.34	1.13	1.13
sp 2.13	-0.25	0.13	0.40	1.12	2.03	2.45	3.40	1.23	1.13
sp 2.14	-0.31	0.13	0.40	1.19	2.05	2.46	3.60	1.26	1.17
sp 2.15	-0.28	0.19	0.45	1.12	1.90	2.31	3.34	1.21	1.08
sp 2.16	-0.20	0.22	0.48	1.09	1.85	2.28	3.31	1.20	1.05
sp 2.17	-0.19	0.20	0.43	1.10	1.92	2.38	3.40	1.23	1.09
sp 2.18	-0.37	0.00	0.18	0.67	1.40	1.83	2.75	0.83	0.78
sp 2.19	-0.38	0.1	0.42	1.34	2.35	2.79	3.63	1.41	1.28
sp 2.20	-0.37	0.18	0.54	1.60	2.45	2.83	3.66	1.54	1.27

APPENDIX 2

Granulometric analysis - Gray sands

	Graphic Readings									
Sample	ϕ5	ϕ16	ϕ25	ϕ50	ϕ 75	ϕ84	ϕ95	SKI	Kg	Kg^{1}
sp 3.1	-0.63	-0.20	0.18	1.16	2.05	2.42	3.27	+0.02	0.85	0.46
sp 3.2	-0.40	0.02	0.35	1.24	2.10	2.50	3.28	+0.07	0.86	0.46
sp 3.3	-0.30	0.22	0.55	1.38	2.20	2.58	3.40	+0.05	0.74	0.43
sp 3.4	-0.10	0.33	0.62	1.36	2.13	2.52	3.43	+0.12	1.16	0.54
sp 3.5	+0.03	0.46	0.68	1.21	1.90	2.30	3.30	+0.23	1.10	0.52
sp 3.6	0.09	0.46	0.65	1.11	1.62	1.89	2.70	+0.15	1.10	0.52
sp 3.7	0.23	0.60	0.77	1.20	1.70	2.02	3.09	+0.24	1.26	0.58
sp 3.8	0.17	0.52	0.71	1.13	1.67	2.00	2.98	+0.25	1.20	0.55
sp 3.9	0.20	0.53	0.76	1.22	1.81	2.18	3.25	+0.25	1.19	0.54
sp 3.10	0.19	0.57	0.76	1.23	1.84	2.20	3.19	+0.25	1.14	0.53
sp 3.11	0.25	0.60	0.77	1.23	1.75	2.08	3.02	+0.22	1.16	0.54
sp 3.12	0.18	0.51	0.70	1.08	1.57	1.89	2.82	+0.25	1.24	0.55
sp 3.13	0.09	0.43	0.62	1.13	1.74	2.10	3.20	+0.25	1.14	0.53
sp 3.14	0.00	0.36	0.56	1.09	1.75	2.12	3.33	+0.26	1.15	0.53
sp 3.15	0.17	0.49	0.63	1.00	1.50	1.81	2.90	+0.30	1.29	0.56
sp 3.16	0.27	0.59	0.77	1.25	1.87	2.27	3.28	+0.28	1.42	0.59
sp 3.17	0.21	0.59	0.80	1.30	1.91	2.28	3.28	+0.22	1.13	0.53

APPENDIX 2

Granulometric analysis - Gray sands (cont)

	Graphic Readings								
Sample	φ5	φ16	φ25	φ50	φ75	φ84	φ95	MZ	σI
sp 3.1	-0.63	-0.2	0.18	1.16	2.05	2.42	3.27	1.13	1.25
sp 3.2	-0.40	+0.02	0.35	1.24	2.10	2.50	3.28	1.25	0.87
sp 3.3	-0.30	0.22	0.55	1.38	2.20	2.58	3.40	1.39	1.15
sp 3.4	-0.10	0.33	0.62	1.36	2.13	2.52	3.43	1.40	1.08
sp 3.5	+0.03	0.46	0.68	1.21	1.90	2.30	3.30	1.32	0.96
sp 3.6	+0.09	0.46	0.65	1.11	1.62	1.89	2.70	1.15	0.75
sp 3.7	+0.23	0.60	0.77	1.20	1.70	2.02	3.09	1.27	0.79
sp 3.8	+0.17	0.52	0.71	1.13	1.67	2.00	2.98	1.22	0.80
sp 3.9	+0.20	0.53	0.76	1.22	1.81	2.18	3.25	1.31	0.87
sp 3.10	+0.19	0.57	0.76	1.23	1.84	2.20	3.19	1.33	0.86
sp 3.11	+0.25	0.60	0.77	1.23	1.75	2.08	3.02	1.30	0.79
sp 3.12	+0.18	0.51	0.70	1.08	1.57	1.89	2.82	1.16	0.75
sp 3.13	+0.09	0.43	0.62	1.13	1.74	2.10	3.20	1.22	0.89
sp 3.14	0.00	0.36	0.56	1.09	1.75	2.12	3.33	1.19	0.94
sp 3.15	0.17	0.49	0.63	1.00	1.50	1.81	2.90	1.10	0.74
sp 3.16	0.27	0.59	0.77	1.25	1.87	2.27	3.28	1.37	0.88
sp 3.17	0.21	0.59	0.80	1.30	1.91	2.28	3.28	1.39	0.89

APPENDIX 2

Granulometric analysis - Rock apron sands (Rock detritus)

	Graphic readings									
Sample	φ5	φ16	φ25	φ50	φ75	φ84	φ95	SKI	Kg	Kg^1
sp 5.13	-0.63	-0.48	-0.30	0.15	0.94	1.40	2.95	+0.45	1.18	0.54
sp 5.14	-0.70	-0.47	-0.25	0.30	1.00	1.47	2.80	+0.32	1.15	0.53
sp 5.15	-0.68	-0.50	-0.33	0.12	0.85	1.30	2.52	+0.41	1.11	0.53
sp 5.16	-0.64	-0.42	-0.20	0.30	1.02	1.48	2.65	+0.34	1.11	0.53
sp 5.17	-0.66	-0.42	-0.25	0.21	0.82	1.19	2.22	+0.31	1.10	0.52
sp 5.18	-0.65	-0.38	-0.14	0.40	1.12	1.58	2.60	+0.28	1.06	0.51
sp 5.19	-0.68	-0.48	-0.26	0.24	0.95	1.40	2.77	+0.35	1.22	0.55
sp 5.20	-0.68	-0.38	-0.10	0.50	1.31	1.78	2.69	+0.26	0.98	0.49
sp 5.21	-0.67	-0.37	-0.11	0.67	1.67	2.18	2.98	+0.28	0.84	0.46

Sample	φ5	φ16	φ25	φ50	φ75	φ84	φ95	MZ	σI
sp 5.13	-0.63	-0.48	-0.3	0.15	0.94	1.40	2.95	0.36	1.01
sp 5.14	-0.70	-0.47	-0.25	0.30	1.00	1.47	2.80	0.43	1.02
sp 5.15	-0.68	-0.50	-0.33	0.12	0.85	1.30	2.52	0.31	0.93
sp 5.16	-0.64	-0.42	-0.20	0.30	1.02	1.48	2.65	0.45	0.96
sp 5.17	-0.66	-0.42	-0.25	0.21	0.82	1.19	2.22	0.33	0.84

APPENDIX 2

Granulometric analysis - Rock apron sands (Rock detritus) (cont)

Sample	φ5	φ16	φ25	φ50	φ75	φ84	φ95	MZ	σI
sp 5.18	-0.65	-0.38	-0.14	0.40	1.12	1.58	2.60	0.53	0.98
sp 5.19	-0.68	-0.48	-0.26	0.24	0.95	1.40	2.77	0.39	0.99
sp 5.20	-0.68	-0.38	-0.10	0.50	1.31	1.78	2.69	0.63	1.05
sp 5.21	-0.67	-0.37	-0.11	0.67	1.67	2.18	2.98	0.83	1.19

APPENDIX 3

TABLE 8.1(a)

Chemical Analyses (concentration of elements in ppm except where % is indicated)

		Elements								
	Sample No. & Depth	Ce	Ba	Zn	Ni	Co	Mn	%TiO_2	V	%CaO
6 3 X 0 —	sp 2.1/10-I5cm	13	49	3	2	11	29	0.60	15	0.01
	sp 2.2/l0-15cm	41	57	2	1	12	47	0.70	26	0.02
	sp 2.3/l0-15cm	72	79	5	8	5	43	0.66	41	0.02
	T 33.1/5-10cm	26	80	3	5	9	44	0.62	31	0.04
	T 33.12/90-100cm	33	91	I	11	6	44	0.75	41	0.01
	T 33-230-240cm	20	46	1	11	7	35	0.79	41	0.01
R) — — u	sp 3.5/l0-15cm	11	24	3	0	0	11	0.39	7	0.03
	sp 3.9/10-15cm	5	32	I	1	C	18	0.37	8	0.02
	T 115.2/5-10cm	7	46	3	0	8	38	0.42	8	0.05
	T 115.4/15-20cm	6	42	4	C	1	24	0.35	4	0.02
	T115.8/50-60cm	6	39	3	Q	0	21	0.36	9	0.02
CO - CO CO	T 15.2/5-10cm	81	273	0	0	17	60	0.50	2C	0.06
	T 15.8/50-60cm	77	47	3	22	11	19	0.75	46	0.02
	T 15.12/90-100cm	53	32	5	25	13	13	0.78	62	0.01

APPENDIX 3

TABLE 8.1(a)

Chemical analyses (concentration of elements in ppm except where % is indicated)(cont)

		Elements								
	Sample No. & Depth	Ce	Ba	Zn	Ni	Co	Mn	$\%TiO_2$	V	%CaO
Magpie	T 99.2/5-10cm	92	279	1	2	8	52	0.56	19	0.05
	T 99.7/40-50cm	82	53	4	14	9	23	0.67	57	0.01
	T 99.12/90-100cm	47	38	0	10	14	33	0.67	45	0.01
Rosella	T 3.3/10-15cm	94	65	1	2	0	74	0.84	51	0.05
	T 3.8/50-60cm	108	53	6	9	6	58	0.84	63	0.01
	T 3.11/80-90cm	130	40	3	4	10	93	0.86	52	0.01
Woylie	sp 5.14/10-15cm	136	627	10	1	8	121	0.43	22	0.23
	sp 5.19/10-15cm	76	716	13	0	13	170	0.41	16	0.45
	T 68.2/5-10cm	30	450	8	2	2	169	0.30	7	0.23
	T 68.6/30-40cm	41	484	6	1	7	78	0.30	6	0.15
	T 68.14/110-120cm	238	355	11	4	20	38	0.38	32	0.03
Pingelly	T 38.2/5-10cm	81	123	22	9	24	283	1.88	288	0.12
	T38.8/50-60cm	109	115	26	12	14	383	2.53	348	0.01
	T 38.14/110-120cm	54	96	15	15	16	239	1.98	270	0.01

APPENDIX 3

TABLE 8.1(b)

Chemical analyses (concentration of elements in ppm except where % is indicated)

		Elements						
	Sample No. & Depth	%K	%S	%P	$\%Na_2O$	Cu	Ga	Cr
Po	sp 2.1/10-15cm	0.19	0.004	0.001	0.266	0	1	11
	sp 2.2/10-15cm	0.23	0.009	0.004	0.056	0	7	19
	sp 2.3/10-15cm	0.29	0.016	0.008	0.045	0	11	35
	T 33.1/5-10cm	0.28	0.013	0.007	0.052	0	8	22
	T 33.12/90-100cm	0.36	0.014	0.006	0.056	0	11	43
	T 33/230-240cm	0.18	0.012	0.004	0.040	0	13	37
Echidna	sp 3.5/10-15cm	0.06	0.004	0.060	0.010	0	0	3
	sp 3.9/10-15cm	0.12	0.002	0.057	0.020	0	1	2
	T 115.2/5-10cm	0.22	0.004	0.056	0.003	0	0	0
	T 115.4/15-20cm	0.15	0.005	0.058	0.007	0	0	1
	T 115.8/50-60cm	0.12	0.003	0.061	0.001	0	0	3
Marshall	T 15.2/5-10cm	1.29	0.009	0.008	0.118	0	8	8
	T 15.8/50-60cm	0.17	0.010	0.005	0.061	0	20	58
	T 15.12/90-100cm	0.11	0.010	0.005	0.036	0	26	72

APPENDIX 3

TABLE 8.1(b)

Chemical analyses (concentration of elements in ppm except where % is indicated)(cont)

		Elements						
	Sample No. & Depth	%K	%S	%P	$\%Na_2O$	Cu	Ga	Cr
Magpie	T 99.2/5-10cm	1.36	0.012	0.006	0.123	0	9	18
	T 99.7/40-50cm	0.17	0.019	0.005	0.032	0	27	60
	T 99.12/90-100cm	0.15	0.018	0.005	0.025	0	18	37
Rosella	T 3.3/10-15cm	0.23	0.034	0.014	0.172	0	20	27
	T 3.8/50-60cm	0.20	0.030	0.009	0.366	0	27	46
	T 3.11/80-90cm	0.13	0.021	0.006	0.366	0	26	42
Woiylie	sp 5.14/10-15cm	2.59	0.009	0.016	0.304	0	10	7
	sp 5.19/10-15cm	2.97	0.009	0.011	1.035	1	12	0
	T 68.2/5-10cm	3.01	0.004	0.003	0.768	0	10	0
	T 68.6/30-40cm	2.65	0.005	0.057	0.026	0	10	5
	T 68.14/110-120	2.69	0.007	0.003	0.221	0	31	18
Pingelly	T 38.2/5-10cm	0.27	0.060	0.042	0.204	7	26	85
	T 38.8/50-60cm	0.31	0.070	0.028	0.262	0	26	95
	T 38.14/110-120cm	0.25	0.136	0.010	0.246	0	28	108

APPENDIX 3

TABLE 8.2

Clay Mineralogy of soils from some SMU's at Tuttanning

SMU	Sample No. & depth	% Clay Mineral in clay fraction						
		Kaolin	Quartz	Illite	Feldspar	Goethite/ hematite	Gibbsite	Vermiculite
Possum	sp 2.1/10-15cm	95	5					trace?
	sp 2.10/10-15cm	95	5					
	T 33/230-240cm	75				5	20	
Echidna	sp 3.5/10-15cm	75	20		5			
	sp 3.10/10-15cm	75	20		5			
	T 115.9/60-70cm	55	30		10			5
Marshall	T 15.2/5-10cm	85	10		5			
	T 15.7/40-50cm	100						
	T 15.12/90-100cm	90	5		5			trace?
Magpie	T 99.2/5-10cm	95					5	
	T 99.7/40-50cm	80	5	5		10		
	T 99.12/90-100cm	100						

APPENDIX 3

TABLE 8.2

Clay mineralogy of soils from some SMU's at Tuttanning (cont)

SMU	Sample No. & Depth	% Clay Mineral in clay fraction						
		Kaolin	Quartz	Illite	Feldspar	Goethite/ hematite	Gibbsite	Vermiculite
Rosella	T 3.4/15-20cm	100						
	T 3.10/70-80cm	100						
Woylie	T 68.2/5-10cm	80	10	5	5			
	T 68.6/30-40cm	90	5	5				
	T 68.14/110-120cm	95	5					
Pingelly	T 38.2/5-10cm	90	5			5		
	T 38.8/50/60cm	80	5	5		10		
	T 38.14/110-120cm	85		5		10		

Parameters

Cobalt, K∝ KV: 35
Fe filter MA: 33
Scatter slit 4°
Receiving slit 0.3°
Divergence slit 1°