PEBBLE MORPHOMETRY
OF THE
TAMBO RIVER, EASTERN VICTORIA

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of the requirements for the
degree of
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Except as stated herein, this thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

To the best of my knowledge and belief this thesis contains no copy or paraphrase of material previously published or written by another person, except when due reference is made in the text.

Signed,

(A. Goede)

Frontispiece

Vertical aerial view of Tambo River at Swifts Creek.

Photo: Royal Australian Air Force

Scale: 1 inch = 1490 feet

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LIST OF SYMBOLS

A	-	area of outcrop above a station (km^2)
Al	-	mean altitude of outcrops at a sample station (metres)
B	-	number of bladed pebbles in a sample
C	-	mean Cailleux roundness of sample
D	-	distance downstream from station 1 (km)
Di	-	mean distance from outcrops at a sample station (km)
E	-	number of elongated pebbles
ΔF	-	magnitude of form change between adjacent stations (chi-square)
I	-	mean length of intermediate axis of a sample (mm)
Ka	-	mean Kaiser roundness of sample
Ku	-	mean Kuenen roundness of sample
Ku25	-	Kuenen breakage index
Ku75	-	Kuenen abrasion index
L	-	mean length of long axis of a sample (mm)
M	-	mean Maximum Projection sphericity of a sample
P	-	number of platy pebbles in a sample
Q	-	the ratio Q_ℓ/Q_0
Q_ℓ	-	percentage content of a particular lithology in a sample of 200 pebbles
Q_0	-	percentage area of the catchment over which a particular lithology outcrops

ra - radius of curvature of sharpest corner of pebble in the maximum projection plane

S - mean length of short axis of a sample (mm)

T - mean pebble weight of a sample (grams)

W - mean Wadell sphericity of a sample

The following additional symbols are used in conjunction with some of the above variables:

X* - actual value for an individual pebble

$\bar{X}$ - mean value for a particular lithology from all sample stations

X_r - indicates value for rhyodacite

X_s - indicates value for sandstone

$|X|$ - indicates modulus of value

ΔX - change in value between two adjacent stations

For convenience a fold out copy of this list is included at the back of the thesis.

ACKNOWLEDGEMENTS

The completion of this study has been made possible only by the assistance, cooperation and encouragement of many people.

The early stages of research into the bedload characteristics of the Tambo River took place while the writer was a research scholar at the Australian National University in 1964-65 and much credit for guiding the initial ideas is due to my supervisor at the time, Dr. J.N. Jennings. Unfortunately this work could not be completed at that time due to ill health.

Subsequently some aspects of the earlier research done in the Tambo Valley were selected and further developed as a thesis topic for the degree of Master of Science at the University of Tasmania. The writer is very grateful for the encouragement and helpful advise given by his supervisor, Professor J.L. Davies, and, in the final stages of preparation of the thesis by Dr. E.A. Colhoun, who took over the task of supervision following the appointment of Professor Davies to a chair at Macquarie University, Sydney.

Special thanks are due to Mr. N.K. Chick who was responsible for writing most of the computer programs required for the analysis of the data. The writer is also indebted to him for numerous discussions concerning problems involved in the application of statistical methods.

The cooperation of several government departments of the state of Victoria is much appreciated: the Lands Department for the supply of maps, aerial photographs and survey data, the Rivers and Water Supply Commission for gauging records of the Tambo River and the Department of Mines for unpublished geological information and the providing of facilities for its transcription. I am particularly grateful to Dr. J.A. Talent for his generous assistance in making available his specialist knowledge of the stratigraphy and geological history of the study area.

The maps and diagrams were drawn by Mr. G. van der Geer and Miss K. Draper and the writer also wishes to thank the former for his advice on cartographic presentation. Acknowledgement should be made of the assistance received from the University Library and the Photographic Department.

In the field the writer has been ably assisted by his wife who spent many hours helping with the sampling and recording of large amounts of numerical data derived from the measurement of large numbers of pebbles. The owners of the Bruthen Inn will be gratefully remembered for providing not only accommodation but also a very pleasant environment during the later stages of the fieldwork.

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ABSTRACT

The study is concerned with the parametric description of a selected size class of the gravel bedload, collected from a number of sample points, of the Tambo River in Eastern Victoria. Lithological composition of the samples is investigated and related to the lithological nature of the basin. Measurements of form, sphericity and roundness are made for samples of the two most abundant lithological types - rhyodacite and sandstone. Changes in mean values of these parameters between stations are related to operative processes, some of which can be characterized by the physical and lithological characteristics of the basin.

A detailed description is presented of the physical environment of the catchment. Consideration is given to sampling procedures and the selection of suitable parameters to describe pebble morphometry. It can be shown that Wadell and Maximum Projection sphericity are partial expressions of form. R-mode factor analysis is used to compare the relative merits of four measures of roundness, on the basis of which the Kuenen and Kaiser measures are used for further work. Subsequently the Kuenen roundness method is shown to be the most suitable for the purpose of this study.

The quantitative relationships between the lithological nature of the basin and the composition of gravel samples are investigated using methods of analysis first introduced by Tricart in France in 1959 but apparently not previously applied in the English speaking world.

The description of the mean form of a sample requires two parameters but values of chi-square can be used as a single parameter measuring the magnitude of change in form between two sampling stations. Changes in form, sphericity and roundness can be related to four basic processes: abrasion, shape sorting, dilution and breakage. In the case of form and sphericity it is shown that all four can be expressed in quantitative form.

Changes in mean roundness of sandstone pebbles show a marked trend with respect to distance downstream, but no such tendency can be observed in the case of rhyodacite particles. Mean Kuenen roundness of samples can be replaced, with very little loss of information, by abrasion and breakage indices devised by the writer.

Matrices of correlation coefficients are used to investigate relationships between variables both within and between samples and in the latter case also between the two dominant lithologies. They assist in reaching a better understanding of the nature of inter-relationships.

Finally, a multiple correlation and regression model is employed to assess quantitatively the relative importance of different processes in producing change in form and sphericity between samples. In the case of rhyodacite highly significant multiple correlations are obtained and it is found that nearly all change can be explained in terms of processes and variations in mean sample size. In the case of sandstone the technique is less successful but even here changes in form at least have a significant multiple correlation with parameters representing processes and sample size.

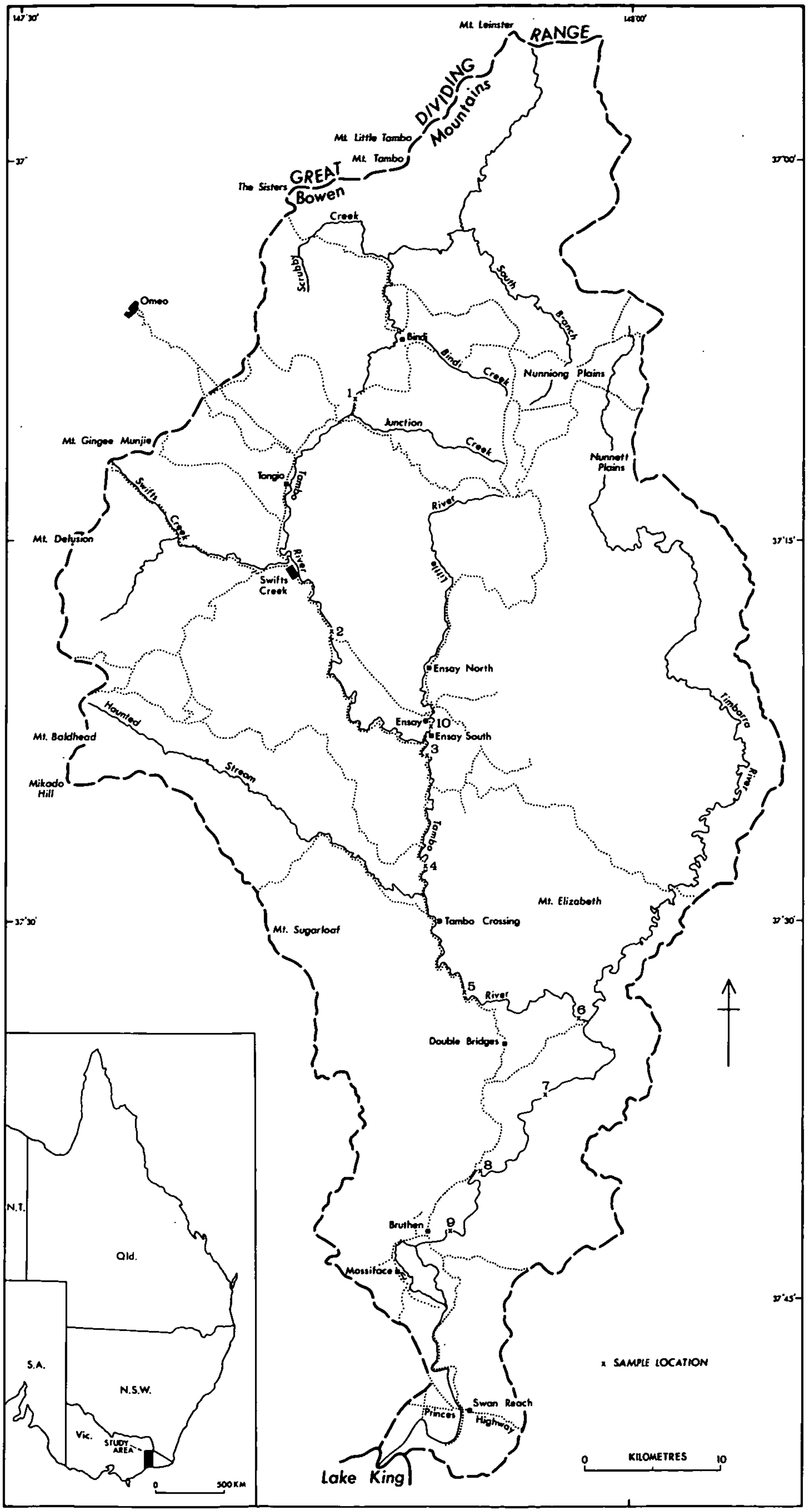
INTRODUCTION

The Tambo River is located in East Gippsland, Victoria and at Bruthen where it emerges from the highlands, it has a catchment area of some 1700 square kilometres (Figure 1). A few kilometres south-west of Swan Reach the river flows into Lake King which forms part of the Gippsland Lakes - a system of coastal lagoons enclosed by a series of dune barriers. The river drains part of the southern slopes of the Victorian Alps. Almost the entire basin upstream from Bruthen is characterized by very steep slopes with local relief, particularly in the headwaters, in many cases exceeding 600 metres. The highest peaks in the northern part of the basin reach heights in excess of 1500 metres. Flat land is virtually absent except for discontinuous stretches of floodplain and river terraces developed where the river passes through more erodible rocks. These stretches are interrupted by long reaches of steep sided valley, which become gorge-like in places. The only other land of low relief is a restricted area of basalt plateau (Nunniong-Nunnett Plains), found in the headwaters of the Timbarra River - a major tributary of the Tambo. With the

FIGURE 1

Location map of the

Tambo River basin


147°30'
148°00'
37°
37°00'
37°15'
37°30'
37°45'
Mt. Leinster
GREAT DIVIDING RANGE
Bowen Mountains
Mt. Little Tambo
Mt. Tambo
The Sisters
Creek
Scrubby
Omeo
South Branch
Bindi
Bindi Creek
Nunniong Plains
1
Junction Creek
Mt. Gingee Munjie
Nunnett Plains
Tongio
Tambo
Swifts Creek
River
Mt. Delusion
Swifts Creek
Little
2
Ensay North
Ensay
10
Ensay South
3
Timbarra River
Haunted Stream
Mt. Baldhead
Mikado Hill
Tambo
4
Mt. Elizabeth
Tambo Crossing
Mt. Sugarloaf
5
River
6
Double Bridges
7
8
Bruthen
9
Mossiface
x SAMPLE LOCATION
Swan Reach
Princes Highway
Lake King
0 KILOMETRES 10
N.T.
Qld.
S.A.
N.S.W.
Vic.
STUDY AREA
0 500 KM

exception of this small area of basalt, the basin upstream from Bruthen has developed in Palaeozoic rocks, the dominant lithologies being granites, sandstones, rhyodacites and schists. The Tambo River carries a heavy bedload and in the floodplain stretches a wide shallow channel has developed. Rapid bank erosion and a tendency towards braiding are characteristic of this channel.

The Tambo River was originally selected for study because of its prominent bedload characteristics, the presence of well preserved terraces in the floodplain reaches, the availability of contoured maps for at least part of the catchment and the near absence of large tributaries. Also the Tambo is parallelled for much of its length by the Omeo Highway, facilitating access. State benchmarks along this road provide convenient starting points for spot height determinations used in the construction of a longitudinal profile of the river bed. The river has a narrow elongated basin, the only major tributary being the Timbarra River. The only other two tributaries of any significance are the Little River and the Haunted Stream.

The fieldwork was conducted utilizing the topographic sheets for the Bairnsdale (1:63,360), Bruthen (1:31,680) and Stirling quadrangles (1:31,680)which have a 50 ft. (approx. 15 m) contour interval. The area covered by base maps has recently been extended due to the publication of the Omeo and Benambra quadrangles at a scale of 1:100,000 with a contour interval of 40 metres and selected 20 metre auxiliary contours. When the thesis was nearing completion preliminary compilation became available for the Murrindal and Orbost quadrangles providing for the first time topographic information for a narrow strip along the eastern margin of the catchment including most of the area drained by the Timbarra River. The plans are at a scale of 1:50,000 with a contour interval of 20 metres.

The purpose of the study is to give a parametric description of a selected size class (long axis between 32 and 64 mm) of the gravel bedload of the Tambo River by sampling at points selected at intervals along the course of the stream. The two rock types selected for the study were rhyodacites and sandstones. The parameters obtained in this way are then related to channel morphology and other environmental conditions. Sampling for this purpose was combined with an assessment of the lithological composition of the gravels in the same size class at each sampling point. Preparation of a lithological map of the basin enabled a comparison to be made between the lithological composition of the sample and the catchment at each sampling station using a method first proposed by Tricart (1959).

Throughout this thesis, wherever statistical techniques have been applied to test either correlations between variables or differences between samples, the term 'highly significant' indicates a level of significance of less than 0.1%, the term 'significant' a level of significance of less than 1% and the term 'probably significant' a level of significance of less than 5%. Any exceptions to this usage are indicated in the text.

CHAPTER I

THE ENVIRONMENT

Climate

It is difficult to obtain a balanced assessment of the climatic conditions of the Tambo River drainage basin as there is a considerable contrast between the higher portions of the catchment which extend into the cool sub-alpine zone and the enclosed basins and narrow valley floors found along the course of the main stream. Settlement and the location of climatic stations are restricted to the latter situation. Even if this were not so the extreme relief would make generalization difficult as it introduces strong local variations depending on site and aspect. The only stations within the basin for which long term records are available are Bindi, Ensay, Tambo Crossing and Bruthen. The rainshadow effect of the mountainous country to the west is reflected in the mean annual rainfalls of these stations which vary between 63 and 74 cms with Bindi having the lowest and Tambo Crossing the highest value. Bindi at approximately 400 metres has the highest elevation.

There are few stations at higher elevations in the East Gippsland region and none within the Tambo drainage basin. The nearest is Omeo at an elevation of 640 metres with a mean annual precipitation of only 66 cms. Temperature and precipitation characteristics of this station are quite atypical of the surrounding region as the Omeo Valley experiences marked foehn and rainshadow effects. Two other stations in the vicinity of Benambra (730 metres) and Hinno Munjie are even drier with mean annual precipitations of only 58 and 63.5 cms respectively. Mean annual precipitation at higher elevations can be approximated by accepting the estimates of Morland (1958) for the Murray River basin that precipitation increases by about 25 cms for every 300 metres rise in altitude in the basin. This means that mean annual totals of 150 to 175 cms can be expected to occur in the highest parts of the Victorian Alps. At low elevations precipitation shows a remarkably even distribution throughout the year but with increasing altitude a trend towards a winter rainfall maximum becomes apparent.

The mean annual temperature near sealevel is approximately 14°C while Hotham Heights (1860 metres) in the Upper Murray Region has a mean annual temperature of only 5°C indicating a normal lapse rate of 0.5°C per 100 metres for the East Gippsland region. The rapidly increasing rainfall coupled with a marked temperature lowering as elevation increases means a rapid rise of rainfall efficiency with altitude and this in turn is reflected in the altitudinal zonation of natural vegetation.

Snowfall also increases with altitude. Snow in the lowlands near sealevel is extremely rare. At Omeo (640 metres) snow occurs annually and has been recorded as often as 10 times in a year while over the highlands snow may occur during any month of the year and in winter most of the precipitation is in this form. Severe blizzard conditions can occur over the exposed Alps. Most of the information on climate has been obtained from Anon. (1954) and Linforth (1969).

Vegetation and Soils

Most of the Tambo River catchment remains under forest vegetation. Land clearing for agriculture has been restricted to flood-plains and terraces bordering the river and to small basins developed on the more erodible rocks. Extensive clearing has taken place near Bindi where the Taravale Mudstones and Shales have given rise to more subdued relief and also around Swifts Creek and Ensay where areas underlain by granitic rocks have been cleared. The forested areas particularly at lower elevations are utilized extensively for timber with the industry centred on Bruthen and

Swifts Creek. The bulk of the vegetation of the area is sclerophyll forest dominated by species of Eucalyptus. At elevations of less than 500 metres the relatively low precipitation and skeletal soils give rise to dry sclerophyll forest, the dominant species being E. globoidea. Undergrowth is often scarce due to the high frequency of fires and consists mainly of shrubs belonging to the genera Acacia, Banksia and Hakea.

At higher elevations up to 1400 metres wet sclerophyll forest is common and is dominated by the eucalypt species E. obliqua and E. delegatensis with pockets of E. regnans on the Nunniong-Nunnett Plains where better soils and low angle slopes favour the development of a distinct vegetation. Undergrowth at higher elevations is much denser, consisting of shrubs belonging to the genera Pomaderris, Bedfordia and others together with abundant ferns. In rainshadow areas a more open forest dominated by Callitris sp. and Eucalyptus albens is found.

Above 1400 metres sub-alpine woodland is found with Eucalyptus pauciflora, snow grass (Poa australis) and a variety of alpine shrubs. No truly alpine vegetation is to be found within the catchment under study.

The soils are predominantly sandy podsolics derived from granites, rhyodacites and sandstones. Apart from some young

PLATE 2

Accelerated erosion of granite

colluvium at Bindi

alluvial soils of limited extent they are all strongly leached. The combination of sandy soils and relatively steep slopes has encouraged soil erosion where land clearing has taken place. Gully erosion is particularly severe at Tongio Gap, near Bindi and to the east of Swifts Creek (Plate 2). Except on one property near Bindi, little or no effort has been made to control accelerated erosion.

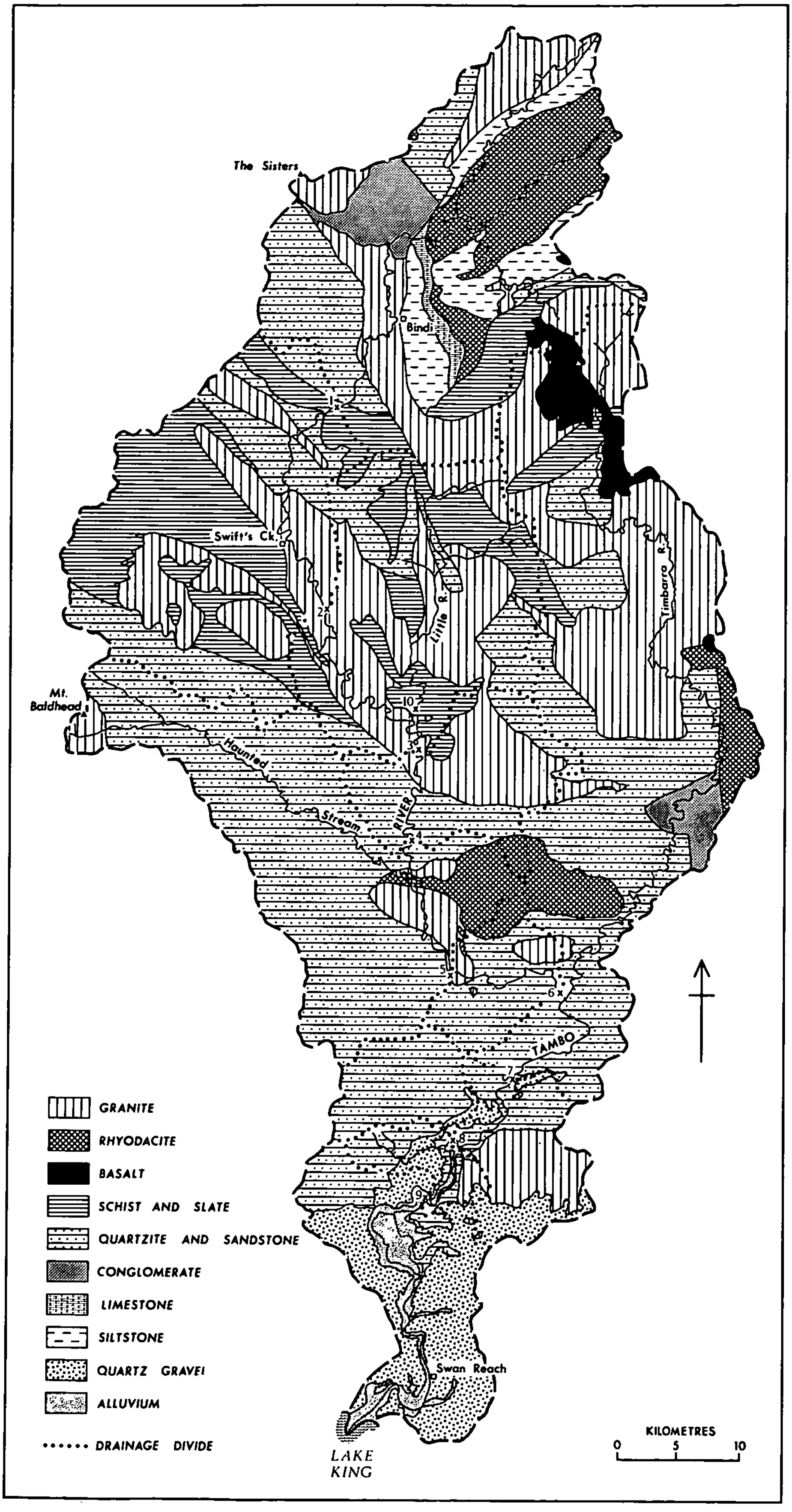
Geology

The geology of the catchment area of the Tambo River has not been mapped systematically with the exception of a small area around the mouth of the Tambo which is included in the Bairnsdale geological sheet (1:63,360) published in 1960. To compile a lithological map of the area (figure 2) one has to rely on published regional studies such as those by Gaskin (1943) of the Bindi area; Fletcher (1963) whose mapping included part of the Timbarra River catchment; and Tattam (1929) who studied the metamorphic belt extending into the Tambo catchment from Omeo to the south-east as far as Ensay. Other material is available in the form of published and unpublished reports and maps produced by the Geological Survey of Victoria including material prepared for inclusion in the Geological Map of Victoria (1:1,000,000) published

FIGURE 2

Lithological map of the

Tambo River basin


The Sisters
Bindi
Swift's Ck.
Little R.
Timbarra R.
Mt. Baldhead
Haunted Stream
RIVER
TAMBO
Swan Reach
LAKE KING
GRANITE
RHYODACITE
BASALT
SCHIST AND SLATE
QUARTZITE AND SANDSTONE
CONGLOMERATE
LIMESTONE
SILTSTONE
QUARTZ GRAVEL
ALLUVIUM
DRAINAGE DIVIDE
KILOMETRES
0
5
10

in 1963. Some information was also obtained from unpublished theses in the Geology Department of the University of Melbourne. The most important study was by W. Williams which included some detailed mapping of the granite complex in the Brookville - Swifts Creek - Ensay area.

An excellent summary of the geology of East Gippsland is given by Talent (1969). While dealing mainly with the stratigraphic sequence and geological history it also includes small sections on landforms and geological structure. A briefer account of the physiography, geology and mineral resources of the East Gippsland region is given by Thomas (1954) while some information on the geological structure of the area is found in Thomas (1958). Determination of potassium-argon ages of some of the East Gippsland granites by Evernden and Richards (1962) has helped to elucidate the geological history. A brief account of the geological history of the area will be given, based largely on Talent (1969).

The oldest rocks that crop out in the catchment area occur as great thicknesses of uniform rhythmically bedded sandstones with minor slates. They are strongly folded and faulted and are characterized by a paucity of fossils. Such fossils as have been found (e.g. at Mount Nunniong) indicate an Upper Ordovician age. These sediments represent a typical turbidite sequence characterized by graded beds, small scale cross bedding, and flute casts. Their deposition was followed by the Benambran Orogeny with the intrusion of granitic rocks in a belt extending south-east from Albury up the Kiewa River valley and from there into the study area as far as Ensay. Associated with this line of intrusions is an extensive belt of metamorphic rocks - mainly schists and gneisses which are considered to be equivalent in age to the unmetamorphosed Ordovician sandstones and slates.

The Ordovician sediments are overlain unconformably by rocks of Silurian age. The oldest unit is the Mitta Mitta Volcanics consisting of a sequence of ignimbrites, rhyodacites, rhyolites and tuffs. This unit is difficult to distinguish from the later Snowy River Volcanics of Devonian age except on stratigraphic grounds. All outcrops of acid and intermediate volcanic rocks in the Tambo basin have been assigned to the Snowy River Volcanics but more detailed mapping may well show that some at least represent the Mitta Mitta Volcanics. These volcanics are overlain by the Wombat Creek Group - a sequence of conglomerates interbedded with minor limestones and fine-grained terrigenous sediments. The unit has a minimum thickness of 3000 metres. Within the Tambo catchment it crops out in a series of fault slices between Bindi and the headwaters of the Indi River where the sequence is known as the Cowombat Group. The conglomerates reach their maximum development in this area where they are mapped as the Mount Waterton formation. Deposition of the Silurian sediments is followed by another orogenic phase - the Bowning Orogeny - associated with further folding and intrusion of granites. Granites south-east of Ensay, near Tambo Crossing appear to have been intruded during this phase as well as a large area of granodiorite (Mt. Stewart Granite) in the middle and upper reaches of the Timbarra River (Evernden and Richards, 1962).

The granite is overlain uncomformably by the lower Devonian Timbarra Formation consisting of a thick sequence of non-marine conglomerates, sandstone and siltstones with a minimum thickness of 1500 metres. The formation is found east of Buchan and extends into the drainage basin of the Timbarra River. In turn this formation is overlain by the Snowy River Volcanics consisting of more than 3000 metres of rhyodacites and tuffs. Although most extensive in the Snowy River area they occupy 7.5% of the Tambo catchment north of Bruthen and make a very significant contribution to the bedload of this river. According to Talent (1969) the next period of deposition represented by the Buchan Group was preceded by a period of epeirogenic block faulting with planation which affected the Snowy River Volcanics and the underlying Cowombat Group.

The Buchan Group has been described in detail in the Buchan area by Teichert and Talent (1958). However, a very similar sequence can be found at Bindi where it has been mapped by Talent (pers. comm.). The Buchan Group has been divided into three formations. The lowest is the Buchan Caves Limestone consisting of grey to dark coloured fossiliferous limestones with a measured thickness at Buchan of between 260 and 280 metres. The formation is well developed at Bindi (Gaskin, 1943) where it has an average dip of 30° to the WSW with a prominent cuesta scarp marking the eastern boundary of the outcrop. Next is the Taravale Formation which reaches a maximum thickness of 580 metres at Buchan and consists of mudstones, shales and impure limestones. This formation also outcrops extensively at Bindi where it forms an area of subdued relief. The third formation recognized at Buchan is the Murrindal Limestone with a maximum thickness of 295 metres. It is interpreted by Teichert and Talent (1958) as a facies change stratigraphically equivalent to the upper part of the Taravale Formation. It has not been recognized in the Bindi area. On the basis of fossil content the whole of the Buchan Group is placed in the lower half of the Middle Devonian.

Deposition was terminated by the Tabberabberan Orogeny which led to deformation of the older rocks accompanied by further intrusions of granites. This tectonic phase occurred from late Middle Devonian to early Upper Devonian times.

The Upper Devonian saw a resumption of sedimentation with the deposition of the Mount Tambo Group containing shales and sandstones interbedded with conglomerates up to 12 metres thick. The thickness of the group is in excess of 3000 metres. It crops out in a belt extending from Mount Tambo to Mount Shanahan near Bindi. The group represents the youngest pre-Cainozoic sediments known to crop out in the Tambo River basin.

Triassic syenites and granite porphyries crop out east of Benambra and a small portion of this extends into the Tambo River catchment at Mount Little Tambo. There is no further evidence for igneous activity until sometime during the Tertiary when basalts were extruded at a number of scattered localities. The only significant outcrop of basalt within the study area is a belt 16 kms long and up to 5 kms wide underlying the Nunniong - Nunnett plains. The exact age of this basalt is uncertain but what evidence there is tends to favour a mid-Tertiary age (Talent, 1969; Beavis 1962).

The deposition of Cainozoic sedimentary rocks within the Tambo River basin is restricted to a small area near the mouth of the Tambo south of an east-west line passing through the town of Bruthen. This area forms part of the eastern portion of the Gippsland sedimentary basin (Boutakoff, 1956). Sedimentation commenced in the Jurassic in the central portion of the basin and first extended into the Swan Reach-Lakes Entrance area during the Upper Eocene where it is represented by the Lakes Entrance Formation.

Deposition of alternating marine and terrigenous deposits probably extends into the Pleistocene. The Cainozoic succession is summarized by Talent (1969) but is not discussed in detail here because no sampling of gravel bedload was carried out south of Bruthen.

An exception must be made for the Plio-Pleistocene quartz gravels extending north-eastward from Bruthen parallel to the present course of the Tambo River. They appear to be the "torrent gravels" referred to by Talent (1969) and others and have been correlated with similar gravels (Haunted Hills Gravels) covering much of the surface of the Gippsland Basin including the area between Bruthen and the mouth of the Tambo River. The gravels to the north-east of Bruthen are clearly fluviatile in origin but are found one hundred metres and more above the present day river. The presence of torrent gravels has been explained either as due to rapid uplift of the highlands to the north (Jenkin, 1968) or as a result of climatic change (Talent, 1969). Talent suggested that deposition of the gravels took place across extensive piedmont areas by streams with greatly augmented flow during the Pleistocene. Whatever their origin, the Tambo is now entrenched at least 100 metres below this level. This entrenchment extends upstream almost as far as Tambo Crossing and may reflect marginal upwarping of the Palaeozoic bedrock bordering the Gippsland basin during the Pleistocene.

Another controversial aspect of the geology of the region is the age of the Kosciusko Uplift - the main period of upward movement responsible for the extensive area of highlands in eastern Victoria and New South Wales. The age of this movement has been placed as recently as late Pliocene and even Pleistocene by some (Jaeger and Browne, 1958; Crohn, 1950) while others (e.g. Beavis, 1962) place the beginning of the uplift as far back as early Tertiary times with intermittent later movements.

Regional Geomorphology

In his description of the geology of East Gippsland, Talent (1969) gives a broad classification of five landform types of which three are represented in the area of study.

(1) Mountainous tracts are defined as areas of strong relief with deeply incised valleys with accordant ridge tops common over distances of many miles. Occasional prominent mountain masses stand above these accordant summit levels as though representing residuals above a former widespread erosion surface.

(2) Tablelands are undulating surfaces with broad valleys and low divides bevelling the high parts of the topography more or less regardless of rock type. Areas of Tertiary basalt (e.g. the Nunniong - Nunnett tablelands) have been included in this type.

(3) Intermontane basins comprise small areas of low relief that are due to differential erosion of more easily eroded rocks. Examples from within the Tambo catchment given by Talent include the Bindi and Ensay - Swifts Creek areas.

A large proportion of the Tambo River catchment can properly be described as mountainous tract. As indicated in the introduction it is characterized by extreme local relief and very steep slopes. Talent claims the common occurrence of accordant summits over considerable distances and to test his claim all summits for the area covered by the Bairnsdale, Bruthen and Stirling topographic sheets were plotted on an overlay, including a considerable area to the west of the Tambo catchment drained mainly by the Nicholson River. Contouring of summits shows a gradual increase in summit heights towards the north but summit accordance is not striking enough to suggest that they may represent portions of old dissected erosion surfaces. Another argument that can be brought to bear against the prevailing opinion that summits represent remnants of a much dissected erosion surface is the complete absence of flat summits within the area examined. Outside this area only the Nunniong - Nunnett Plains show marked accordance of flat summits (Talent 1965) but they are more readily explained as modified remnants of the surface of the uppermost member of the sequence of basalt flows which underlies this area.

Of considerable importance in relation to this study is the occurrence of periglacial and possibly glacial landforms and deposits in the Victorian Alps as it must be considered highly likely that much of the gravel bedload of the present day Tambo River was made available by the prevalence of mechanical weathering by freeze and thaw, particularly at higher elevations during the cold stages of the Pleistocene.

Evidence for Pleistocene glaciation in the Victorian Alps has been brought forward by Carr and Costin (1955) who have claimed that the presence of ground moraine, asymmetrical hills, U-shaped valleys, truncated spurs and hanging tributary valleys is evidence of cirque and valley glaciation on the Bogong High Plains, Mount Bogong, Mount Hotham and Mount Feathertop. Beavis (1959) has since made a critical re-examination on the Bogong High Plains of the evidence presented by Carr and Costin and contends that their evidence is not substantiated by detailed field examination. He claims that "... it is possible to assert that no indisputable evidence of Pleistocene glaciation has been found on the Bogong High Plains". More recently the evidence for glaciation of the Victorian Alps has been re-examined by Peterson (unpublished thesis, 1969) in a number of areas and his findings are essentially in agreement with those of Beavis in that no unequivocal evidence of glaciation has been found. None of the localities where the presence of glacial features has been suggested falls within the area drained by the Tambo River and on present evidence glaciation cannot be considered as a process contributing to the gravel bedload of the river during glacial periods.

On the contrary, evidence of periglacial landforms appears to be widespread at higher elevations although little work has been done to assess their extent. Carr and Costin (1955) briefly mention the occurrence of boulder runs (?), stone polygons and stripes from several localities particularly in association with basalt. The only detailed study of periglacial landforms is by Talent (1965) who has described blockstreams of rhyodacite boulders from Mt. Wombargo, Big Hill and the Cobberas extending down to altitudes of about 1200 metres as well as the occurrence of stone banked terraces composed of the same rock type. Evidence of the fossil nature of both landforms is presented. His observations indicate the susceptibility of the rhyodacites to frost weathering and this is of interest because these rocks outcrop extensively at higher elevations in the headwaters of the Tambo River and pebbles derived from them form a substantial proportion of the gravel load of the Tambo in the size range studied.

In the Victorian Alps little information is available on the lower limit to which periglacial processes were active but on the highlands of southern New South Wales this limit is thought to be at least 1000 metres and possibly 700 metres (Galloway, 1965) while in Tasmania the limit was down to 300 metres or even lower (Davies, 1965, 1967). Using these figures as a guide, the general level of the lower limit of periglacial processes in the past must have lain somewhere between 500 and 1000 metres. Davies (1969, pages 12-13) has stressed however that this limit may vary depending on lithology and states that "different rock types react differently to frost weathering and frost-induced mass movement - they vary in their readiness to be mobilised by frost. Because of this, periglacial conditions may appear to have extended nearer to sea level on some rock types than on others". Much of the bedload transported by the Tambo River at present is probably derived by the reworking of colluvial aprons, fan deposits and older alluvial terraces built up under periglacial conditions. Remnants of massive gravel terraces and alluvial fans are particularly well preserved near Swifts Creek between Tongio and Doctors Flat.

Natural reworking of older gravels by the river has been accelerated by anthropogenic factors of which mining has been the most important. The late 19th century saw an upsurge of mining in the area, mainly of deposits of gold and cassiterite occurring in the form of alluvial deposits as well as some reefs and veins. Mining appears to have caused a sudden increase in the bedload of the Tambo River leading to marked aggradation in the lower reaches of the stream particularly near Bruthen where the river enters the piedmont downs (Plate 3). Daily records of gauge heights for the Tambo River at Bruthen have been kept by the Victorian State Rivers and Water Supply Commission since September 1885 with a break in the record from 1932 to 1937. Figure 3 shows fluctuations in low water level due to aggradation from 1885 to 1961 and indicates very rapid aggradation between 1890 and 1898 causing an elevation of low water level by 3.5 metres. This period coincides with the mining boom in East Gippsland. Slow aggradation continued until the early 1920's. A photograph of a braided stretch of the Tambo River upstream from Bruthen published by Hills (1940, fig. 72) was probably taken during this period as it shows spool bars composed of sand - a feature that cannot be seen today as the bedload is now dominated by gravels. Local information also indicates a marked reduction in the sand load of the river in recent years. The effects of mining operations have been to increase the amounts of older alluvial deposits being reworked by the stream as well as introducing "foreign" material

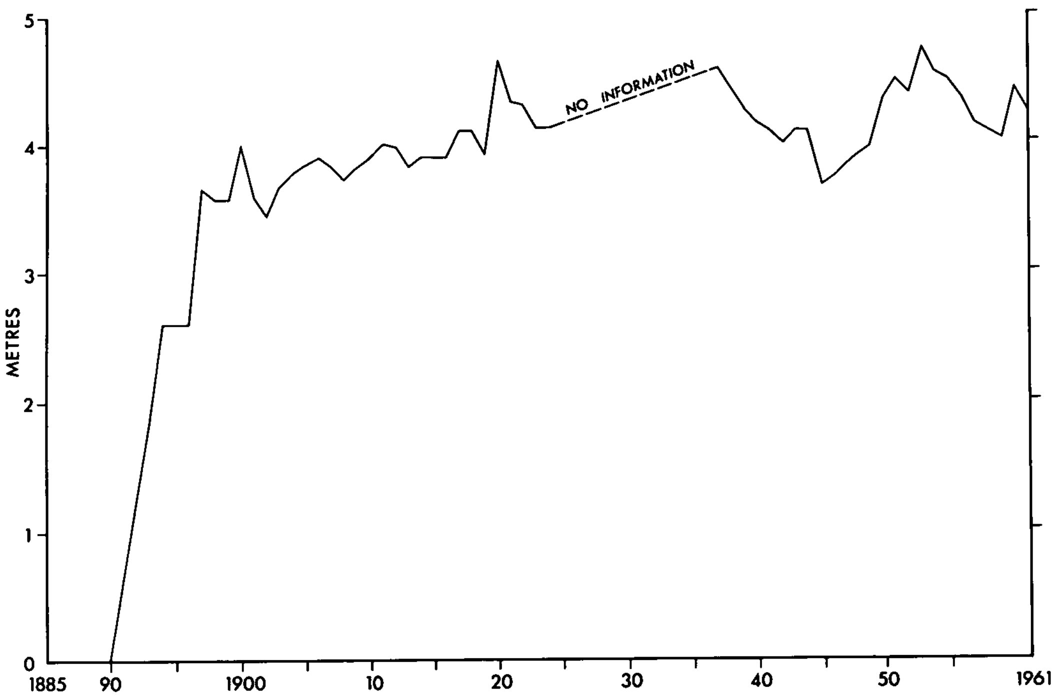
PLATE 3

Channel morphology of Tambo

River at Bruthen

FIGURE 3

Change with time of elevation of low water surface of Tambo River at Bruthen



METRES
0
1
2
3
4
5
1885
90
1900
10
20
30
40
50
1961
NO INFORMATION

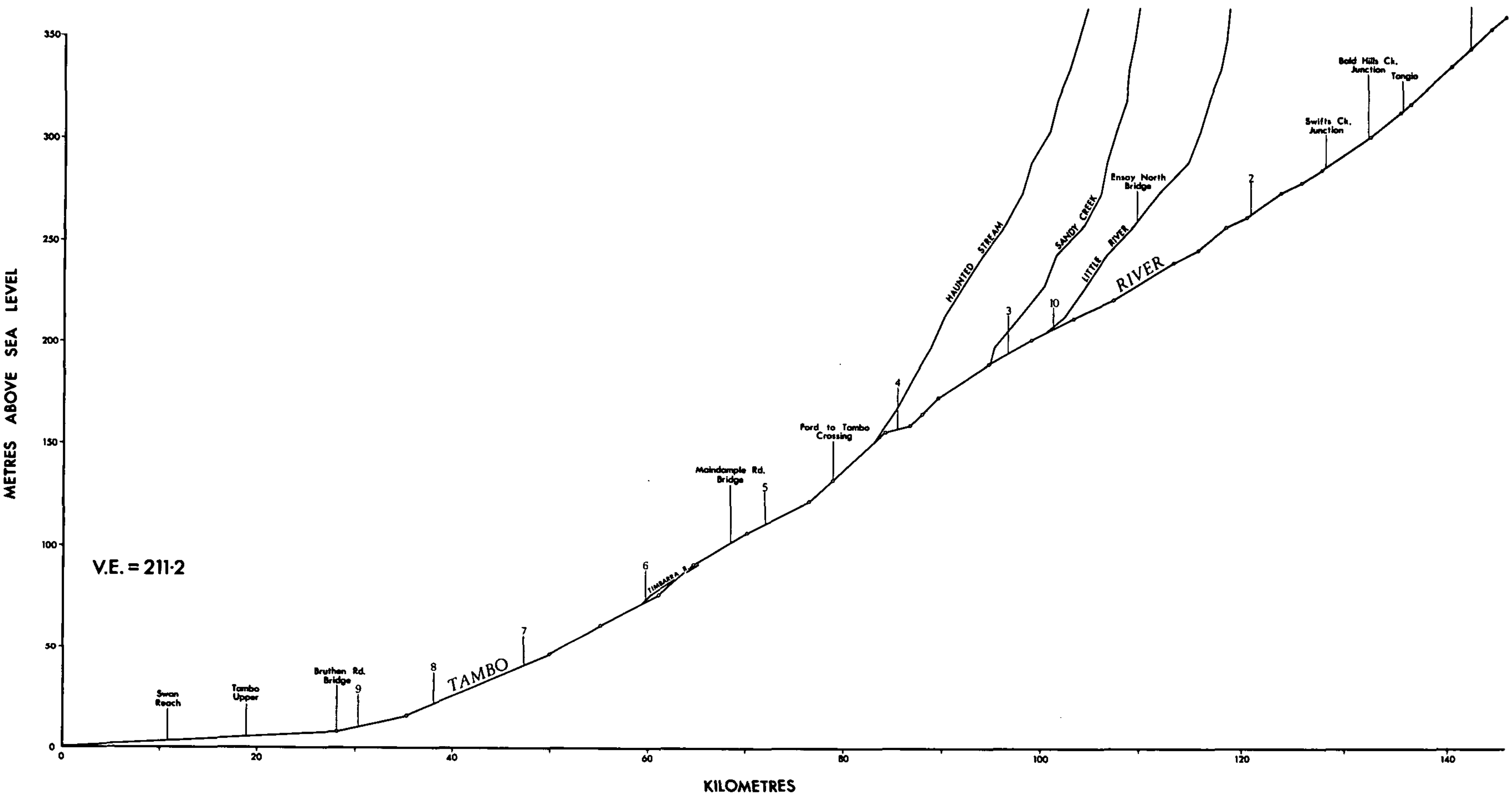
from hard rock mining operations - the vein quartz found in the gravel samples is probably derived from this source. The increase in load was undoubtedly further augmented by the resulting undercutting of alluvial banks adding still further to the supply of sand and gravel bedload of the stream. The greater abundance of sand in the recent past may also have resulted in effects of abrasion different from those prevailing at present.

In order to determine the effect - if any,- of variations in gradient on the morphometry of the gravels, a long profile of the stream was constructed by using a self-reducing tacheometer to measure differences in height between a series of more or less regularly spaced bench marks along the Omeo Highway and low water level of the river. Ideally a continuous traverse should have been carried out but this was precluded by the length of channel involved (148 kms) and the difficulties of access and terrain. The long profile is shown in figure 4 where each height determination is indicated by an open circle. Tributary profiles were constructed from contour information only and must be regarded as very approximate. The Tambo profile is almost straight from sample station 1 down to 48 kilometres from its mouth with an average gradient of 3.2 metres per kilometre and it is only in the lower reaches that the profile becomes concave upwards and a marked reduction in the gradient can be observed. Sand as bed

FIGURE 4

Longitudinal profile of

Tambo River



METRES ABOVE SEA LEVEL
KILOMETRES
V.E. = 211·2
TAMBO
RIVER
HAUNTED STREAM
SANDY CREEK
LITTLE RIVER
Swan Reach
Tambo Upper
Bruthen Rd. Bridge
Maindample Rd. Bridge
Ford to Tambo Crossing
Ensay North Bridge
Swifts Ck. Junction
Bald Hills Ck. Junction
Tongio
0
50
100
150
200
250
300
350
20
40
60
80
100
120
140
1
2
3
4
5
6
7
8
9
10

material becomes much more abundant below station 7 and no significant amounts of gravel bed material have been observed downstream from the Bruthen Road bridge. The gradient from here to the coast averages only 0.54 metres per kilometre. Between Tongio and Doctors Flat near the upstream end of the surveyed reach there is a tendency for the profile to become concave upwards once more - a characteristic which appears to be related to the obvious reduction in size of bed material in the downstream direction in this section as observed in the field.

The survey revealed only one marked irregularity in the profile. Sample station 4, just upstream from the Haunted Stream junction, appears to be located in a short low gradient reach with marked steepenings both above and below. The lower steepening may be associated with the introduction of coarse bedload material into the Tambo River by Haunted Stream.

CHAPTER II

PARAMETRIC DESCRIPTION AND SAMPLING PROCEDURE

Choice of Parameters

The parametric description of pebble morphology in this study involves the use of two distinct groups of parameters: shape and roundness. A very extensive literature is available and some of the earlier work is referred to in Pettijohn (1956). Important contributions to the description of shape not mentioned by Pettijohn were made by Folk (1955) and Sneed and Folk (1958). Similarly significant advances in the measurement of roundness were made by Cailleux (1945) and Kuenen (1956).

Measures of shape: Early classifications of shape were descriptive and used such terms as prismoidal, pyramidal, wedge-shaped, etc. as approximations to regular geometrical bodies. However, it was soon realized that a numerical measure of shape was required to enable the use of statistical methods in the comparison of samples from different populations. Provided that the particles are not too irregular in shape they can be assumed to approximate to a triaxial ellipsoid whose three axes can be measured with vernier calipers using the method suggested by Krumbein (1941). The terminology of Sneed and Folk (1958) is followed and the longest axis of a pebble is designed L^*, the intermediate axis I^* and the shortest axis S^*. The intermediate axis in defined as the longest dimension at right angles to L^*. The plane in which both L^* and I^* lie is known as the maximum projection plane of the particle. The short axis S^* is defined as the greatest dimension at right angles to the maximum projection plane and the plane in which I^* and S^* lie is termed the minimum projection plane. All three axes are mutually perpendicular but need not pass through the same point.

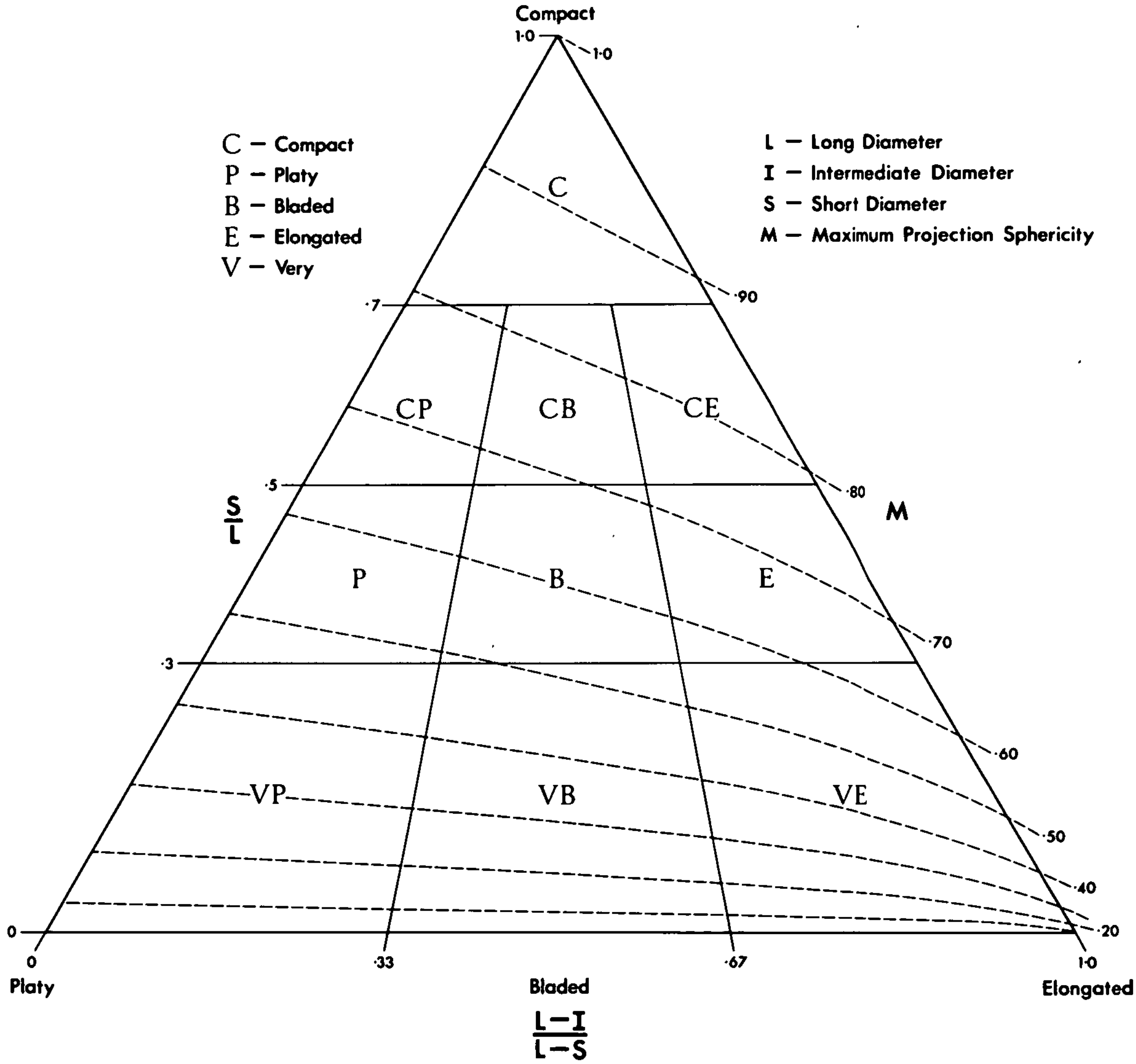
Using these three basic measurements a number of indices have been designed to express particle shape. Most of them are measures of <u>sphericity</u> and measure the degree to which the particle approximates to a sphere. The advantage of all sphericity parameters is that they can be expressed as a single number so facilitating statistical comparison. Their greatest disadvantage lies in the fact that they fail to discriminate between the large range of shapes exhibited by particles with low sphericity. Discs, blades and rods cannot be distinguished from each other by using sphericity as a parameter. Yet the types of low sphericity shapes present and their relative abundance can be important indicators of the processes operating in moulding particle shapes. For example it has frequently been claimed that pebbles subjected to wave action tend to become discoid in shape while current action tends to produce blade- and rod-like shapes (Williams, 1965). It is not possible to describe shape adequately with one parameter. A shape parameter proposed by Williams (1965) has the advantage of distinguishing between disc and rod-like shapes but fails to separate blades from spheroids.

An adequate description of the shape of a pebble approximating to a triaxial ellipsoid requires two parameters. One of the earliest attempts to do this was made by Zingg (1935) who devised a classification of pebble shapes in which I^*/L^* is plotted against S^*/I^*. The possible range of values of both ratios is between 0 and 1. The diagram was subdivided to distinguish four classes: discs, spheroids, blades and rollers. A more elaborate classification of shape was proposed by Sneed and Folk (1958) who introduced the term "form" for a two parameter description of shape. The form of each pebble is plotted on a triangular diagram (Figure 5) using the axial ratios S^*/L^* and L^*-I^*/L^*-S^*. The diagram takes the form of an equilateral triangle with the three corners representing the end points of three dimensional shape variation - sphere, rod

FIGURE 5

Form diagram after Sneed and

Folk (1958)



Compact
1·0
1·0
C — Compact
P — Platy
B — Bladed
E — Elongated
V — Very
L — Long Diameter
I — Intermediate Diameter
S — Short Diameter
M — Maximum Projection Sphericity
C
·90
·7
CP
CB
CE
·5
·80
M
S/L
P
B
E
·70
·3
·60
VP
VB
VE
·50
·40
·20
0
0
Platy
·33
Bladed
·67
1·0
Elongated
(L−I)/(L−S)

and disc. Pebbles approaching these end points are referred to respectively as compact, elongated and platy by Sneed and Folk. The authors divide the field of variation into ten classes which gives a much more equal quantitative division of pebble frequencies than the Zingg classification as well as being more suitable for detailed work.

In this study it was decided to use two measures of sphericity. Wadell sphericity (W^*) was first introduced by Wadell (1934) and modified by Krumbein (1941) for use with calipers. It has been widely used particularly in the United States. Its formula is

$$W^* = \sqrt[3]{\frac{I^* S^*}{L^{*2}}}$$

Maximum projection sphericity (M^*) was developed by R.L. Folk in 1946 but its first introduction in the literature was in Folk (1955) under the name of "effective settling sphericity". In a later paper (Sneed and Folk, 1958) its name was changed to maximum projection sphericity. It has the formula

$$M^* = \sqrt[3]{\frac{S^{*2}}{L^* I^*}}$$

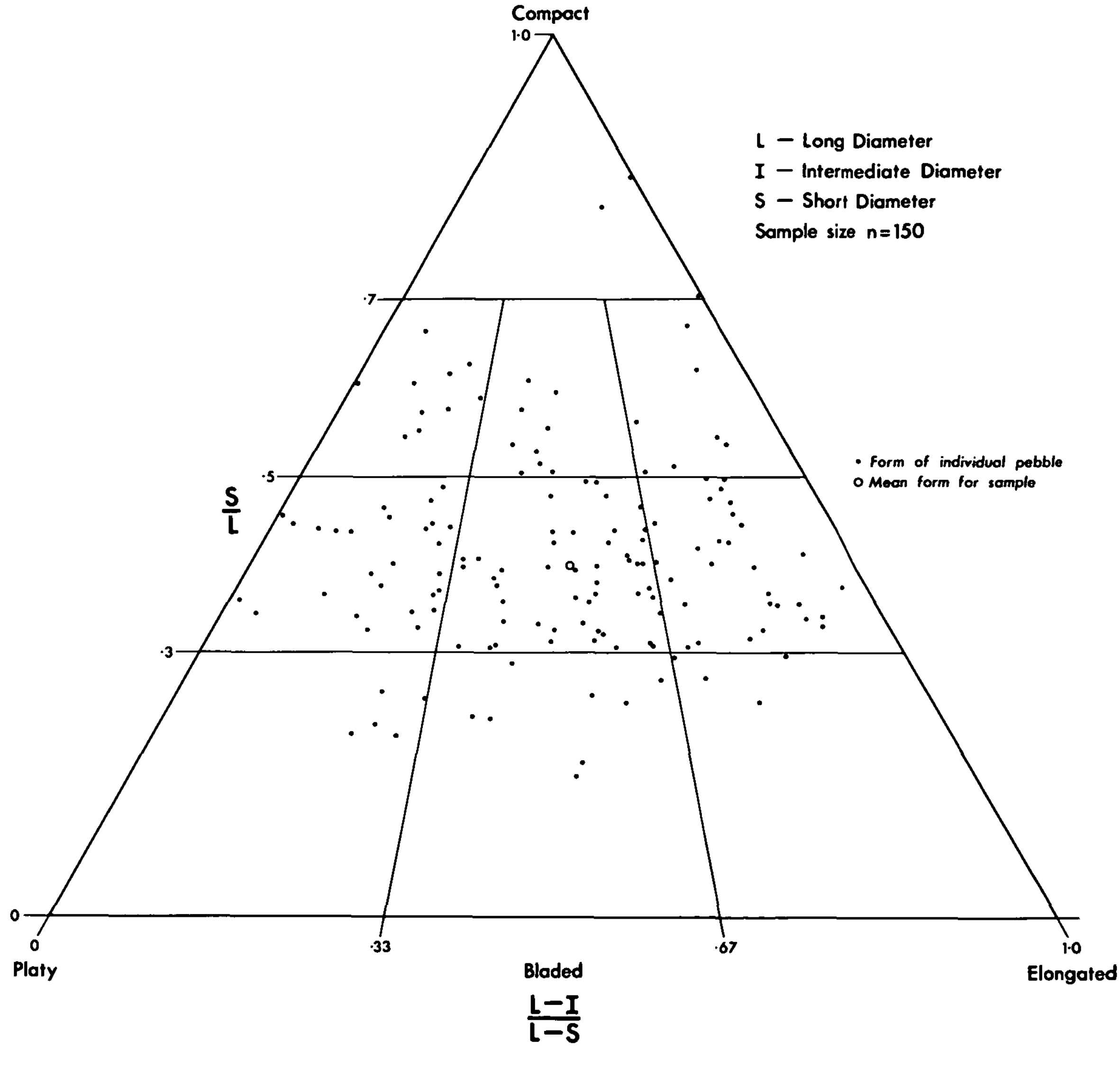
This sphericity parameter was advocated (Sneed and Folk, 1958) as a more natural measure of sphericity than the Wadell index since it had been designed to take into account the hydraulic behaviour of the particles according to Stokes' Law. Experiments by Sneed and Folk (1958) indicated that values of maximum projection sphericity correlated much more closely with both settling velocity and rolling velocity than is the case with Wadell sphericity. In order to test the relative merits of the two parameters under field conditions it was decided to make use of both. In addition to the two sphericity measures it was decided to use Sneed and Folk's form classification to group pebbles in each sample into ten form classes (Figure 6).

Measures of roundness: Roundness is concerned with the sharpness of the edges and corners of a particle and is a parameter which should be independent of size and shape within samples. Sedimentary particles - especially the more angular ones - may have many corners. Computation of some early indices of roundness requires the measurement of the radii of curvature of all corners of the particle - usually in a particular plane - which are then summed and averaged to give the overall roundness. Since an adequate sample must contain a large number of pebbles such a method is far too laborious for practical use. Other methods such as the one proposed by Powers (1953) rely on visual comparison with a standard.

FIGURE 6

Form diagram with rhyodacite

sample 4 plotted



Compact
1·0
·7
·5
·3
0
S/L
L — Long Diameter
I — Intermediate Diameter
S — Short Diameter
Sample size n=150
• Form of individual pebble
o Mean form for sample
0
·33
·67
1·0
Platy
Bladed
Elongated
L−I/L−S

Although this method allows rapid measurement of roundness an element of subjectivity is introduced. Folk (1955) studied operator error in the determination of roundness using Powers' roundness images as a standard and found it to be considerable.

An improved index was proposed by Cailleux (1945) who suggested measuring only the sharpest corner in the maximum projection plane. To determine the radius of curvature of this corner he placed the particle on a chart on which a series of concentric rings were drawn with the radii indicated in millimeters. The particle was placed with the maximum projection plane parallel to the chart and moved across until the sharpest corner fitted one of the curves. The radius of curvature (ra) was then read directly from the chart ("Cible morphoscopique"). The Cailleux roundness is calculated using the formula

$$C^* = \frac{2ra}{L^*}$$

After doing some experimental work on rounding, Kuenen (1956) observed that the Cailleux index contained elements not only of roundness but also of shape. The maximum value of the index is 1 but can only be reached by particles which develop into perfect spheres or discs. The greater the disparity in length between the long axis (L) and the other two (I and S) the lower the maximum value of the Cailleux index. Rod-like shapes tend to roll with the L-axis horizontal and at right angles to the current direction. Under these conditions continued abrasion can be expected to cause a progressive decrease in the Cailleux index. Therefore the index is likely to be least satisfactory where particles are highly rounded and where the proportion of rod-like particles in the sample population is high. To remedy these shortcomings Kuenen suggested a new roundness index which is calculated using the formula

$$Ku^{*} = \frac{2ra}{I^{*}}$$

At an early stage in the present study it was decided to use both indices to test their relative merits. Subsequently, however the writer became aware of another index proposed by Kaiser (1956) in an obscure publication but referred to by Blenk (1960) who gives the formula

$$Ka^{*} = \frac{4ra}{L^{*}+I^{*}}$$

It was thought that factor analysis would be a useful tool to assess the relative merits of the three indices proposed. The ideal roundness index for the purpose of this study is one which is completely independent of both size and shape within a sample because roundness variations between samples can then be considered solely as a function of environmental factors and sampling error.

Factor Analysis: Factor analysis is a generic term for a variety of techniques that attempt to describe complex relationships among many variables in terms of simpler relationships among fewer variables (Spencer 1966) and can be carried out by two distinct but related procedures known as R-mode (factor) and Q-mode (factor) analysis. The procedure relevant to our problem is R-mode which attempts to describe a large number of variables in terms of a smaller number of independent variables or factors explaining between them nearly all the observed variation. In other words a large number of variables which are in part measuring the same thing is reduced to the smallest possible number of independent sources of variation. The technique is discussed in detail in Rummel (1967), Harman (1960), Cole and King (1968) and Krumbein and Graybill (1965).

Briefly the procedure has as its starting point a data matrix of n x N spaces where N is the number of individuals and n the number of variables. From sample location 7, a sample of 150 pebbles within the size range (32 mm $< L^* <$ 64 mm) was collected from each of the two most abundant lithological types -

rhyodacites and sandstones and the following eight variables were recorded for each pebble: weight, long axis, intermediate axis, short axis, radius of curvature of sharpest corner in maximum projection plane and the three roundness indices of Cailleux, Kuenen and Kaiser. This gave a data matrix of 8 x 150 for each of the two rock types considered. Factor analysis was then applied using an existing programme written by Dr. Christopher Gee formerly of the Geology Department at the University of Tasmania.

The first step in factor analysis is the conversion of the data matrix to standard form to make the total variance of the matrix equal to n. It is then converted to a correlation matrix of n x n spaces (tables I and II). For any variable in standard form we can write the linear expression $Z_j = a_{j1}F_1 + a_{j2}F_2 + \ldots a_{jm}F_m + a_jU_j$ where the coefficients $a_1, a_2, \ldots, a_j$ are known as factor loadings. The factors involved in more than one variable (common factors) are denoted by $F_1, F_2 \ldots F_m$ and these factors account for intercorrelation between variables. The unique factors are involved in only one variable and are denoted by $U_1, U_2 \ldots U_n$. Communality of the standardized variable Z_j is the sum of the squares of the common factor coefficients, and expresses the proportion of the total unit variance accounted for by the common factors (Harman, 1960).

Table I - Factor analysis of size, shape and roundness parameters for rhyodacite sample 7. (Values rounded off to three decimal places.)

Correlation Matrix

	Weight	L*	I*	S*	ra	C*	Ku*	Ka*
Weight	-	.771	.833	.827	.511	.240	.127	.204
L*		-	.680	.521	.415	.056	.098	.076
I*			-	.620	.568	.345	.100	.262
S*				-	.342	.176	.062	.141
ra					-	.917	.854	.915
C*						-	.909	.987
Ku*							-	.962
Ka*								-

Average correlation coefficient .598. Number of samples 150.

Significant factor loading .049.

Table of Eigenvalues

Factor	Eigenvalue	% Explanation	Cumulative %
1	4.476	55.945	55.945
2	2.559	31.988	87.933
3	.512	6.398	94.331
4	.350	4.369	98.701

Four eigenvalues greater than 0.1.

Table I (Continued)

Initial Factor Matrix

Factor	1	2	3	4
Weight	.696	-.677	.075	-.035
L*	.543	-.646	-.468	-.250
I*	.698	-.564	-.083	.425
S*	.556	-.619	.508	-.193
ra	.963	.221	-.099	.038
C*	.843	.510	.092	.127
Ku*	.758	.604	-.052	-.224
Ka*	.831	.554	.041	-.004

Varimax Matrix

Factor	1	2	3	4	Communality
Weight	.136	-.709	-.513	.407	.950
L*	.045	-.310	-.919	.224	.993
I*	.179	-.421	-.391	.794	.993
S*	.071	-.961	-.193	.151	.988
ra	.891	-.188	-.277	.283	.987
C*	.969	-.091	.071	.204	.995
Ku*	.980	.003	.098	-.145	.992
Ka*	.994	-.061	.007	.077	.999

Table I (Continued)

Variance from Varimax Matrix

Factor	% Explanation	Cumulative %
1	46.77	46.77
2	21.83	68.60
3	17.36	85.97
4	12.73	98.70

Table II - Factor analysis of size, shape and roundness parameters for sandstone sample 7. (Values rounded off to three decimal places.)

Correlation Matrix

	Weight	L*	I*	S*	ra	C*	Ku*	Ka*
Weight	-	.735	.849	.809	.367	.125	-.037	.070
L*		-	.626	.408	.293	-.048	-.020	-.034
I*			-	.625	.418	.226	-.073	.125
S*				-	.224	.098	-.098	.027
ra					-	.925	.835	.919
C*						-	.886	.985
Ku*							-	.951
Ka*								-

Average correlation coefficient .551. Number of samples 150.
Significant factor loading .056.

Table of Eigenvalues

Factor	Eigenvalue	% Explanation	Cumulative %
1	3.976	49.695	49.695
2	2.942	36.769	86.464
3	.627	7.843	94.307
4	.340	4.250	98.557

Four eigenvalues greater than 0.1.

Table II (Continued)

Initial Factor Matrix

Factor	1	2	3	4
Weight	.510	-.831	-.045	-.058
L*	.355	-.706	.579	-.178
I*	.524	-.737	-.013	.419
S*	.382	-.717	-.503	-.274
ra	.975	.139	.086	.040
C*	.900	.395	-.128	.110
Ku*	.790	.553	.105	-.201
Ka*	.885	.462	-.040	.000

Varimax Matrix

Factor	1	2	3	4	Communality
Weight	.072	-.708	.532	.409	.957
L*	.001	-.238	.947	.197	.992
I*	.109	-.454	.380	.795	.994
S*	.016	-.972	.146	.155	.990
ra	.928	-.142	.226	.218	.979
C*	.974	-.072	-.109	.164	.993
Ku*	.964	.086	.051	-.207	.982
Ka*	.997	-.013	-.048	.034	.998

Table II (Continued)

Variance from Varimax Matrix

Factor	% Explanation	Cumulative %
1	46.89	46.89
2	21.76	68.64
3	17.66	86.30
4	12.26	98.56

The process of extraction of factors is best understood in terms of a geometric model (Rummel, 1967) in which individuals are presented as axes at right angles to one another forming a framework within which each parameter can be represented as a vector. The space used in the analysis of factors relating to more than three individuals is multi-dimensional space, also known as hyperspace or vector space.

The correlation matrix factor analysis produces first of all the unrotated or initial factor matrix where projection of the vectors on each of the axes gives factor loadings for each factor for each variable. In this matrix the first factor defines the largest pattern of relationships in the data, the second the next largest pattern and so on. A disadvantage of the initial factor matrix is that it groups unrelated clusters. This matrix can be used to compute a table of eigenvalues for each factor with the percentage and cumulative percentage of the variance explained by each factor. The eigenvalue of a factor is the amount of the variance in standard form explained by that factor.

The next step is orthogonal rotation where axes are rotated in a rigid framework at right angles to each other so that the first axis coincides with the most prominent cluster of vectors. Various computational techniques are available but the one employed here is the "varimax" technique. Orthogonal rotation was felt to be particularly well suited to the problem as it is specifically designed to isolate uncorrelated cluster patterns. Thus from a suitably arranged data matrix containing information on the size, shape and roundness characteristics of a sample of pebbles, orthogonal rotation should, after varimax rotation, extract a roundness factor which is independent of both size and shape. This factor can be identified from the varimax matrices (tables I and II) which represent the factor loadings for each factor in respect of each variable. The loadings measure which variables are involved in which factor pattern and to what degree and can be interpreted like correlation coefficients (Rummel, 1967). It follows that the roundness factor can be identified as factor 1 in the tables by its high loadings on roundness indices and low loadings on variables measuring size and shape. The higher the loading for a particular index the less dependent it is on other factors.

The actual percentage of variation of an index explained by the roundness factor is obtained by squaring the loading and multiplying by one hundred. The varimax matrices would seem to indicate that the most satisfactory index to use is the Kaiser Index. In the case of the rhyodacite sample (table I) this index has 98.88% of its variance explained by the roundness factor while the least satisfactory is clearly the raw roundness measure which has only 79.46% of its variation explained by this factor. The

Cailleux and Kuenen Indices are intermediate with 93.99 and 96.08% explanation respectively. The sandstone sample shows a similar pattern. As a result of the assessment of roundness measures using factor analysis further work was limited to the use of the Kaiser and Kuenen Indices shown to be the least dependent on both size and shape.

Methods of sampling

The sampling procedures had to satisfy a number of requirements. As the study was originally designed to enable comparison to be made between present bed material and fossil gravels in river terraces the methods used had to be as nearly similar as possible to those that could be used to sample fossil outcrops in road cuttings, gravel quarries and river banks.

The characteristics of the bedload gravels selected for investigation were:

(i) Lithological composition. The method selected basically followed the pioneer study in this field by Tricart (1959) which despite its original approach seems to have made little if any impact in the English speaking world.

(ii) Form. (or shape) was investigated using the form classification first proposed by Sneed and Folk (1958).

(iii) Sphericity. The two parameters selected for use were Wadell sphericity (Wadell, 1934) and Maximum Projection Sphericity (Sneed and Folk, 1958).

(iv) Roundness. The original selection of roundness parameters for the study consisted of the Cailleux and Kuenen indices. However, at a later stage the writer became aware of the existence of the Kaiser index and of the possibility of using factor analysis to assess the extent to which roundness indices were influenced by factors related to size and shape. Following factor analysis the Cailleux index was replaced by the Kaiser index.

Since parameters measuring all four characteristics listed above may in part be a function of particle size, sampling ought to be restricted to as narrow a size range as possible but in practice this restriction is limited by the practical problem of collecting a large enough sample in a reasonable time. The choice of size class is limited in the upward direction by the same consideration. Samples composed of large pebbles would be too bulky to transport. If on the other hand a small size class is selected measurement becomes inaccurate in relation to size. The size class selected was based on long axis measurements between 32 and 64 mm, the same class used by Sneed and Folk (1958) in their study of pebbles in the Colorado River. It must be pointed out that even in this narrow range Sneed and Folk found that particle size had a great effect on sphericity and form. However, practical considerations require the use of the same size class. In any case the Tambo River may well behave in an entirely different way to the Colorado.

It may also be argued that weight is a more satisfactory criterion of size than long axis measurements and that size selection on the basis of weight will be more satisfactory. While this is probably true it creates practical problems when collecting in the field. However the correlation matrices produced for samples of rhyodacites and sandstones from station 7 (tables I and II) show that the intermediate axis correlates more highly with the weight of a pebble than either the long or the short axis and some slight advantage may be gained in future studies by the use of a size class based on measurements of the intermediate axis.

Nine sample stations were selected on gravel bars (either point or spool bars) along the course of the river. A typical example of a point bar is shown in plate 4. More or less equal spacing of stations was aimed for but actual sample localities frequently depended on accessibility and the presence of abundant pebbles in the right size class. At the selected point a peg was

PLATE 4

Gravel point bar with slip face

facing downstream

driven in and a circle one metre in diameter set out. Working from the centre outwards two hundred pebbles within the required size limits were collected and identification of lithological content was made on the spot. Only in one case (sample 1) was it found necessary to go outside the sample circle for a sufficient number of pebbles.

The rock types selected for measurement of form, sphericity and roundness had to be sufficiently abundant at all sample sites to enable collection of a large sample in a reasonable time and only two - rhyodacites and sandstones - met this requirement. Ideally the selected lithologies should be unaffected by chemical weathering in the study area and both were satisfactory in this respect. Slight weathering out of quartz and feldspar phenocrysts was observed in some rhyodacite pebbles at stations 8 and 9 but this was not sufficiently marked to affect their morphometry. A desirable characteristic of any rock type selected for measurement would also be that it is as isotropic as possible, i.e. it should not show preferred orientation of weaknesses which tend to control form and sphericity to such an extent that the influences of the processes involved in bedload transport may not be discernible. In this respect the rhyodacites - being massive rock types - appeared to be the most suitable. The sandstones were less ideal from this point of view.

The rhyodacite and sandstone pebbles obtained in the lithological sample were added to until 150 pebbles of each lithology were obtained. This sample size was considered sufficiently large for the purpose of this study following extensive reading of the literature dealing with aspects of particle morphometry. In the case of each pebble the three axes (L^*, I^* and S^*) and the radius of curvature (ra) of the sharpest corner in the maximum projection plane were measured. Axial measurements were made to the nearest 0.1 mm using a pair of calipers with vernier scale. As mentioned earlier Cailleux's "cible morphoscopique" was used to measure ra. All sphericity and roundness indices were multiplied by 1000 to facilitate computation and representation of information. This conforms with common practice by European workers and enables easy comparison to be made with their results.

The original plan included sampling of the larger tributaries of the Tambo but, with one exception, this did not prove practical because not sufficient bedload material in the selected size class could be found. The Timbarra River for example has had its gradient steepened above its junction with the Tambo and for several miles upstream it flows in a narrow deeply incised bedrock channel containing little or no bed material. The exception was the Little River which was sampled at site 10. This sample contained no rhyodacite pebbles but its lithological composition was determined and measurements made on a sample of sandstone pebbles.

In order to process the 11,400 items of numerical information obtained in this way a computer programme was written with the assistance of Mr. N. Chick. This produced for each sample the distribution of the pebbles in the ten form classes. For the Kaiser and Kuenen roundness indices, as well as the Wadell and Maximum Projection sphericities, the mean, standard deviation, skewness, kurtosis and frequency distribution of twenty classes are calculated. Finally the programme also computed correlation coefficients and regression lines between all possible combinations of the four parameters of roundness and sphericity within each sample (Appendix). The computer processed information forms the basis for the later discussion of relationships both within and between samples.

CHAPTER III

ANALYSIS OF THE DATA

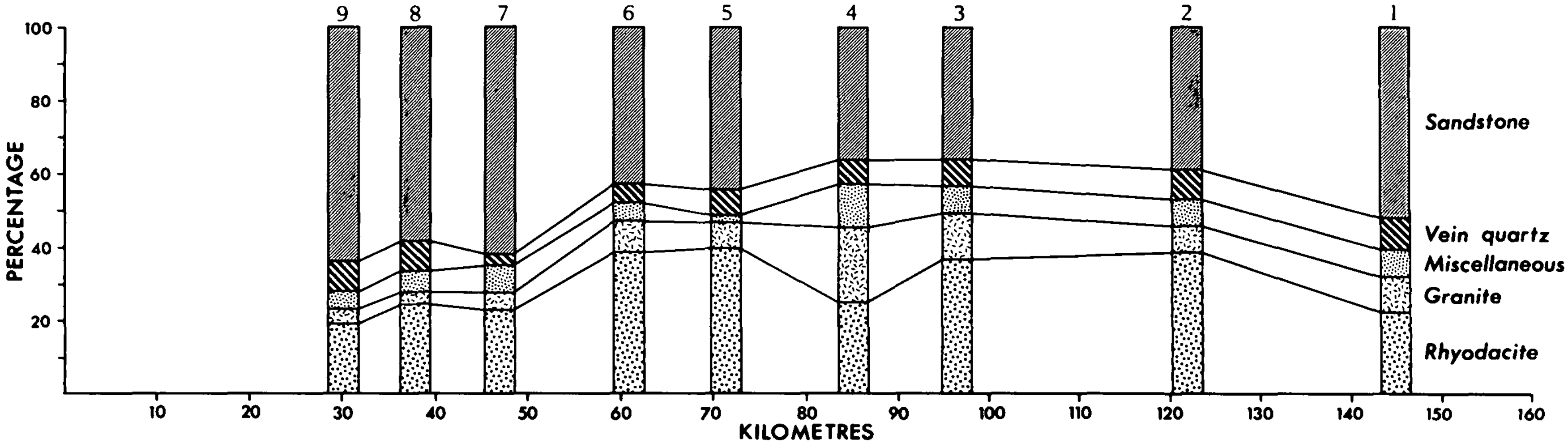
Lithological composition.

The lithological composition of each of the nine samples collected along the Tambo River is illustrated in figure 7. It can readily be seen that the composition of the bedload within the size range studied is dominated by two lithologies: rhyodacites and sandstones. Others form only a minor component including granites which nevertheless crop out over large areas. The deficiency in granite content appears to be due to the observed rapid granular disintegration of granite pebbles present in the bed material. The percentage of rhyodacite pebbles decreases markedly downstream from the Timbarra River junction (between stations 6 and 7) and reflects the more limited extent of outcrops of this rock in the Timbarra catchment.

In order to relate the lithological composition of

FIGURE 7

Lithological composition of samples


9
8
7
6
5
4
3
2
1
100
80
60
40
20
PERCENTAGE
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
KILOMETRES
Sandstone
Vein quartz
Miscellaneous
Granite
Rhyodacite

samples to outcrop patterns a lithological map of the whole of the Tambo catchment was compiled (figure 2.) and all information available up to 1968 included. Unfortunately the patchy nature and variable quality of geological mapping in the area, as outlined in Chapter I renders the investigation of relationships between areas of outcrop and gravel composition less rewarding than might otherwise have been the case.

The approach used is similar to that used by Tricart (1959) for a number of rivers in France. For each rock type within each sample, Q_ℓ - the percentage content in a particular sample - has been calculated. Similarly at each sample point and for each lithology, Q_0 - the percentage area of the catchment over which a particular lithology crops out - was also computed. Q is the ratio Q_ℓ/Q_0 and is a parameter first suggested by Cailleux as giving an indication of the yield of material from a particular lithology, within the size class examined, in relation to other rock types. A value greater than 1 indicates an above average yield, a value of less than one a below average yield (Table III). For each rock type the values of Q from the nine stations have been averaged to give $\bar{Q}$. Although there is a good deal of variation between samples, a characteristic value of $\bar{Q}$ characterizes each lithology.

Table III

Relationships between lithology of samples and outcrops

Sample No.	Granites			Rhyodacites			Sandstones, quartzites			Limestones		
	Q_ℓ	Q_0	Q	Q_ℓ	Q_0	Q	Q_ℓ	Q_0	Q	Q_ℓ	Q_0	Q
1	9.5	25.75	0.37	22.5	20.56	1.10	52.5	27.02	1.94	-	2.05	-
2	7.0	27.32	0.25	38.5	11.63	3.31	40.0	27.19	1.47	-	1.15	-
3	12.5	32.28	0.39	38.0	8.72	4.36	36.0	25.76	1.40	-	0.87	-
4	20.0	33.29	0.61	30.0	7.55	3.97	36.5	28.39	1.29	-	0.78	-
5	7.0	28.02	0.25	39.5	8.07	4.90	44.5	40.00	1.11	-	0.62	-
6	8.5	27.45	0.31	38.5	8.14	4.74	46.5	41.40	1.12	-	0.59	-
7	4.5	29.95	0.15	23.0	8.07	2.86	62.5	41.75	1.50	-	0.44	-
8	3.0	29.20	0.13	24.5	7.87	3.11	60.0	43.30	1.39	-	0.43	-
9	4.0	29.34	0.14	20.5	7.49	2.74	64.0	44.40	1.44	-	0.41	-
$\bar{Q}$			0.29			3.45			1.41			-

Table III (Continued)

Relationships between lithology of samples and outcrops

Sample No.	Basalts			Vein quartz			Schists, slates			Siltstones		
	Q_ℓ	Q_0	Q	Q_ℓ	Q_0	Q	Q_ℓ	Q_0	Q	Q_ℓ	Q_0	Q
1	-	0.80	-	8.5	?	-	7.0	8.61	0.81	-	15.21	-
2	1.0	0.45	2.22	8.0	?	-	5.5	23.66	0.23	-	8.60	-
3	1.0	0.34	2.94	7.5	?	-	5.0	25.58	0.20	-	6.45	-
4	-	0.31	-	6.5	?	-	7.0	23.75	0.29	-	5.93	-
5	-	0.24	-	7.0	?	-	2.0	18.46	0.11	-	4.58	-
6	-	0.23	-	5.0	?	-	1.5	17.74	0.08	-	4.40	-
7	3.5	1.49	2.35	3.0	?	-	3.5	14.13	0.25	-	4.21	-
8	2.5	1.45	1.72	7.0	?	-	3.0	13.80	0.22	-	4.10	-
9	-	1.38	-	8.0	?	-	3.5	13.12	0.27	-	3.90	-
$\bar{Q}$			2.31			-			0.26			

Values of $\bar{Q}$ can not be determined for limestones and siltstones because no pebbles from any of the samples can be identified as belonging to either of these lithologies. Therefore no values can be calculated for Q_{ℓ}. For basalts Q_{ℓ} can not be determined for five samples because no basalt pebbles are present and the value of $\bar{Q}$ represents the mean of the values of Q of the four remaining samples. The first reason for the absence of pebbles belonging to these rock types appears to be the relatively small areas of outcrop within the basin, particularly of limestones and basalts. The second reason is that pebbles of limestones and siltstones are rapidly removed during transport - the latter are prone to rapid disintegration and the former are attacked by solution processes and are also subject to rapid abrasion on account of their low hardness.

In the case of vein quartz it is not practicable to determine areas of outcrop and this problem has been discussed at length by Tricart (1959). Vein quartz is probably most common in the granitic rocks but also occurs in other rock types. Even if areas of outcrop could be calculated the value of $\bar{Q}$ would be suspect as a true measure of relative yield of debris under natural conditions in the size class being considered. Mining operations may well have provided a significant source of vein quartz in the recent past.

For rhyodacites, sandstones and basalts the value of $\bar{Q}$ is above 1 although figures for basalt must be treated with caution because of the small number of pebbles involved. Rhyodacites yield more material per unit area of catchment than any other rock type. This may reflect their susceptibility to frost weathering during cold climatic conditions (Talent, 1965). The occurrence of outcrops at higher elevations, together with the resistance of these rocks both to abrasion and chemical weathering under the prevailing environmental conditions, are other factors that must be considered.

For schists, slates and granites the value of $\bar{Q}$ was less than 1 reflecting the tendency for these rocks to yield fragments that are rapidly broken down into smaller detritus during transport.

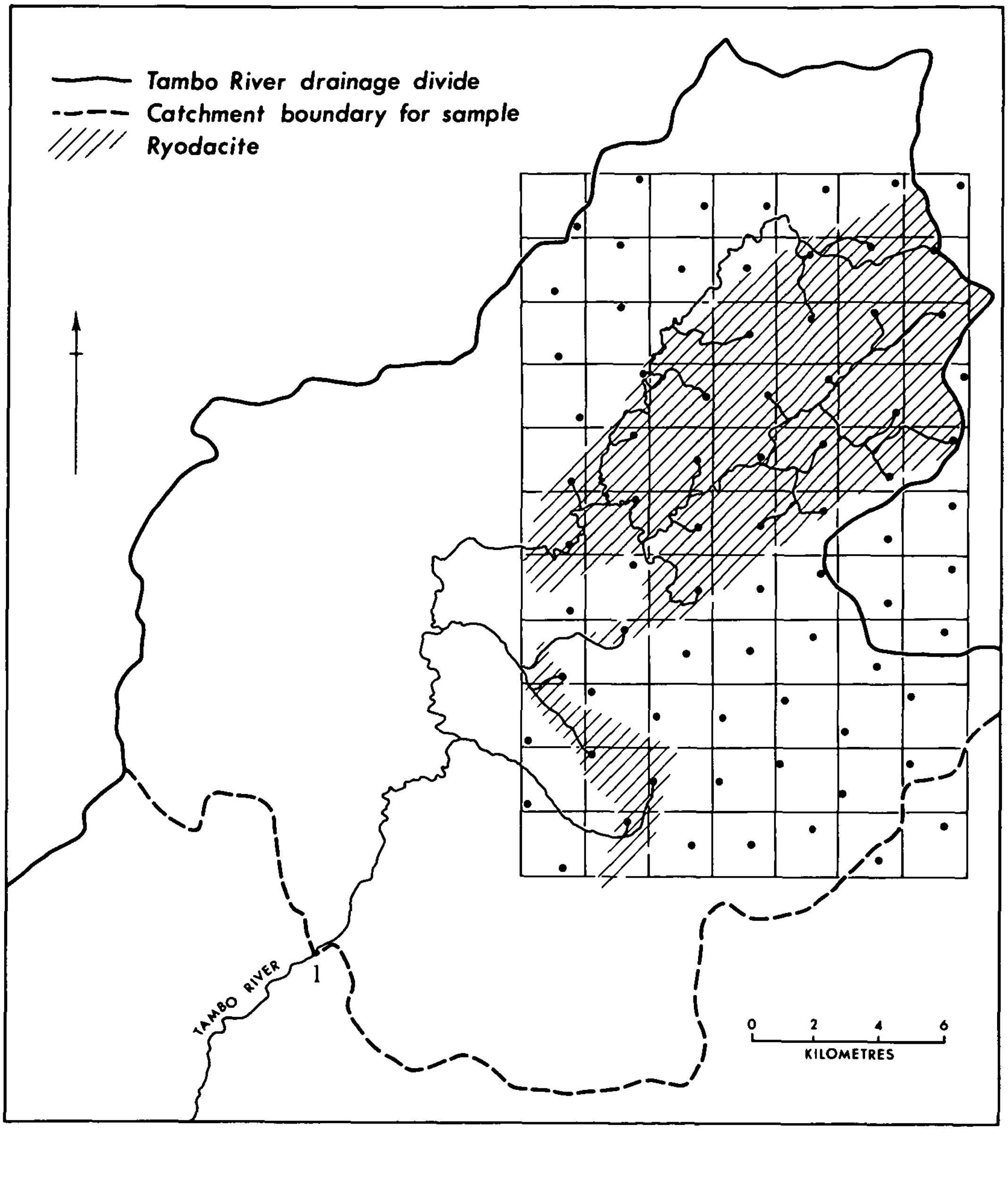
It was decided to investigate for one lithology - rhyodacite - the possible relationships of Q with mean distance from outcrop (Di_r') and mean altitude of outcrops (AL_r) for each station. Because of the time consuming procedure required to obtain these parameters for just one rock type this part of the investigation was restricted to rhyodacite only which, because of its homogeniety and massive nature, is also the most useful lithology for the investigation of factors affecting roundness, form and sphericity for which the same data can be used.

The first step was the superimposition of a 2000 metre sampling grid over the catchment. Most of the area is covered by the 1:100,000 Omeo and Benambra topographic sheets with metric contours and grid enabling the existing grid to be used for sampling. On non-metric maps covering the remainder of the area a metric sampling grid was superimposed. One sample point was selected within each grid square using the stratified systematic unaligned method of sampling in order to ensure an unbiassed estimate of mean altitude (Berry and Baker, 1968). For each sampling point mean altitude of outcrops (Al_r) was determined as follows. If a point fell on a contour its height was considered to be that of the contour while if it fell between two contours its height was taken as being half-way between the two. Where contour information was in feet the same procedure was followed but in conversion to metric units each value was rounded off to the nearest multiple of 20 metres. From each point the distance to the location of the nearest gravel sample station was measured by the horizontal distance down the slope to the nearest stream and from there downstream along the channel. The horizontal distance rather than the slope distance was used because it is more easily measured. With the values involved in this study horizontal distances are very large compared with vertical distances. Changes in values obtained by substituting slope distance for horizontal distance would be very small and well

FIGURE 8

Sampling grid for outcrops

of rhyodacite


Tambo River drainage divide
Catchment boundary for sample
Ryodacite
TAMBO RIVER
1
0 2 4 6
KILOMETRES

within the margins of error for measurement of horizontal distance from topographic maps. Figure 8 illustrates the sampling procedure in the area upstream from sample station 1. From this information the mean distance (Di_r) from rhyodacite outcrops to the sample location was calculated for each station.

Where measurement of distance was made on a scale other than 1:100,000 the measurements were not simply converted to kms but a correction factor applied to take into account the variation in detail for an irregular stream path shown at different scales. This factor was obtained empirically by measurement where maps of two different scales were available for the same area. For example, distance measurements made on a map scale of 1:31,680 after conversion to kms had to be multiplied by a factor of 0.92 to make them comparable with measurements made on a 1:100,000 map scale. The results are shown in table IV.

The next step was the correlation of Q with Al_r and Di_r. The correlation coefficient between Q and Al_r was .036 indicating virtually no relationship between Q and mean altitude of outcrops. Correlation between Q and Di_r yields a coefficient of .480 ($t = 1.155$) and while this is not significant this may well be due to the small number of samples involved ($n = 9$). It indicates that 23% of the variation in Q can be explained in terms of variations in distance from outcrops.

Table IV - Values of Al_r and Di_r for samples of rhyodacite

Sample No.	No. of points	Q	Al_r (m) (mean altitude of rhyodacite outcrops)	Di_r (km) (mean distance from rhyodacite outcrops)
1	31	1.10	1040.00	35.20
2	31	3.31	1040.00	57.91
3	31	4.36	1040.00	82.81
4	32	3.97	1040.38	92.03
5	40	4.90	928.00	87.54
6	41	4.74	921.95	97.59
7	54	2.86	830.37	95.23
8	54	3.11	830.37	104.50
9	54	2.74	830.37	112.16

When it is considered that Q is subject to errors in geological mapping and sampling as well as identification of rhyodacite in the field and furthermore - since Q is related to Q_ℓ - is also dependent on variations induced by the presence of other rock types the positive relationship between Q and Di_r is at least suggestive. As indicated earlier the characteristically high values for Q found for rhyodacite reflect at least in part their resistance to abrasion and chemical weathering during transport and a positive relationship between Q and mean distance from outcrops (Al_r) can therefore be expected on theoretical grounds.

Further explanation of the variations in Q for rhyodacites may be possible when Di is calculated for outcrops of other lithologies contributing significantly to the load within the size range investigated, especially sandstones and to a lesser extent schists and granites but lack of time to carry out the procedures involved did not allow further investigation.

Another related aspect of the lithological composition of the gravels investigated by Tricart (1959) was the relationship between changes in Q_ℓ (ΔQ_ℓ) and changes in Q_0 (ΔQ_0) between stations. He considered the significance of three possibilities.

Case 1 - $\Delta Q_\ell > \Delta Q_0 > 0$

Case 2 - $\Delta Q_\ell > 0 > \Delta Q_0$

Case 3 - $\Delta Q_\ell < \Delta Q_0$

He further claimed that the three cases just stated gave information relating to the physical behaviour and degree of reworking of particular rock types between two stations. Before considering this further it must be pointed out that Tricart's three cases are not exhaustive - other relationships may occur. To cover all possible relationships the following cases must be considered.

Case 1 - $\Delta Q_\ell > \Delta Q_0$	(a)	both positive
	(b)	ΔQ_ℓ positive, ΔQ_0 negative
	(c)	both negative
Case 2 - $\Delta Q_\ell < \Delta Q_0$	(a)	both positive
	(b)	ΔQ_ℓ negative, ΔQ_0 positive
	(c)	both negative
Case 3 - $\Delta Q_\ell = \Delta Q_0$		rare occurrence

Values of ΔQ_ℓ and ΔQ_0 are set out in table V for three lithologies: rhyodacite, sandstone and granite. Behind each pair of values the case which applied to the relationship between them is indicated. It can be seen that the relationship appears to vary in a completely random manner both within and between lithologies. The influences of lithological constituents other than the one being considered probably affect the values of both ΔQ_ℓ and ΔQ_0 to such an extent that the relationship between them has little if any meaning.

Table V - Values of ΔQ_ℓ and ΔQ_0 for rhyodacite, sandstone and granite

	Rhyodacite			Sandstone			Granite		
Sample No.	ΔQ_ℓ	ΔQ_0	Case	ΔQ_ℓ	ΔQ_0	Case	ΔQ_ℓ	ΔQ_0	Case
1									
	+16	-8.93	1(b)	-12.5	+0.17	2(b)	-2.5	+1.57	2(b)
2									
	-0.5	-2.91	1(c)	-4.0	-1.43	2(c)	+5.5	+4.96	1(a)
3									
	-8.0	-1.17	2(c)	+0.5	+2.63	2(a)	+7.5	+1.01	1(a)
4									
	+9.5	+0.52	1(a)	+8.0	+11.61	2(a)	-13.0	-5.27	2(c)
5									
	-1.0	+0.07	2(b)	+2.0	+1.40	1(a)	+1.5	-0.57	1(b)
6									
	-15.5	-0.07	2(c)	+16.0	+0.35	1(a)	-4.0	+2.50	2(b)
7									
	+1.5	-0.20	1(b)	-2.5	+1.55	2(b)	-1.5	-0.75	2(c)
8									
	-4	-0.38	2(c)	+4.0	+1.10	1(a)	+1.0	+0.14	2(a)
9									

Form Composition

The pebbles in samples of 150 collected from both rhyodacites and sandstones at each of the nine stations were grouped into ten form classes using the method of Sneed and Folk (1958). Differences between successive samples were then tested using the chi-square test. This sometimes necessitated grouping of classes to meet the requirement that the expected frequency in any class shall not fall below five. This requirement has been adhered to throughout although it has recently been claimed by Snedecor and Cochran (1967) that it is too strict and that the chi-square test is accurate enough if the smallest expected frequency is at least 1. The research on which this statement is based is documented in Cochran (1952). Classes were grouped only where they shared a common border in the form diagram (figure 5). In the case of sandstones the degree of grouping needed for comparisons varied slightly causing variation in the number of degrees of freedom. The results are shown in table VI.

In most cases form differences between samples are not significant but both rock types show a significant change - highly significant in the case of sandstone - between stations 6 and 7. It is between these two stations that the Timbarra River - the Tambo's largest tributary - joins the main stream. In addition sandstone shows a probably significant change between stations 7 and 8 and

Table VI - Between sample changes in form composition

Sandstone	C	CP	P	VP	CB	B	VB	CE	E	VE	Values of chi^2 ΔF_s	Degrees of freedom	Significance of difference
1	2	5	13	4	20	43	23	7	24	9	6.176	7	
2	0	7	12	9	24	40	13	11	29	5	9.158	7	
3	4	8	6	2	21	49	16	8	30	6	11.264	7	
4	2	8	18	6	20	41	24	7	17	7	13.902	7	
5	5	9	9	3	16	39	15	14	31	9	5.556(5.273)	8 (7)	
6	6	9	12	2	28	32	11	15	25	10	25.774	7	highly sign.
7	3	10	20	8	11	41	26	5	18	8	15.806(15.002)	8 (7)	prob. sign.
8	1	4	20	5	14	46	15	18	19	8	9.361	7	
9	2	13	25	6	12	47	14	9	19	3			
10	3	9	13	1	25	38	10	13	35	3			

Rhyodacite	C	CP	P	VP	CB	B	VB	CE	E	VE	ΔF_r	Degrees of freedom	Significance of difference
1	2	8	21	1	12	37	23	11	30	5	3.728	6	
2	5	7	15	4	16	45	15	4	34	5	4.488	6	
3	4	9	12	1	11	56	10	11	31	5	9.128	6	
4	3	10	26	5	8	49	8	8	29	4	25.874	6	highly sign.
5	11	6	12	1	30	46	5	16	21	2	3.140	6	
6	3	10	11	2	23	51	9	19	17	5	19.532	6	sign.
7	1	3	19	4	13	58	20	8	20	4	3.070	6	
8	1	8	23	0	13	57	14	9	23	2	3.874	6	
9	3	10	20	3	13	51	12	16	19	1			

C - compact, P - platy, B - bladed, E - elongated, V - very
Values of chi-square in brackets are adjusted for 7 degrees of freedom.

rhyodacite shows a highly significant change between stations 4 and 5 where material from the Mt. Elizabeth rhyodacite complex is beginning to be fed into the Tambo River.

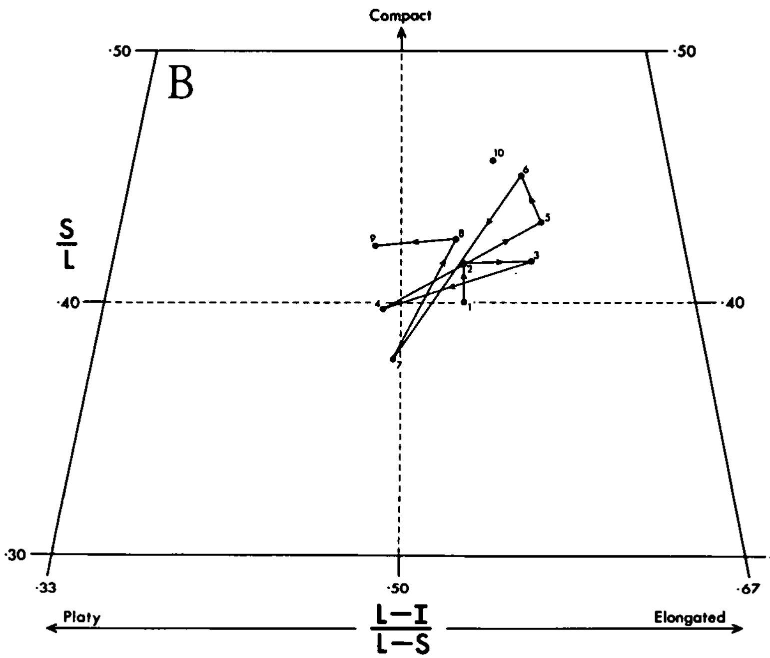
There appears to be no systematic change in form in the downstream direction for either rock type. Comparison between sandstone samples 1 and 9 indicates a probably significant difference while in the case of rhyodacite there is no significant difference. Changes in mean form were also plotted on a triangular diagram (figure 9) in the manner of Sneed and Folk (1958) with arrowed lines indicating the direction of form changes between samples. It will be noted that the mean form for all samples in both lithologies falls into the bladed class and that the changes are of a relatively small magnitude. Between the upstream stations (1 and 4) changes in mean form for rhyodacites and sandstones are remarkably similar in direction but this similarity disappears further downstream although there is a slight tendency between downstream stations (6 and 9) for it to reappear. In both rock types the diagrams fail to indicate any progressive change in form downstream confirming the results of earlier comparisons between stations 1 and 9 using the chi-square test. Although the mean form diagrams fail to show consistent behaviour between the two lithologies with regard to direction of change there does - from visual inspection - appear to be a closer relationship between the two with regard to the

FIGURE 9

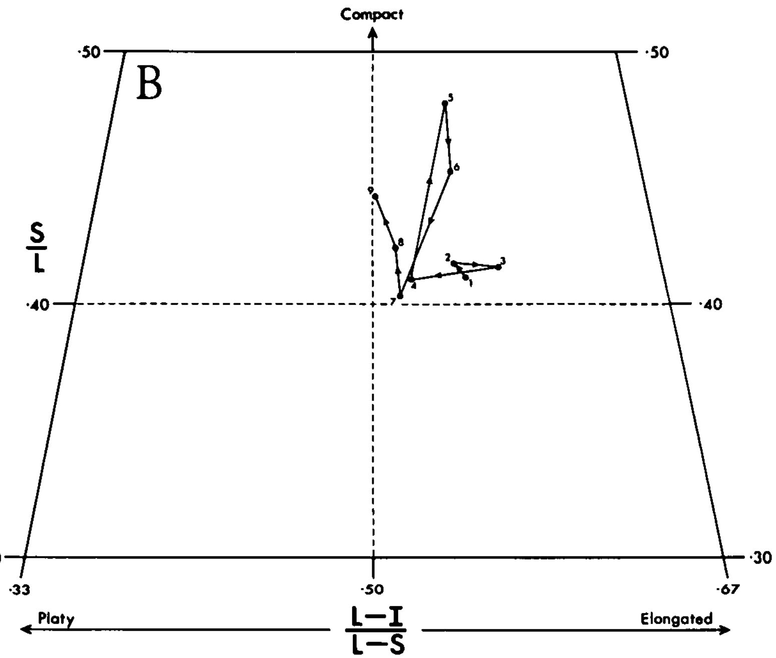
Mean form and changes

between samples

SANDSTONE



RHYODACITE



magnitude of the form change between stations. This can be tested quantitatively by correlating the values of chi-square obtained for changes in the form of sandstone pebbles with the corresponding values obtained for rhyodacite.

However, before such a correlation is carried out, an adjustment has to be made to the two values of ΔF_s related to eight degrees of freedom (Table VI). Such an adjustment can be achieved by substituting two values of chi-square which, with seven degrees of freedom, have exactly the same level of significance as the original values. This is done graphically by plotting values of chi-square with eight degrees of freedom against those with seven degrees of freedom for every level of significance for which values are given in the chi-square tables (Snedecor and Cochran, 1967, page 550). A linear relationship is obtained and the graph is used to make the conversions. The two adjusted values are shown in brackets in table VI and replace the original values wherever ΔF_s is used as a variable in correlation regression analysis.

When the values of chi-square for sandstone (ΔF_s) are correlated with those for rhyodacite (ΔF_r) a positive correlation ($r = .639$, $v = 6$) is obtained which is almost significant at the 10% level - a very good result considering the small number of values (8) that is being compared. The correlation coefficient indicates that 40.79% of the variation in form of one lithology can be explained in terms of the other.

We can conclude that while the direction of form changes between the two lithologies may be different or even opposed, as for example between stations 5 and 6, the magnitudes of the changes (ΔF_r and ΔF_s) tend to be more closely related. In seven cases out of eight - the exception being between stations 4 and 5 - the magnitude of the changes for sandstone (ΔF_s) is greater than it is for rhyodacite (ΔF_r). This may well be due to the observed tendency for rhyodacite pebbles to spall rather than break across as usually happens with sandstone pebbles.

It is now appropriate to consider the possible processes which can act to change the mean form (and sphericity) of gravels in transport in a stream channel. In the absence of significant chemical weathering of pebbles during transport four such processes can be envisaged:

(i) abrasion,

(ii) form sorting,

(iii) dilution by material with different form characteristics,

(iv) breakage.

(i) Abrasion. A considerable amount of abrasion is required to significantly modify pebble form. Except for some extremely vigorous streams, only where long distance transport and/or easily abraded rock types are involved can this process be considered as a significant factor. It can be expected to be important for all rock types in a wave environment but in the case of the vast majority of streams only pebbles of weak rocks can normally be expected to have their form influenced significantly by abrasion as distance of transport is always limited by stream length.

That abrasion is not a significant factor in explaining form changes in this study can be easily demonstrated in the field in the case of sandstone. Sandstone pebbles derived from interbedded conglomerates in the Upper Devonian Mount Tambo Group are characterized by a reddish ferruginous surface coating which persists for tens of miles downstream from the source. The fact that such a long distance of transport is required to remove a thin surface coating strongly supports the suggestion that abrasion is a slow process. The rhyodacites are extremely hard rocks and can be expected to be at least as resistant to abrasion as the sandstones. It can therefore be asserted with some confidence that, in the environment studied, form changes in rhyodacite and sandstone pebbles as a result of abrasion can be neglected.

(ii) Form sorting. It can be argued on theoretical grounds that pebbles of some shapes are likely to travel faster than others. If this is so one may expect a progressive change in mean form in the downstream direction. However, when form is compared for the most upstream and downstream stations (1 and 9) as has already been done for both lithologies (page 72) the differences are found to be much smaller than between some adjacent stations. This is further supported by the absence of a trend in the change of mean form in the downstream direction (figure 9). It is quite obvious that significant form sorting is not operative in the study area.

(iii) Dilution. Dilution of the pebble load by material with different form characteristics is the third process to be considered. There are several reasons why pebbles contributed by tributaries may have mean form characteristics differing from pebbles contained in the main stream. There are bound to be some differences in lithological composition and micro-structure between different outcrops although these are likely to be much less pronounced with rhyodacites than with sandstones as, in the study area, rhyodacites are a remarkably uniform rock type. A second reason may be that pebbles in the Tambo River will on average have been subject to a much greater distance of transport than those from a tributary and, in so far as form is a function of distance travelled, there may be contrasts in form between the two. It has been observed earlier however that for both rock types the form diagrams (figure 9) fail to indicate any progressive change in form downstream so that this may not be a major factor. A third possibility is that mean form characteristics rapidly approach a steady state related to the dynamics of flow and sediment transport of a stream and that every stream is characterized by its own steady state imparting certain form characteristics to the bedload which are characteristic for that particular stream.

In order to estimate the influence of dilution ΔF_s and ΔF_r were correlated with changes in area of outcrop between stations (ΔA_s and ΔA_r). Correlation of ΔF_s and ΔA_s gave a positive correlation ($r = .636$, $v = 6$) which is significant at the 10% level and indicates that 40.43% of the between sample variation in form of sandstone pebbles can be explained in terms of changes in area of outcrop. Correlation of ΔF_r with ΔA_r was also positive ($r = .850$, $v = 6$) and significant at the 1% level. The correlation coefficient shows that 72.34% of the between sample variation in form of rhyodacite pebbles can be explained in terms of changes in area of outcrop (see table VII).

The high percentage explanation related to dilution in accounting for changes in form is somewhat unexpected and rather difficult to explain. It may be that the amount of bedload delivered by tributaries, most of them small, is more

Table VII - Form changes in relation to changes in outcrop.

	RHYODACITE			SANDSTONE		
Sample Station	A_r (km^2)	ΔA_r (km^2)	ΔF_r (chi-square)	A_s (km^2)	ΔA_s (km^2)	ΔF_s (chi-square)
1	109.99			144.55		
		0	3.728		112.60	6.176
2	109.99			257.15		
		0	4.488		67.82	9.158
3	109.99			324.97		
		5.39	9.128		68.28	11.264
4	115.38			393.25		
		28.24	25.874		318.46	13.902
5	143.62			711.71		
		6.88	3.140		54.63	5.556
6	150.50			766.34		
		49.33	19.532		266.07	25.774
7	199.83			1032.41		
		0	3.070		64.38	15.806
8	199.83			1096.79		
		0	3.874		88.62	9.361
9	199.83			1185.41		
		r = .850, t = 3.9516			r = .636, t = 2.1274	

substantial in relation to the load carried by the main stream than their size would lead one to expect. Another possibility is that the form characteristics of the bedload carried by the Tambo River have reached a steady state in relation to prevailing flow and transport characteristics and that this state is upset by the introduction from a tributary of a bedload of different form characteristics together with its associated discharge. Even if the addition is small in relation to the total bedload carried by the trunk stream, the change introduced into the system may cause positive feedback processes to become dominant for a time bringing about a significant change in the form characteristics of the bedload as a whole.

(iv) Breakage. This is obviously a factor as freshly broken pebbles can be observed throughout the river channel. Since the same processes are responsible for breakage of both rhyodacite and sandstone pebbles, the magnitude of form changes (ΔF) between stations should be closely related for the two lithologies in so far as form changes are in fact due to breakage. Of the four processes that can be envisaged as giving rise to form changes abrasion and form sorting can be regarded as of little or no significance while dilution can reasonably be expected to produce form changes in the two lithologies which are not related to each other. Provided that this assumption is correct - and as we have already seen that some forty percent of the variation in form of one lithology can be explained in terms of the other - it is not unreasonable to suggest that breakage is responsible for almost half of the magnitude in form change observed for the two rock types as long as no other processes have been overlooked. By sheer chance the assumption that changes in ΔA_s are independent of those in ΔA_r does not hold in this particular study. Correlation of the two variables gives a surprisingly high correlation coefficient of .859 and this means that the effect of breakage has been considerably overestimated.

It has been shown that changes in form between stations for both sandstone and rhyodacite can be largely attributed to two processes: dilution by material of different form characteristics brought in by tributaries and to a lesser extent by breakage. If a numerical measure of breakage can be found, multiple correlation regression analysis can be used to explain form changes in terms of the operative processes. This approach will be considered further in a later chapter.

Sphericity and roundness within samples

As part of the computer processing of pebble data, Kaiser and Kuenen roundness, Wadell and Maximum Projection sphericity were correlated with each other and the results shown in table VIII. In addition the correlation coefficients of Cailleux roundness with Kuenen roundness, Wadell and Maximum Projection sphericity were obtained from an earlier run before Kaiser roundness was substituted for Cailleux roundness and these values are shown in the last three columns.

As was expected and as is shown by the correlation coefficients for Ka* against Ku* and C* against Ku* the three roundness indices are closely related to each other and to a slightly lesser extent this is true for the sphericities (W* against M*). Of considerable significance however, are the relationships between roundness and sphericity parameters. Cailleux roundness has a significant relationship or better with Wadell sphericity in all cases in sandstone samples and all but one in rhyodacite samples. Its relationship with Maximum Projection sphericity is less pronounced: probably significant or better relationships occur in three out of ten cases in sandstone and two out of nine cases in rhyodacite. Kaiser roundness has a probably significant or better relationship with Wadell sphericity in six cases out of ten in sandstone samples and in five cases out of nine in rhyodacite samples. Again its relationship with Maximum Projection sphericity is less marked and probably significant or better relationships occur in two out of ten cases in sandstone

Table VIII - Within sample linear correlation - roundness and sphericity parameters. n = 150

Sandstone	Ka*/Ku*	Ka*/W*	Ka*/M*	Ku*/W*	Ku*/M*	W*/M*	C*/Ku*	C*/W*	C*/M*
1	.957	.148	.142	-.068	.094	.721	.895	.272	.170
2	.962	.223	.051	.032	.037	.659	.909	.323	.061
3	.958	.106	.037	-.115	-.027	.752	.899	.227	.072
4	.950	.164	.065	-.057	.020	.716	.885	.278	.088
5	.944	.173	.081	-.083	.020	.703	.872	.300	.109
6	.942	.076	.005	-.189	-.100	.785	.864	.219	.061
7	.957	.123	-.002	-.100	-.080	.734	.899	.248	.049
8	.965	.163	.002	.001	.005	.693	.912	.245	-.010
9	.965	.224	.198	.059	.210	.638	.911	.316	.184
10	.968	.209	.197	.020	.158	.687	.918	.317	.214

Rhyodacite

Rhyodacite	Ka*/Ku*	Ka*/W*	Ka*/M*	Ku*/W*	Ku*/M*	W*/M*	C*/Ku*	C*/W*	C*/M*
1	.960	.199	.125	-.006	.103	.672	.897	.320	.135
2	.954	.095	.116	-.130	.047	.744	.879	.236	.156
3	.951	.154	.102	-.071	.083	.638	.881	.284	.112
4	.946	-.015	-.114	-.250	-.114	.615	.864	.133	-.106
5	.962	.064	-.046	-.133	-.093	.755	.902	.183	-.017
6	.954	.320	.229	.092	.159	.749	.894	.430	.257
7	.969	.262	.093	.090	.078	.671	.921	.354	.098
8	.971	.214	.107	.039	.086	.619	.926	.314	.115
9	.974	.296	.184	.142	.174	.648	.931	.389	.185

Critical values of r for various levels of significance are: p=.10, r=.136; p=.05, r=.161; p=.02, r=.190; p=.01, r=.210; p=.001, r=.267.

and in two out of nine cases in rhyodacite samples.

Kuenen roundness shows the least relationship with sphericity parameters. It has a probably significant or better relationship with Wadell sphericity in only one case out of ten in sandstone and one case out of nine in rhyodacite samples. It has a probably significant or better relationship with Maximum Projection sphericity in only one case out of ten in sandstone and one case out of nine in rhyodacite samples. It must be remembered that the two sphericity measures are partial expressions of form and between them contain the sum total of form information. In other words if both Wadell and Maximum Projection sphericity are known for a particle its form is determined and its position on the form diagram can be plotted (Sneed and Folk, 1958, page 120).

It is interesting to observe that both Kuenen and Kaiser roundness values correlate more highly with Wadell sphericity than with Maximum Projection sphericity. Wadell sphericity tends to differentiate elongated shapes (rods) from other shapes most effectively while Maximum Projection sphericity does the same for platy particles (discs). For further details see Sneed and Folk (1958, page 120). Kuenen (1956) has demonstrated that the Cailleux index is a particularly poor measure of abrasion in the case of elongated particles because its maximum possible value is low and may even decrease with continued abrasion. Since by definition rods tend to have a low Wadell sphericity a positive relationship would be expected between it and Cailleux roundness. This is the case, confirming Kuenen's objections to the use of the Cailleux index. To a lesser extent the Kaiser index which can be regarded as a compromise between the Cailleux and Kuenen indices suffers from the same disadvantages as the Cailleux index.

The assessment clearly shows that the Kuenen roundness index is the most satisfactory parameter to use if one requires a measure of roundness which, at least within samples, is independent of shape. This would appear to contradict the earlier conclusion reached on the basis of factor analysis that Kaiser roundness was slightly superior. It must be remembered however that the analysis was based on samples of rhyodacite and sandstone from only one locality (sampling station 7) while the present assessment is based on all samples collected.

Sphericity variations between samples

As pointed out in the preceding section measures of sphericity are partial expressions of form and while sphericity has the advantage that - unlike form - it can be expressed as a single number it does so only by sacrificing a certain amount of information. If Wadell and Maximum Projection sphericity are used together they express the same amount of information as form but in both cases two numerical values are used to describe either the form of a particle or the average form of a sample.

In figures 10 and 11 the variations in mean Wadell and Maximum Projection sphericity are plotted against distance from river mouth for both rhyodacite and sandstone. The mean values are indicated by the centre line in each column. The two lines above and below indicate one and two standard errors of the mean respectively and give an indication of the possible magnitude of sampling error. In order to test the significance of differences in sphericity between stations one must know whether or not the samples approach a normal distribution pattern. In the latter case less powerful non-parametric tests of significance must be used.

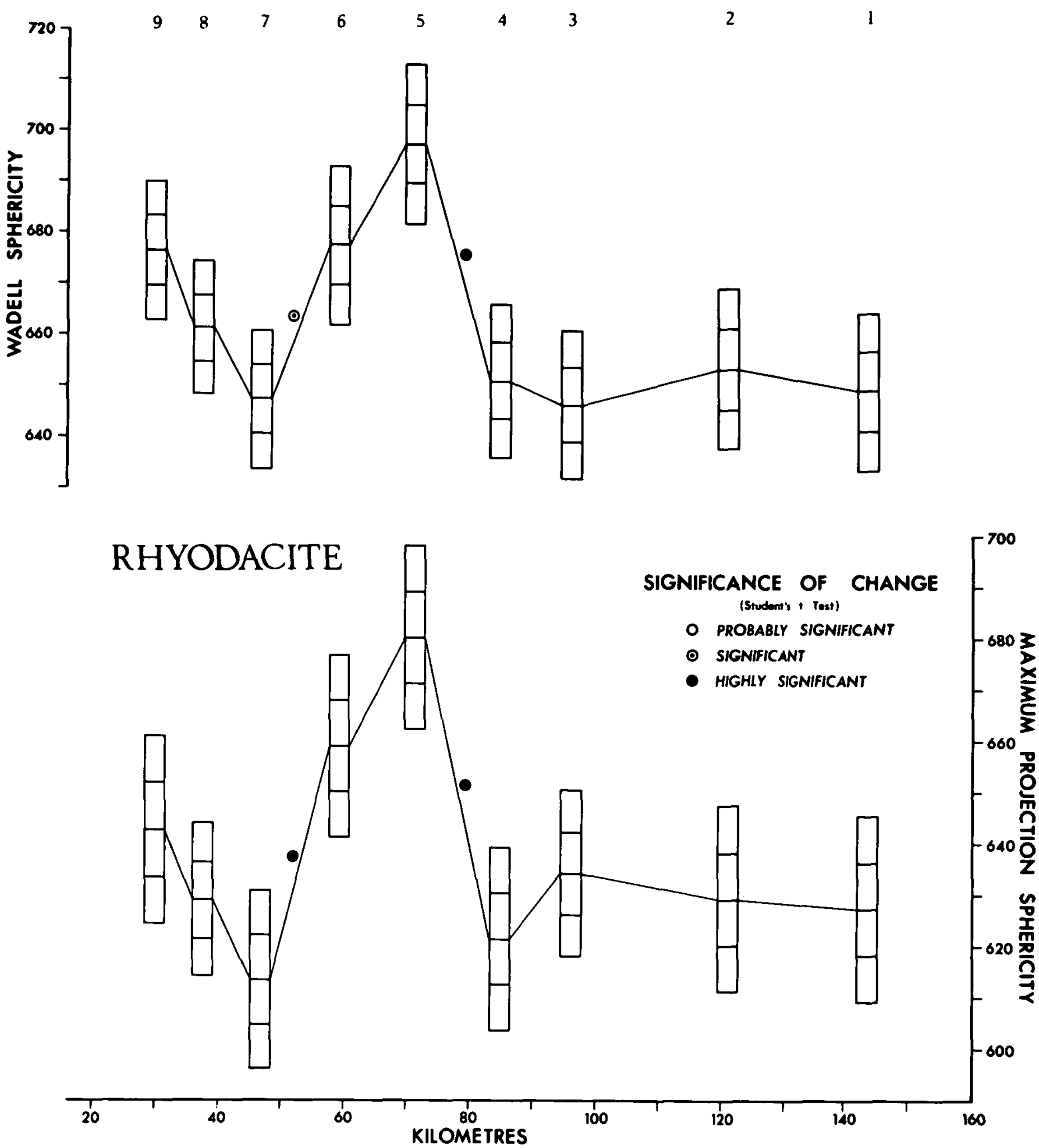
Computer processing of morphometric parameters included the calculation of moment measures for skewness and kurtosis for both measures of sphericity for each of the two lithologies (Appendix). For each rock type and for each sphericity parameter the sample with the highest skewness value - regardless of sign - was selected for a test of normality. These four samples were also characterized by high kurtosis values and were therefore most likely to show significant deviations from normality.

FIGURE 10A

Mean sphericity of rhyodacite samples.

Student's t test used to measure

significance of change.



9
8
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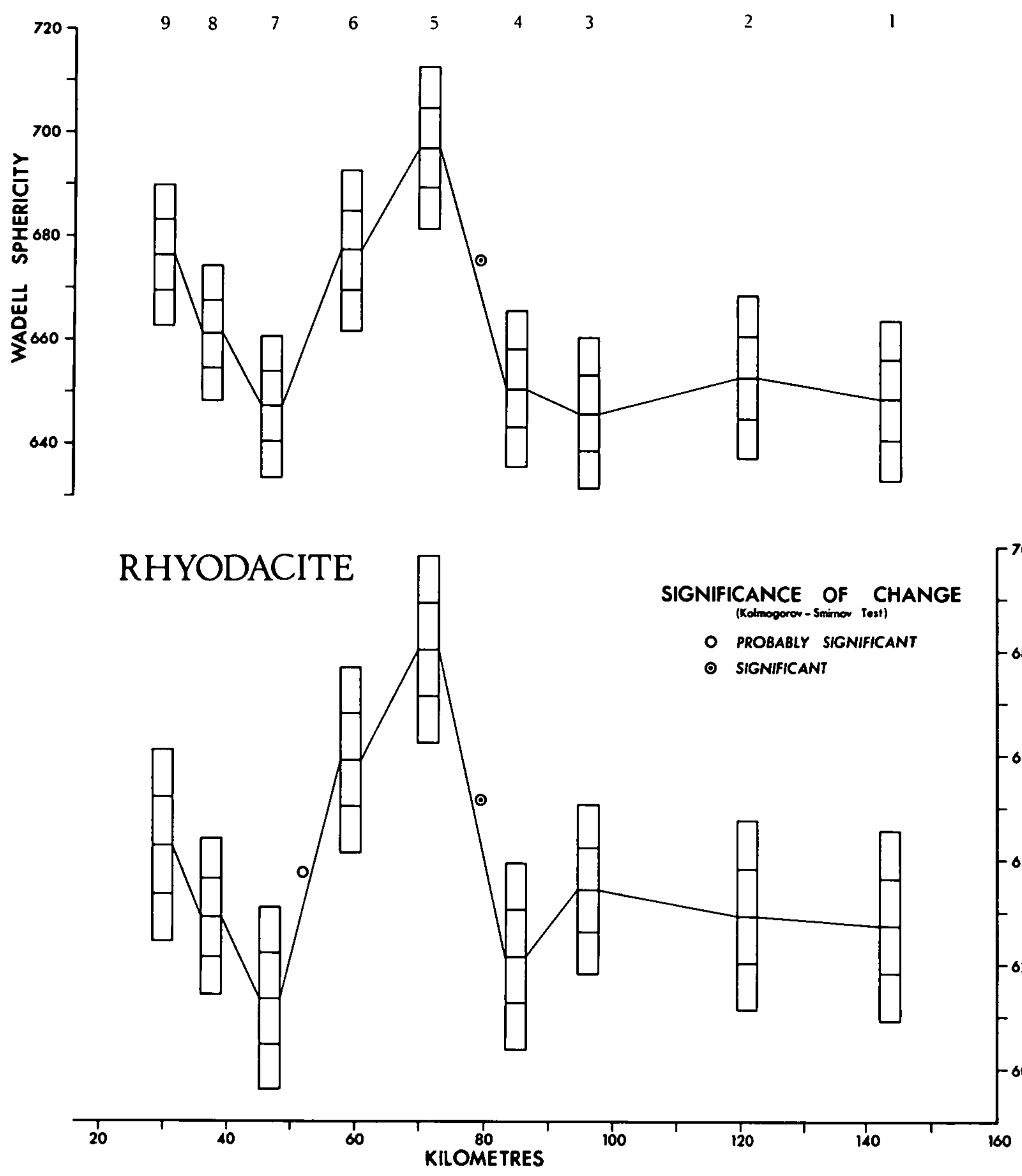
6
5
4
3
2
1
720
700
680
660
640
WADELL SPHERICITY
RHYODACITE
SIGNIFICANCE OF CHANGE
(Student's t Test)
PROBABLY SIGNIFICANT
SIGNIFICANT
HIGHLY SIGNIFICANT
700
680
660
640
620
600
MAXIMUM PROJECTION SPHERICITY
20
40
60
80
100
120
140
160
KILOMETRES

FIGURE 10B

Mean sphericity of rhyodacite samples.

Kolmogorov-Smirnov test used to measure

significance of change.



RHYODACITE
WADELL SPHERICITY
MAXIMUM PROJECTION SPHERICITY
KILOMETRES
SIGNIFICANCE OF CHANGE
(Kolmogorov - Smirnov Test)
PROBABLY SIGNIFICANT
SIGNIFICANT
9
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6
5
4
3
2
1
720
700
680
660
640
600
620
20
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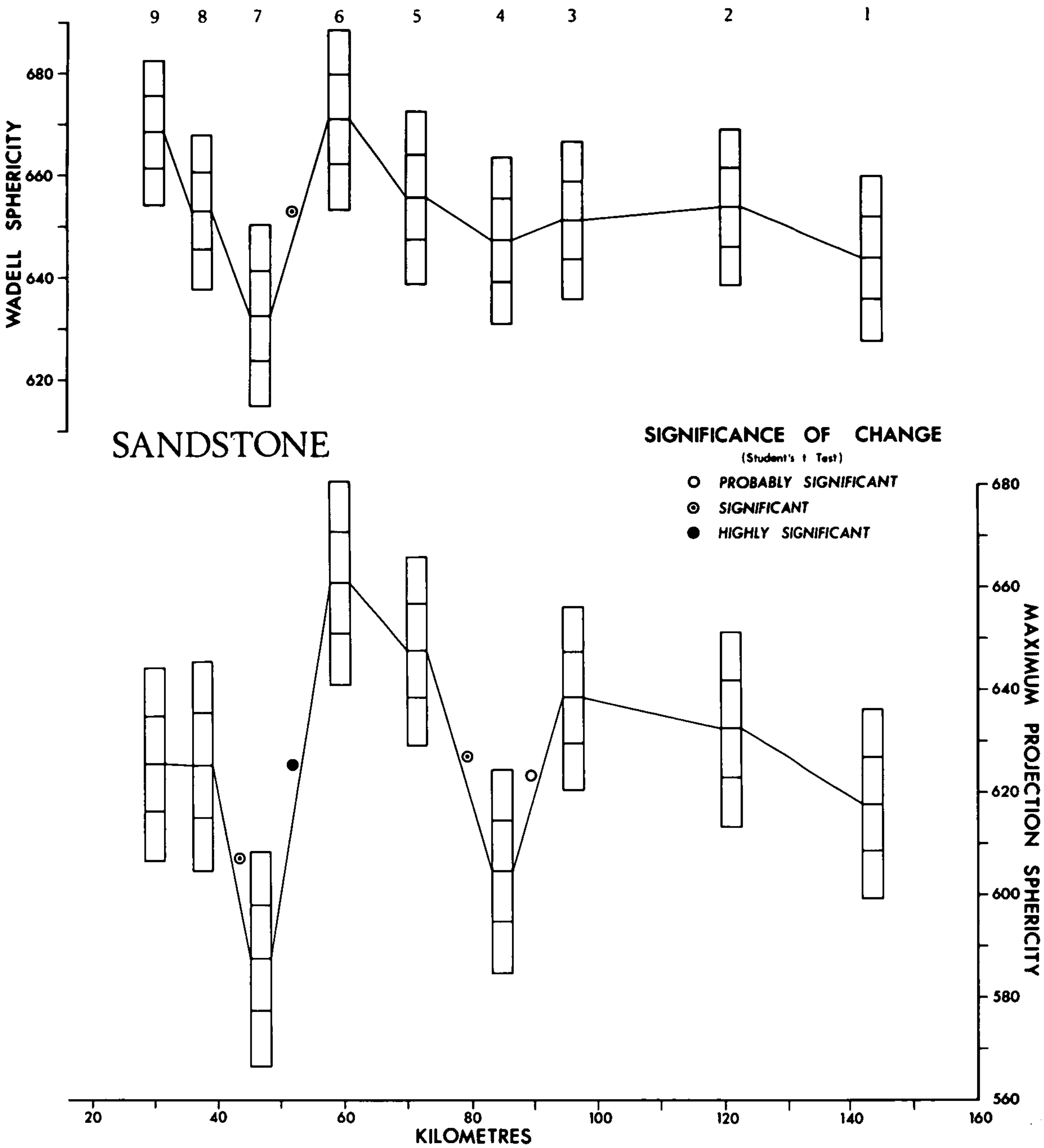
60
80
100
120
140
160

FIGURE 11A

Mean sphericity of sandstone samples.

Student's t test used to measure

significance of change.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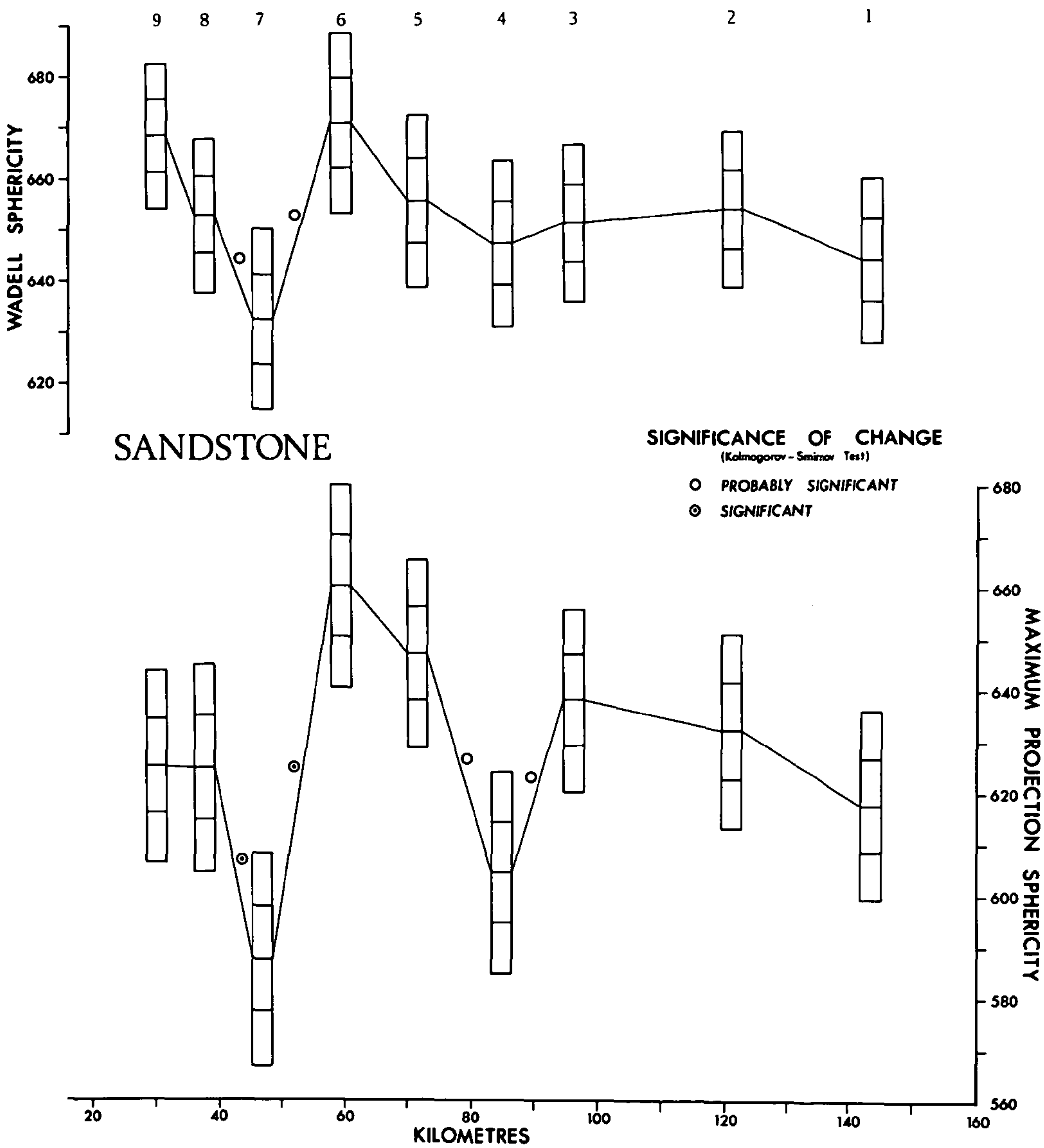
WADELL SPHERICITY
680
660
640
620
SANDSTONE
SIGNIFICANCE OF CHANGE
(Student's t Test)
PROBABLY SIGNIFICANT
SIGNIFICANT
HIGHLY SIGNIFICANT
MAXIMUM PROJECTION SPHERICITY
680
660
640
620
600
580
560
20
40
60
80
100
120
140
160
KILOMETRES

FIGURE 11B

Mean sphericity of sandstone samples.

Kolmogorov-Smirnov test used to measure

significance of change.


9
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7
6
5
4
3
2
1
WADELL SPHERICITY
680
660
640
620
SANDSTONE
SIGNIFICANCE OF CHANGE
(Kolmogorov - Smirnov Test)
PROBABLY SIGNIFICANT
SIGNIFICANT
MAXIMUM PROJECTION SPHERICITY
680
660
640
620
600
580
560
20
40
60
80
100
120
140
160
KILOMETRES

Using the mean and standard deviation of each sample, straight lines representing cumulative normal distribution patterns were drawn on normal probability paper. These lines were then used to predict expected cumulative frequencies for normal distribution patterns with values at each class boundary rounded off to the nearest whole number.

The significance of the differences between the expected and observed frequencies requires a non-parametric test. Two tests that can be applied are the chi-square and Kolmogorov-Smirnov tests whose relative merits have recently been discussed in detail by Mitchell (1971). The chi-square test is not ideally suited since extensive grouping of sphericity classes is needed to meet the requirement of minimum size for expected frequencies. The Kolmogorov-Smirnov test was preferred and applied as set out in Miller and Kahn (1962). The graphs supplied in this reference were used to determine the significance of differences (Table IX), but none of the differences even approaches significance at the 5% level.

Since none of the distributions appears to be significantly non-normal it was felt that, with some reservations, Student's t test applied to the standard error of the difference could be used to test the significance of difference between samples (figures 10A and 11A). For comparison the non-parametric

Table IX - Comparison of some observed cumulative sphericity frequencies with values expected for normal distributions.

	RHYODACITE				SANDSTONE			
Class Boundary	Wadell Spher. Sample 3		Max. Proj. Spher. Sample 9		Wadell Spher. Sample 6		Max. Proj. Spher. Sample 7	
	fo	fe	fo	fe	fo	fe	fo	fe
250	-	-	-	-	-	-	0	1
300	-	-	-	-	-	-	0	2
350	-	-	1	1	-	-	2	4
400	-	-	2	2	0	1	11	10
450	0	2	7	6	3	3	18	20
500	8	7	16	15	10	8	35	36
550	20	21	26	31	25	19	53	57
600	44	46	51	53	42	38	87	81
650	90	78	80	80	58	64	106	103
700	113	110	106	105	87	92	124	122
750	131	132	125	126	111	116	136	135
800	142	144	139	138	131	134	147	143
850	148	148	146	146	146	143	147	147
900	149	150	149	148	150	148	149	149
950	150	150	150	150	150	149	150	150
1000	-	-	-	-	150	150	-	-
	dn = .080		dn = .033		dn = .040		dn = .040	
n = 75	Signif $_{.05}$ ≈ .156				Signif. $_{.01}$ ≈ .185			

Kolmogorov-Smirnov test was also used and the results shown in figures 10B and 11B.

In the case of rhyodacite samples Student's t test (figure 10A) indicates a highly significant change in Wadell sphericity between stations 4 and 5 and a significant change between 6 and 7 while changes in Maximum Projection sphericity are highly significant between stations 4 and 5 and also between 6 and 7. The Kolmogorov-Smirnov test gives a very similar pattern but at a lower level of significance (figure 10B).

When considering sandstone samples Student's t test (figure 11A) indicates a significant change in Wadell sphericity between stations 6 and 7 while Maximum Projection sphericity shows a highly significant change between 6 and 7, significant changes between 4 and 5 as well as 7 and 8 while a probably significant change occurs between stations 3 and 4. Once again the Kolmogorov-Smirnov test results are similar with generally lower levels of significance except that a probably significant change in Wadell sphericiety now appears between stations 7 and 8.

The tests indicate that some of the changes are almost certainly 'real' and not due to sampling error. It is therefore worthwhile to attempt an explanation of sphericity changes in terms of processes.

Roundness variations between samples

Variations in mean sample roundness between samples (Kaiser and Kuenen) are plotted in the same manner as mean sphericity values against distance from river mouth for both sandstone and rhyodacite (figures 12 and 13) and it can be seen that Kaiser and Kuenen values give very similar patterns. This is to be expected as we have seen earlier (Table VIII) that within samples there is a very high correlation between the two. In order to test the significance of differences in roundness between stations the methods used are identical to those employed for sphericity. The two samples with the highest skewness (rhyodacite sample 5 and sandstone sample 4) are identical for both Kuenen and Kaiser roundness. Expected cumulative frequencies for normal distribution patterns were obtained as for sphericity and compared with the observed frequency distributions of the samples (Table X) using the Kolmogorov-Smirnov test. Once again none of the differences approaches significance at the 5% level. Student's t test was then applied to the standard error of the difference between adjacent samples (figures 12A and 13A) and also the Kolmogorov-Smirnov test (figures 12B and 13B).

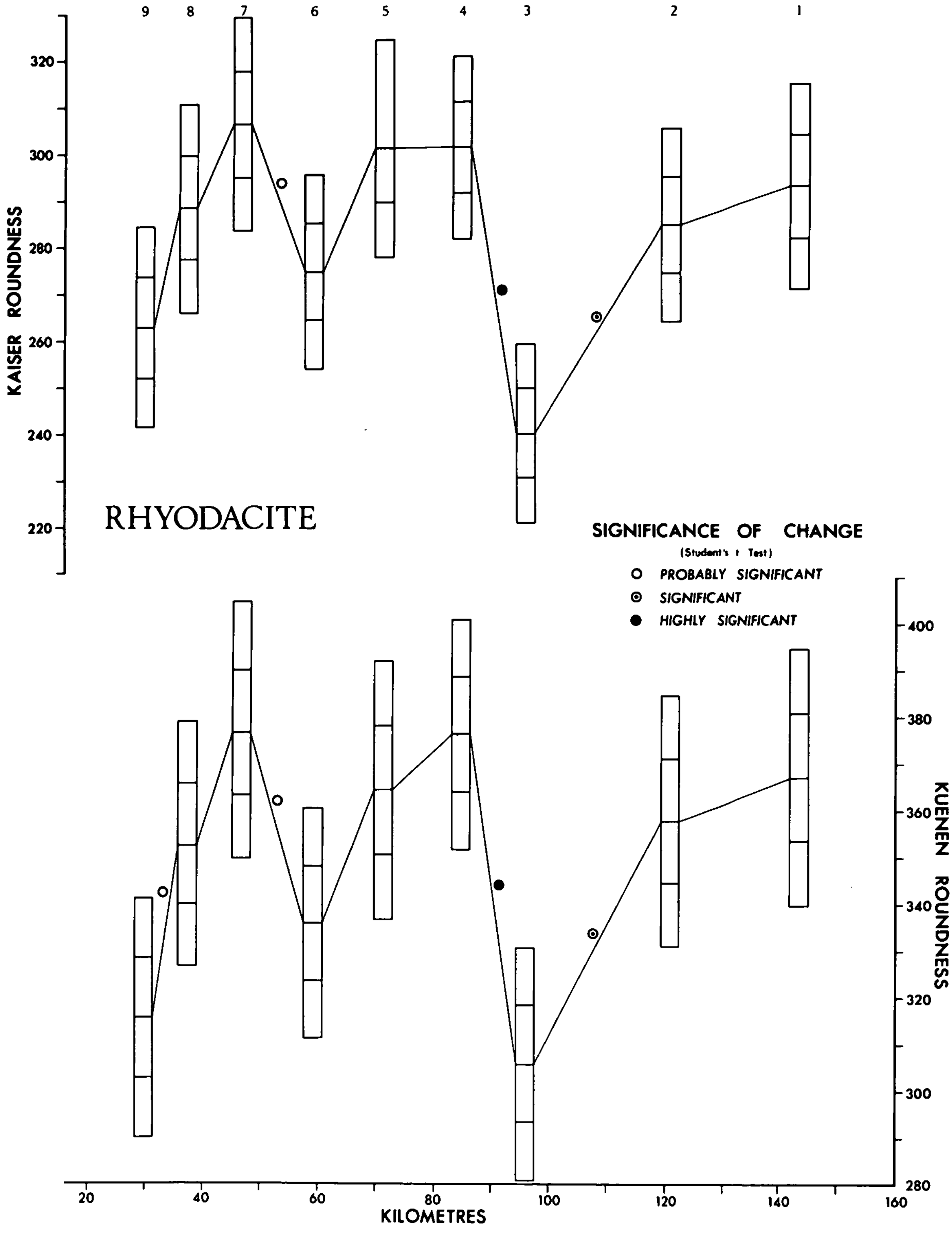
The most interesting feature of roundness variations between samples is that the two lithologies behave in an entirely

FIGURE 12A

Mean roundness of rhyodacite samples.

Student's test used to measure

significance of change.


9
8
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4
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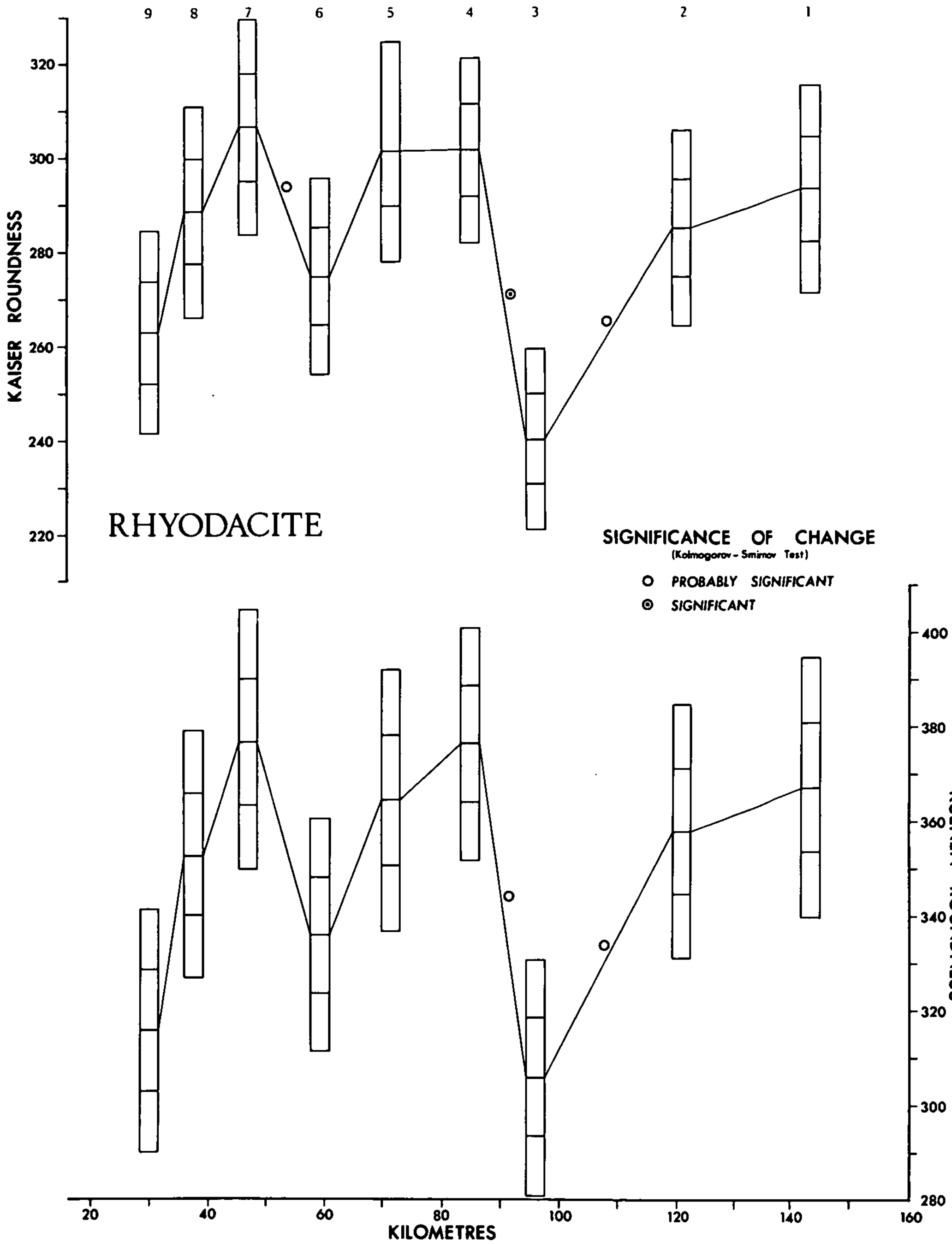
2
1
KAISER ROUNDNESS
320
300
280
260
240
220
RHYODACITE
SIGNIFICANCE OF CHANGE
(Student's t Test)
PROBABLY SIGNIFICANT
SIGNIFICANT
HIGHLY SIGNIFICANT
KUENEN ROUNDNESS
400
380
360
340
320
300
280
20
40
60
80
100
120
140
160
KILOMETRES

FIGURE 12B

Mean roundness of rhyodacite samples.

Kolmogorov-Smirnov test used to measure

significance of change



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KAISER ROUNDNESS
320
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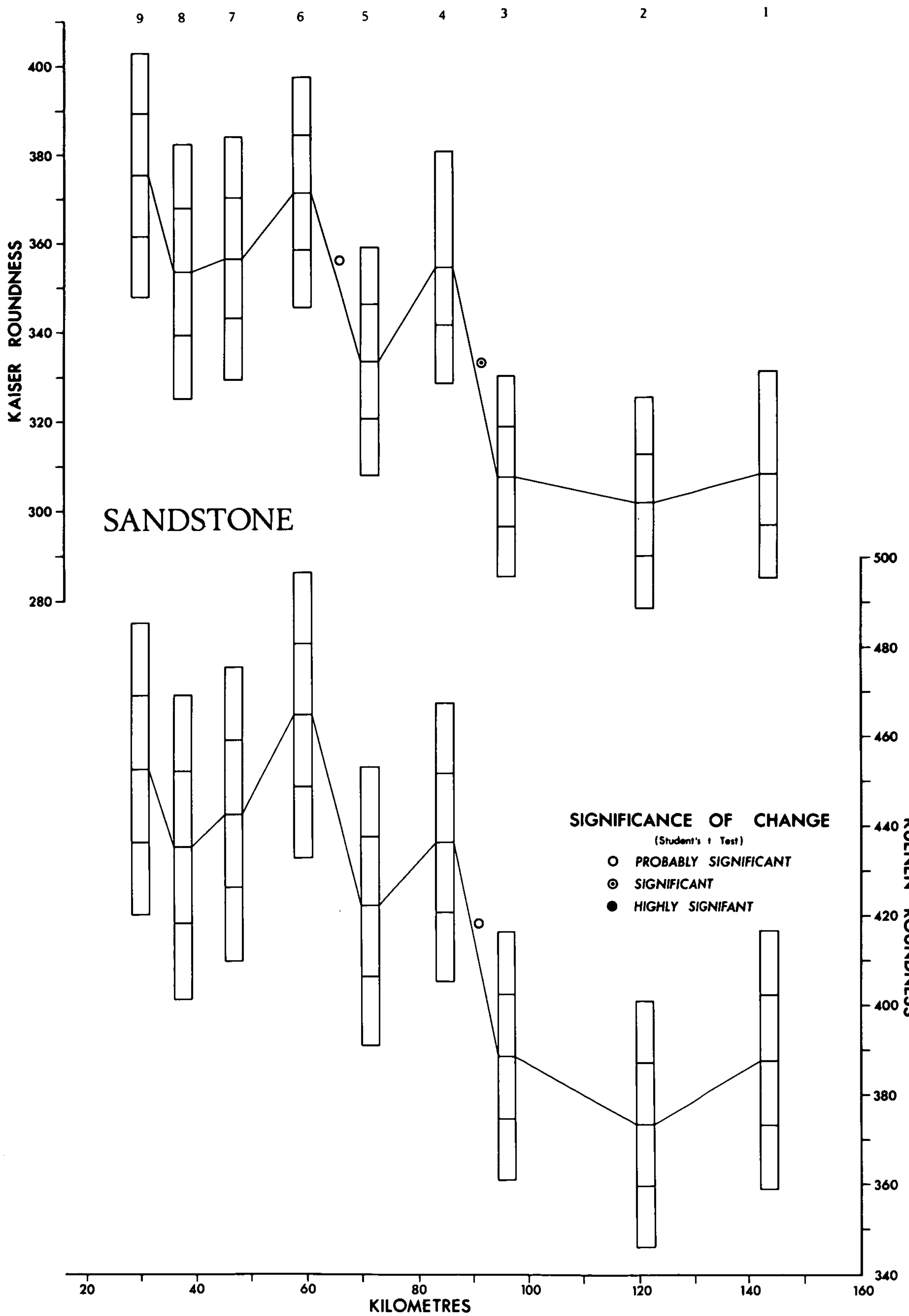
280
260
240
220
RHYODACITE
SIGNIFICANCE OF CHANGE
(Kolmogorov - Smirnov Test)
PROBABLY SIGNIFICANT
SIGNIFICANT
KUENEN ROUNDNESS
400
380
360
340
320
300
280
20
40
60
80
100
120
140
160
KILOMETRES

FIGURE 13A

Mean roundness of sandstone samples.

Student's t test used to measure

significance of change.



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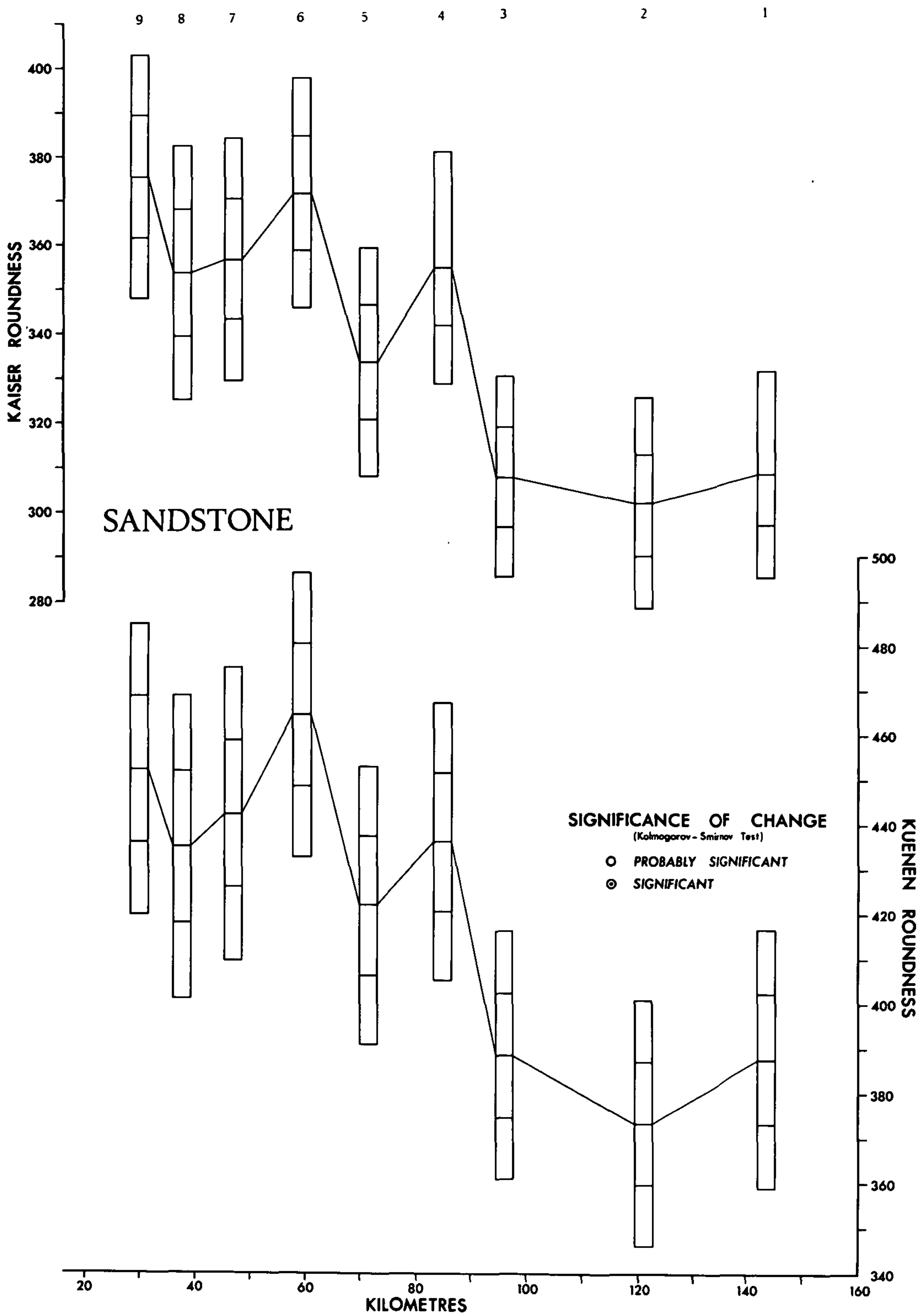
2
1
KAISER ROUNDNESS
400
380
360
340
320
300
280
SANDSTONE
KUENEN ROUNDNESS
500
480
460
440
420
400
380
360
340
SIGNIFICANCE OF CHANGE
(Student's t Test)
PROBABLY SIGNIFICANT
SIGNIFICANT
HIGHLY SIGNIFANT
20
40
60
80
100
120
140
160
KILOMETRES

FIGURE 13B

Mean roundness of sandstone samples.

Kolmogorov-Smirnov test used to measure

significance of change.



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KAISER ROUNDNESS
400
380
360
340
320
300
280
SANDSTONE
SIGNIFICANCE OF CHANGE
(Kolmogorov - Smirnov Test)
PROBABLY SIGNIFICANT
SIGNIFICANT
KUENEN ROUNDNESS
500
480
460
440
420
400
380
360
340
20
40
60
80
100
120
140
160
KILOMETRES

Table X - Comparison of some observed cumulative roundness frequencies with values expected for normal distributions

	RHYODACITE				SANDSTONE			
Class Boundary	Kuenen Roundness Sample 5		Kaiser Roundness Sample 5		Kuenen Roundness Sample 4		Kaiser Roundness Sample 4	
	fo	fe	fo	fe	fo	fe	fo	fe
50	0	5	0	6	0	3	0	4
100	2	9	5	12	0	6	3	8
150	11	15	20	21	4	10	10	15
200	26	25	41	36	13	16	23	25
250	41	38	61	54	24	24	43	39
300	60	53	87	75	41	36	64	55
350	81	70	96	95	56	49	78	74
400	89	88	117	113	72	64	100	93
450	108	104	132	128	85	80	112	109
500	120	119	140	138	98	96	123	123
550	129	130	143	144	114	109	138	134
600	136	138	143	147	120	122	142	141
650	141	143	144	149	131	131	143	145
700	143	147	147	150	139	138	145	148
750	147	148	149	150	142	143	145	149
800	149	149	150	150	145	146	146	150
850	149	150	-	-	145	148	148	150
900	149	150	-	-	146	149	149	150
950	149	150	-	-	147	150	149	150
1000	150	150	-	-	150	150	150	150
	dn = .073		dn = .080		dn = .053		dn = .060	
n = 75	$\text{Signif}_{.05} \approx .156$				$\text{Signif}_{.01} \approx .185$			

different manner in contrast to variations in form and sphericity where some similarities in behaviour can be discerned. This is clearly seen when values for mean Kuenen roundness for rhyodacite are correlated with mean Kuenen values for sandstone giving a correlation coefficient of -.028. A comparison of mean Kaiser values for both lithologies gives r = .134. There is virtually no correlation between variations in mean roundness between rhyodacites and sandstones.

In the case of rhyodacite there is no trend towards increasing mean roundness values in the downstream direction. Using Student's t test both Kuenen and Kaiser roundness show a highly significant change between stations 3 and 4, a significant change between 2 and 3 and a probably significant change between stations 6 and 7. As well Kuenen roundness exhibits a probably significant change between stations 8 and 9. The Kolmogorov-Smirnov test indicates a similar pattern at lower significance levels as expected. When the furthest upstream and furthest downstream samples (1 and 9) are compared both roundness parameters surprisingly indicate less rounded pebbles at station 9 than at station 1. Student's t test indicates a difference significant at the 1% level for Kuenen and almost significant at the 5% level for Kaiser roundness. The Kolmogorov-Smirnov test indicates a difference significant at the 5% level for Kuenen but no significant difference for Kaiser roundness.

With sandstone there appears to be a definite trend of increasing roundness - both Kuenen and Kaiser - in the downstream direction. Student's t test shows a significant change in Kaiser and a probably significant change in Kuenen roundness between stations 3 and 4. As well Kaiser roundness shows a probably significant change between stations 5 and 6. The Kolmogorov-Smirnov test indicates no significant changes between adjacent stations for either Kuenen or Kaiser roundness.

When samples 1 and 9 are compared, pebbles at station 9 are found to be much more rounded. Student's t test indicates a significant change in Kuenen and a highly significant change in Kaiser roundness. The Kolmogorov-Smirnov test indicates a probably significant change in Kuenen and a significant change in Kaiser roundness.

Since Kuenen and Kaiser roundness values are closely related, and as it has already been shown that the Kuenen index is superior in its independence within samples from size and shape, further considerations of changes in mean roundness between samples will be limited to Kuenen values only.

Processes affecting roundness

The four possible processes which - in the absence of significant chemical weathering - can act to change the mean form and sphericity of gravels in transport can equally well be considered in the explanation of changes in roundness. They are:

(i) Abrasion,

(ii) Roundness sorting,

(iii) Dilution,

(iv) Breakage.

(i) Abrasion. Whereas abrasion appears to play no significant role in affecting form and sphericity changes it is obviously an important process in increasing roundness. Since the amount of abrasion that takes place can be considered as a function of the distance travelled one can therefore expect a positive relationship between mean distance of bed material from source and mean roundness value at least until a limiting value for roundness is reached. Mean distance from source of bed material has not been calculated for sandstone but since sandstones are well distributed throughout the basin it will be related to distance downstream (D) which for convenience is measured from station 1. Correlation of D with mean Kuenen roundness values for sandstone samples gives a positive correlation coefficient of .842 which is significant at the 1% level and indicates that 70.90% of variations in mean roundness are explained by distance downstream. Since downstream distance is only an approximation for distance of material from source the correlation probably underestimates the true strength of the relationship. It would appear that abrasion is an important factor in causing variation in mean roundness of sandstone pebbles between stations as long as it can be shown that the correlation between D and Kuenen roundness is not significantly influenced by roundness sorting as it may be expected that the effect of this process - if it does operate - would also bear a positive relationship to D.

Correlation of D with mean Kuenen roundness values for rhyodacite pebbles gives a negative correlation coefficient of -.218 which is not significant. However for rhyodacite we do have values for mean distance from outcrop (Di_r) for each station. Correlation of Di_r with mean Kuenen roundness gives $r = -.308$ which again is negative and not significant. Clearly mean roundness of rhyodacite pebbles does not increase with increasing distance from source. If anything the reverse is true. It would appear that rhyodacite pebbles quickly reach a limiting roundness after which there is a dynamic balance between abrasion tending to increase roundness and other factors tending to decrease it.

(ii) Sorting. This process must be considered because it is not unreasonable to expect that more highly rounded particles will travel faster than angular ones during transport. If such a process does occur it should affect both rock types in a similar manner and can be expected to lead to an increase in roundness in the downstream direction thus strengthening the effects of abrasion. As we have already observed that rhyodacites respond in an entirely different manner to sandstones and if anything show a slight decrease in roundness in the downstream direction sorting can be dismissed as a significant process for both lithologies in this study.

(iii) Dilution. The effects of dilution can be tested in a similar manner to form changes by correlating the magnitude of changes in mean Kuenen roundness, $|\Delta Ku|$, with changes in areas of outcrop (ΔA) between each sample station and for both lithologies. Correlation of ΔA_s with $|\Delta Ku_s|$ gives $r = -.250$ which is not significant with six degrees of freedom and explains only 6.25% of the variance. When ΔA_r is correlated with $|\Delta Ku_r|$ we obtain $r = -.170$ which again is not significant and explains only 2.9% of the variance. We must conclude that dilution effects have little or no influence on the changes in mean roundness that take place between stations.

(iv) Breakage. As we have already seen, most of the changes in mean Kuenen roundness values in sandstone appear to be due to abrasion. In so far as this is not the case the changes must be attributed to breakage and sampling error as sorting and dilution do not appear to have significant effects. Sorting and dilution can similarly be disregarded in explaining changes in mean roundness of rhyodacite pebbles but in addition, when abrasion is considered as a function of mean distance from outcrop, it appears to bear little or no relationship to changes in mean roundness. One must conclude that such changes between rhyodacite samples are very largely the result of breakage in so far as they are not due to sampling error. We have seen earlier (page 75) that changes in mean form for rhyodacite are smaller than those for sandstone and can be explained largely in terms of dilution effects. It would therefore appear that breakage occurs either predominantly by mechanical spalling with little effect on form or if particles do break across form changes of individual pebbles compensate each other in such a way that there is little change in mean form.

It has been shown that any roundness index reflects the possible operation of four distinct processes: abrasion, sorting, breakage and dilution. Since in our study sorting and dilution do not appear to influence changes in mean roundness significantly, Kuenen roundness values in the main reflect two of these processes - abrasion and breakage.

Abrasion and breakage indices

It would be an advantage if instead of employing a single roundness index we are able to use two indices - an abrasion and a breakage index - to measure, more or less in isolation, the effects of the two processes on the bedload material. Particles which have undergone much abrasion without breakage should have high roundness values while recently broken particles may have had little time to become abraded afterwards and will have low roundness values, provided that the breakage has not been parallel to the maximum projection plane.

It is felt that the upper and lower quartiles (Ku75 and Ku25) of the frequency distributions of Kuenen roundness for each sample can be expected to provide measures of abrasion and breakage respectively. These parameters have the further advantage that they can easily be calculated as computer processing of raw data has already provided frequency distributions of Kuenen roundness in terms of 20 classes with a class interval of 50 units. The following values were obtained and are shown in table XI.

When abrasion index values for sandstone (Ku_s75) are correlated with distance downstream (D) a correlation coefficient of .899 is obtained which is significant at the 0.1% level and explains 80.8% of the variance of Ku_s75 in terms of D. This

Table XI - Abrasion and breakage indices for sandstone and rhyodacite.

	SANDSTONE			RHYODACITE		
Sample No.	Kuenen Roundness (Ku_s)	Abrasion Index (Ku_s75)	Breakage Index (Ku_s25)	Kuenen Roundness (Ku_r)	Abrasion Index (Ku_r75)	Breakage Index (Ku_r25)
1	387.82	490.28	261.50	366.79	495.31	242.50
2	373.51	495.31	252.68	357.49	471.88	231.62
3	388.72	486.61	276.39	305.71	397.32	208.48
4	436.33	547.66	290.44	376.06	461.25	256.88
5	422.16	547.66	274.11	364.12	471.88	239.17
6	464.89	606.94	322.12	335.67	438.28	211.88
7	442.77	601.25	297.92	376.46	488.54	252.34
8	435.42	578.41	298.44	352.25	456.25	225.43
9	452.91	611.25	305.83	315.50	401.11	209.13

correlation coefficient is higher than that found between mean Kuenen roundness (Ku_s) and D. Correlation of abrasion index values for rhyodacite (Ku_r75) with mean distance from outcrop (Di_r) gives $r = -.525$ which is almost significant at the 10% level. This tends to suggest that the action of the process of abrasion is outweighed by that of breakage.

If the breakage index has real meaning changes in its value between stations ($\Delta Ku25$) should show significant negative correlation with changes in form (ΔF) at least for sandstones as it has been shown earlier that form changes could be attributed to breakage and dilution in approximately equal proportions. In the case of rhyodacites form changes are predominantly due to dilution and a high degree of correlation between Ku_r25 and ΔF_r cannot therefore be expected.

When changes in breakage index values for sandstone (ΔKu_s25) are correlated with ΔF_s we find $r = -.688$ which is almost significant at the 5% level and indicates that 47.30% of changes in form can be explained in terms of breakage. On the other hand changes in breakage index values for rhyodacite when correlated with ΔF_r gives $r = .374$ which is not significant.

The breakage index is clearly a useful parameter, providing a numerical measure which can be used together with other variables such as ΔA (changes in area of outcrop) in multiple correlation regression analysis to explain form changes in terms of processes. This will be taken up in a later chapter.

CHAPTER IV

RELATIONSHIPS BETWEEN VARIABLES

To further check the conclusions reached from the investigation of relationships between variables three correlation matrices were prepared by computer showing the linear correlations between the principal variables (tables XII, XIII and XIV). The first table shows between sample linear correlation of parameters for sandstones, the second gives the same information for rhyodacites and the third shows correlation of sample parameters between the two lithologies.

Between sample correlations for sandstone

Highly significant correlations ($p < .001$): The high correlation between mean Kaiser and Kuenen roundness indices (Ka_s and Ku_s) is to be expected in view of the even closer relationship between the mean lengths of long, and intermediate axes (L_s and I_s). This in turn implies that variations in mean form between samples are principally a function of variations in the mean length of the short axis (S_s) which is reflected by the high degree of correlation between that parameter and mean Wadell sphericity (W_s). The tendency for mean Wadell sphericity to be determined by the mean length of one of the three axial measurements seems to be a characteristic not shared to the same extent by the Maximum Projection sphericity (M_s). The highly significant positive correlations of mean lengths of long and intermediate axes (L_s and I_s) with the number of platy pebbles (P_s) indicate that these tend to be more common in the larger sizes.

Significant correlations ($p < .01$): A positive correlation between mean Maximum Projection sphericity (M_s) and the number of elongated pebbles (E_s) is not unexpected as this sphericity parameter is designed to separate out platy pebbles at the lower end of its range while elongated pebbles tend to have relatively high values. The significant positive correlations of mean Kaiser and Kuenen roundness with distance downstream (D) have already been discussed.

Probably significant correlations ($p < .05$): The correlations of mean Kaiser roundness with mean lengths of long and intermediate

Table XII - Sandstones - between sample linear correlation of parameters n = 9

	Ka_s	Ku_s	W_s	M_s	L_s	I_s	S_s	P_s	B_s	E_s	D
Ka_s	-	H.S. .985	.376	-.078	P.S. .746	P.S. .723	.644	.630	-.523	-.322	S .861
Ku_s		-	.364	-.011	.634	.602	.613	.511	-.542	-.217	S .841
W_s			-	P.S. .793	.135	.185	H.S. .925	-.011	-.593	.383	.313
M_s				-	-.463	-.438	.579	-.578	-.479	S .835	-.038
L_s					-	H.S. .990	.452	H.S. .912	-.247	P.S. -.673	.632
I_s						-	.469	H.S. .921	-.205	P.S. -.710	.589
S_s							-	.258	P.S. -.701	.206	.570
P_s								-	-.239	P.S. -.759	.575
B_s									-	-.426	-.623
E_s										-	-.178
D											-

P.S. - probably significant. Level of significance < 5%
S - significant. " " " < 1%
H.S. - highly significant. " " " < 0.1%

axes reflects the dependence of this parameter on size. To a lesser extent this is also true of Kuenen. The relationship between mean Wadell and Maximum Projection sphericity is not surprising since they are both partial measuresof form. The number of elongated pebbles shows a negative relationship with mean long and intermediate axes and also with platy pebbles reflecting the tendency for smaller particles to be elongated. To a lesser extent the same tendency is shown by the number of blades (B_s) but the relationship between the number of blades and the mean length of the short axis is the only one which is probably significant.

Between sample correlations for rhyodacite

Highly significant ($p < .001$) and significant ($p < .01$) correlations: As in the case with sandstone and for the same reasons a very high correlation is found between mean Kaiser (Ka_r) and Kuenen (Ku_r) roundness indices. The fact that this coefficient is slightly lower than for sandstone can be explained by the lower coefficient of correlation between the mean lengths of the long and intermediate axes (L_r and I_r). However, the latter correlation is still significant at the 1% level and indicates that in rhyodacites also the variations in form between samples are predominantly a function of variations in the mean length of the short axis (S_r) as shown by the highly significant correlation between S_r and mean Wadell sphericity (W_r) and also by the probably significant relationship between S_r and mean Maximum Projection sphericity (M_r). The close relationship between W_r and M_r is shown by the highly significant correlation coefficient of .922 (c.f. sandstone).

The highly significant correlation between distance downstream (D) and mean distance from outcrops (Di_r) indicates that in an elongated basin with complex outcrop patterns distance downstream gives a good approximation to mean distance from outcrops as well as having the advantage of being much more easily measured. The highly significant negative correlation of mean altitude of outcrop (Al_r) with distance downstream (D) is not unexpected as in the Tambo River basin as in most river basins altitude decreases towards the mouth of the stream.

It is surprising however to find a highly significant relationship between mean altitude of outcrops (Al_r) and the number of elongated pebbles (E_r). In part this is undoubtedly an indirect relationship since Al_r has a correlation of -.743 with mean distance from outcrops (Di_r). In a rock which is more or less isotropic, in other words lacks weaknesses with preferred orientation, breakage of pebbles will tend to occur in the minimum projection plane and the number of elongated pebbles may

Table XIII - Rhyodacites - between sample linear correlation of parameters n = 9

	Ka_r	Ku_r	W_r	M_r	L_r	I_r	S_r	P_r	B_r	E_r	D_r	Di_r	Al_r
Ka_r	-	H.S. .969	.069	-.108	.246	.253	.085	.226	.070	-.435	-.018	-.139	-.159
Ku_r		-	-.134	-.248	.180	.082	-.112	.254	-.054	-.261	-.217	-.308	.058
W_r			-	H.S. .922	.005	.432	H.S. .912	-.370	.234	-.255	.433	.402	-.478
M_r				-	-.287	.093	P.S. .763	-.576	.132	.089	.165	.186	-.193
L_r					-	S .879	.390	P.S. .713	-.283	-.390	.277	.282	-.185
I_r						-	P.S. .708	.490	-.013	-.612	.582	.539	-.537
S_r							-	-.078	.023	-.270	.427	.424	-.413
P_r								-	-.577	-.149	.059	.114	.092
B_r									-	-.647	.585	.405	P.S. -.764
E_r										-	S -.837	P.S. -.689	H.S. .899
D_r											-	H.S. .955	H.S. -.906
Di_r												-	P.S. -.743
Al_r													

P.S. - probably significant. Level of significance < 5%
S - significant. " " " < 1%
H.S. - highly significant. " " " < 0.1%

be expected to decrease with increasing distance from outcrops. In fact correlation of the number of elongated pebbles (E_r) with mean distance from outcrop gives $r = -.689$ which is significant at the 5% level. However, since the relationship between Al_r and E_r is highly significant ($r = .899$) there is a strong indication of a direct influence of altitude on pebble shape. Perhaps more intense frost action at higher elevations during the late Pleistocene produced a higher proportion of elongated pebbles to be delivered to the river as load during recent times. Another possible explanation is that the micro-structure of the rhyodacites that crop out in the headwaters at higher altitudes differs from that of rhyodacites at lower altitudes further downstream.

The significant negative correlation between distance downstream (D) and number of elongated pebbles (E_r) is to be expected from the relationship just examined since D correlates highly with both Di_r and Al_r.

<u>Probably significant correlations</u> ($p < .05$): The relationship between Maximum Projection sphericity (M_r) and mean length of short axis (S_r) with $r = .763$ reflects earlier observations that variations in form between samples are principally a function of variations in S_r. As with sandstones M_r is less influenced by

variations in S_r than is mean Wadell sphericity (W_r). The positive correlation between mean lengths of intermediate and short axes (I_r and S_r) is to be expected since both are partial measures of size. The positive relationship between mean length of long axis (L_r) and the number of platy pebbles (P_r) indicates that platy pebbles are more common in the larger sizes - a characteristic that is much more pronounced in the case of sandstone.

The fact that a probably significant correlation exists between mean altitude of outcrops (Al_r) and the number of bladed pebbles (B_r) while correlation of B_r with D and Di_r are not significant is of interest as it suggests that their occurrence like that of elongated pebbles is in part due to an influence of mean altitude of outcrops which is independent of mean distance from outcrop. The relationship of B_r to Al_r is opposite to that of E_r to Al_r indicating that while the number of elongated pebbles decreases with decreasing mean altitude of outcrops the number of bladed pebbles increases. The probably significant correlations between E_r and Di_r, Al_r and Di_r have already been considered in the previous section.

Correlation of sample parameters between lithologies

This matrix (table XIV) adds little to our understanding of interrelationships other than to show the degree to which the two lithologies behave in a similar manner. The correlation coefficients enclosed within the double lines are all between parameters relating to size and shape of pebbles and in so far as they are significant they reflect the similarities in behaviour between the two lithologies which have already become apparent earlier in the thesis following consideration of form and sphericity changes between stations.

The probably significant relationship between mean Kaiser roundness of sandstones (Ka_s) and mean length of intermediate axis of rhyodacites (I_r) is easily explained when one reflects that I_r and I_s are highly correlated ($r = .901$) and also that I_s has a probably significant correlation with Ka_s as seen earlier. The correlations of both Ka_s and Ku_s with E_r, Di_r and Al_r are all significant at the 5% level or better and are due to the fact that all five variables are closely related to distance downstream (D).

The probably significant relationship between Al_r and B_s ($r = .718$) is interesting because it is opposite to that between Al_r and B_r ($r = -.764$). The mean altitude of outcrops for

Table XIV - Linear Correlation of Sample Parameters Between Lithologies n = 9

RHYODACITES

SANDSTONES	Ka_r	Ku_r	W_r	M_r	L_r	I_r	S_r	P_r	B_r	E_r	Di_r	Al_r
Ka_s	.134	-.051	.405	.126	.480	P.S. .704	.506	.316	.321	P.S. -.712	S .834	P.S. -.767
Ku_s	.156	-.028	.453	.211	.353	.608	.501	.205	.371	P.S. -.677	S .815	P.S. -.761
W_s	-.499	-.626	.659	.649	.108	.352	P.S. .693	-.127	-.048	.088	.380	-.209
M_s	-.474	-.529	.621	S .809	-.458	-.204	.448	-.576	.028	.397	.034	.064
L_s	.256	.119	.125	-.244	S .846	H.S. .898	.385	P.S. .720	-.014	P.S. -.694	.578	-.565
I_s	.163	.040	.084	-.268	S .888	H.S. .901	.279	P.S. .739	-.075	-.617	.556	-.498
S_s	-.262	-.442	P.S. .718	.572	.308	.606	P.S. .782	.080	.039	-.247	.600	-.469
P_s	.238	.123	-.008	-.366	S .873	S .855	.280	.556	.162	-.722	.485	-.562
B_s	-.129	.083	S -.840	P.S. -.670	-.100	-.498	P.S. -.765	.393	-.582	.559	-.522	P.S. .718
E_s	-.112	-.134	.517	P.S. .726	P.S. -.722	-.464	.207	P.S. -.735	.198	.308	-.172	.085

sandstone (Al_s) has not been calculated but Al_r has a close negative relationship with D and since sandstones are well distributed throughout the basin and general elevation of the basin decreases towards the coast one can also expect a close negative relationship between Al_s and D which implies a positive relationship between Al_r and Al_s.

It was suggested earlier that the relationship of B_r and E_r to Al_r reflect the operation of either a process or structural factor related to altitude. However, since sandstone responds in an opposite manner to rhyodacite a process factor alone cannot be responsible since it would be expected to affect the two lithologies in a similar manner. Most likely we are looking at the result of a complex inter-play of processes and structural factors.

CHAPTER V

MULTIPLE CORRELATION REGRESSION

The technique of multiple correlation regression analysis may be used where a single independent variable X cannot adequately predict the value of a dependent variable Y. In such a situation Y may be related to a set of independent variables X_1, X_2, ... X_k which between them enable one to make a much more accurate prediction of the value of Y.

One of the first applications of the technique in the earth sciences is found in Krumbein (1959) who used it to predict the foreshore slope of a beach composed of quartzose material in terms of four independent variables consisting of sedimentary parameters related to beach "firmness". Full details of the general linear model which will be used here are given in Krumbein and Graybill (1965).

The asumption is made that the following model fits the situation at least as a first approximation

$$Y = \mu_y + e$$

where $$\mu_y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 \ldots \beta_n X_n$$

with β_0, β_1, β_2, etc. as the unknown parameters and e as an error term.

One of the objectives of multiple regression analysis is to find a prediction equation for Y where the expected value of Y is denoted by E(Y) and

$$E(Y) = \hat{\beta}_0 + \hat{\beta}_1 X_1 + \hat{\beta}_2 X_2 \ldots \hat{\beta}_n X_n$$

where $\hat{\beta}_0$, $\hat{\beta}_1$, $\hat{\beta}_2$, etc. are the estimators of β_0, β_1, β_2, etc. respectively.

Predictor equations can be calculated for any one (simple linear model) or any combination of more than one independent variable (general linear model). In the case of the simple linear model the adequacy of the independent variable in predicting a value for Y is measured by the correlation coefficient (r) while in the general linear model the measure of adequacy to predict a value for Y is the multiple correlation coefficient denoted by R which is basically the simple correlation coefficient between the actual and the predicted values of Y.

The adaptation of Krumbein's method used to evaluate the relative importance of different factors in explaining variations in a dependent variable is the one employed by Chorley (1964) in his geomorphological evaluation of factors controlling shearing resistance of surface soils in sandstone in the Cambridge area of England. Basically the method consists of building up a table of reductions of the sums of squares effected by the independent variables both singly and in all possible combinations. The reductions of the sums of squares effected by all combinations of the independent variables are expressed in terms of percentages and are calculated by squaring the correlation coefficient (which may be simple or multiple) and multiplying the squared value by 100 to obtain a percentage. Such a value indicates the percentage of the total variance of the dependent variable which can be explained in terms of any one or any combination of more than one independent variables.

Initially some analyses were carried out with two independent variables using a Canon Canola L121 electronic desk computer and following the abbreviated Doolittle method as outlined in Krumbein and Graybill (1965). The method however becomes far too laborious when more than two independent variables are being considered. For later work frequently involving more than two independent variables use was made of a computer programme (MULTREG-F, U1666,F) adapted for use with the University of Tasmania's Elliott 503/PDP-8L computer by Chick, N.K. (1972) from the original programme (DUMRA) developed for Elliott 803 by Dr. B.A. Davies, University College of Wales, Aberystwyth, U.K.

It should be borne in mind that in the following analyses the assumption is made that all interrelationships between variables are linear. In so far as this is not true the use of simple and general linear models used may under-estimate the true strength of some interrelationships. More complex models have not been considered firstly because highly significant results have been obtained with the linear model and secondly since the number of samples was rather small one could expect to gain but little by postulating more complex relationships.

Abrasion and Breakage Indices

Multiple correlation, regression analysis is used first of all to assess the extent to which variations in abrasion and breakage indices account for variations in mean Kuenen roundness of both rhyodacites and sandstones. In an earlier chapter it was suggested that changes in mean roundness were due very largely to abrasion and breakage and that the upper and lower quartiles (Ku75 and Ku25) of the frequency distributions of Kuenen roundness for each sample could be expected to provide measures of abrasion and breakage respectively. If Kuenen roundness is treated as the dependent variable and the abrasion and breakage indices as the independent variables one may expect that nearly all the variation in mean roundness can be explained in terms of two independent variables. The data used in the analysis are shown in table XI.

When the analysis is carried out for sandstone the multiple regression of Ku_s on the independent variables Ku_s75 and Ku_s25 gives the following regression equation.

$$E(Ku_s) = 43.562 + .333Ku_s75 + .682Ku_s25$$

The multiple correlation coefficient R = .977 and the percentage of the variance explained is 95.49%.

When the analysis is repeated for rhyodacite the multiple regression of Ku_r on the independent variables Ku_r75 and Ku_r25 produces a similar regression equation.

$$E(Ku_r) = 13.959 + .360Ku_r75 + .749Ku_r25$$

The multiple correlation coefficient $R = .983$ and the percentage of the variance explained is 96.58%.

The analyses indicate that variations in mean roundness are explained almost entirely in terms of variations in the two indices and that little information is lost when the roundness index is replaced by the abrasion and breakage indices enabling us to separate the two main processes responsible for variations in roundness.

Factors affecting Form and Sphericity

The principal application of multiple correlation regression analysis in this thesis is in the quantitative evaluation of the factors responsible for changes in mean form and sphericity between samples. The relationships were examined for both rhyodacites and sandstones but for reasons indicated later the rhyodacites provide a far more satisfactory lithology for such analysis than do the sandstones.

Form and Sphericity - Rhyodacite: As indicated earlier form cannot be expressed in terms of a single parameter. However, the changes in mean form between successive samples can be expressed in this manner if the chi-square values (ΔF_r) obtained when testing such differences are used as parameters indicating the magnitude of the change. It must be noted that while ΔF_r indicates the magnitude of the change itgives no indication of the direction. When ΔF_r is to be used as the dependent variable in multiple correlation regression analysis as is intended here it is essential that the independent variables to which it is to be related are used in such a manner that they also indicate magnitude only.

Five independent variables were selected for the analysis. The first is ΔA_r which measures the change in area of outcrop between two adjacent stations and has already been shown to be significantly correlated with ΔF_r. The second is $|\Delta Al_r|$ which measures the magnitude of the change in mean altitude of rhyodacite outcrops between stations. This parameter has been included to discover whether changes in altitude have any effects on form which are independent of changes in area of outcrop. This possibility has already been suggested in the last chapter where the writer stated that "... since the relationship between Al_r and E_r is highly significant ($r = .899$) there is a strong indication of a direct influence of altitude on pebble shape".

The variables ΔA_r and $|\Delta Al_r|$ are of course far from being independent of each other. Their combined effects on ΔF_r provide an indication of the importance of the dilution effect in changing mean form of samples.

It has been suggested earlier that breakage is an important process in controlling form changes between stations. Changes in the Kuenen breakage index ($\Delta Ku_r 25$) provide a suitable parameter for use in the analysis. A fourth parameter included is $|\Delta Di_r|$, the magnitude of change in mean distance from rhyodacite outcrops - a measure of the average distance travelled by the gravels from their source and therefore an indirect measure of the amount of abrasion. If an earlier conclusion reached by the writer that "form changes in rhyodacite and sandstone pebbles as a result of abrasion can be neglected" is correct one would not expect $|\Delta Di_r|$ to contribute significantly to an explanation of the variance in ΔF_r.

The fifth independent variable used is a parameter related to changes in mean size of the pebbles contained in each sample. It was included because of the conclusions reached by Sneed and Folk (1958) who studying pebble morphogenesis in the lower Colorado River and using the same size class as the present writer found that: "..., even within this narrow range, particle size has a greater effect on sphericity and form than 200 miles of fluvial transport - larger pebbles tend to have lower sphericity and a rodlike form, while small ones are more discoidal". To obtain a size parameter independent of the axial measurements used to determine form and sphericity each sample was weighed and the size characteristics expressed as the mean pebble weight in grams (T_r). The variable used in the analysis was $|\Delta T_r|$, the magnitude of the change in mean pebble weight between two adjacent stations. This was found to be quite variable ranging in value from .250 grams between stations 7 and 8 to 10.919 grams between stations 8 and 9.

Multiple correlation regression analysis of mean Wadell (W_r) and mean Maximum Projection sphericity (M_r) of samples as dependent variables was carried out along similar lines as for form except that the sphericity parameters - being only partial expressions of form - can be expressed as single numbers. This enables the examination of changes in both magnitude and direction and therefore the independent variables used in the analysis were A_r, $Ku_r25\%$, Al_r, Di_r and T_r.

Form and Sphericity - Sandstone: A similar analysis in relation to sandstone is also attempted but the form and sphericity of sandstone pebbles cannot be expected to yield as high a percentage of explanation of variance as for rhyodacite. The reasons are firstly that areas mapped as sandstone vary widely in age as well as nature and include Ordovician sandstones with minor shales and slates, conglomerates in the Silurian Cowombat Group, the Devonian Timbarra Formation and Mount Tambo Group as well as the Plio-Pleistocene quartzitic gravels (Haunted Hills Gravels). When analysing the lithological composition of river gravels in the field it is not practicable to distinguish between sandstone and quartzite. Secondly the metamorphic rocks in the area surrounding Swifts Creek have been mapped as predominantly schist and slate and are shown as such in figure 2. However, they undoubtedly contain some quartzites which contribute to the bedload of the Tambo River.

Thirdly, the exact areal extent of sandstones, conglomerates and quartzites which tend to be inter-bedded with and to laterally merge into other sedimentary and metamorphic rocks cannot be determined accurately from the present standard of geological mapping which is frequently of a reconnaissance nature. The rhyodacites on the other hand are a very distinctive lithology with generally sharply defined boundaries and the areal distribution of outcrops is therefore much more accurately known.

In summary, pebbles referred to as sandstone may be composed of quartzite as well as sandstone. Source areas cannot be as strictly defined and are far more heterogeneous than is the case for rhyodacite. It is for these reasons that the parameters

Al_s (mean altitude of outcrops at a station) and Di_s (mean distance from outcrops at a station) have not been calculated.

In multiple correlation regression analysis of form and sphericity of sandstone $|\Delta Al_s|$ and Al_s respectively have been omitted and $|\Delta Di_s|$ and Di_s have been replaced by $|\Delta D_s|$ and D_s respectively where D_s is the distance downstream from station 1. In a strongly elongated basin such as that of the Tambo River with a complex pattern of outcrop D_s and Di_s may be expected to be closely related as has already been demonstrated with respect to rhyodacite (Table XIII). Sandstone form and sphericity have therefore been related to five independent variables instead of six such variables as in the case of rhyodacite.

<u>Results of Analysis</u>: The results for the analysis of form, Maximum Projection sphericity and Wadell sphericity are shown in Tables XV, XVI and XVII in the same manner as has been done by Chorley (1964). The tables show the reductions of the sums of squares effected by all combinations of the independent variables.

The meaning of these tables is best expressed by quoting from Chorley (1964, pages 1510-1512) who stated that:

> "The amount of 'explanation' is represented by the percentage reduction of the sum of squares so

effected. When ... the effects of the independent variables are calculated in combination with one another, it is often apparent that these combined effects differ markedly from those which one might expect from the simple addition of their individual explanations. This property of simple additivity is most obviously demonstrated to be incorrect when the total reduction of the sum of squares for all the assumed independent variables, operating singly, exceeds 100%. It must be concluded that there is a great deal of overlap, or data redundancy, wherein one variable is repeating information already supplied by another ... Thus, when the effect of a number of variables in combination is less than that which might be expected by summing the individual effects, damping has obviously occurred and overlap of the effects of the variables is taking place. Sometimes, however, the gestalt principle operates, in which the total effect of a combination of variables exceeds that which might be assumed from simple additivity and the variables reinforce each other, often in a most devious and significant manner."

Table XV - Reductions of the sums of squares of rhyodacite form effected by all combinations of the independent variables

X_1 ΔA_r	*1* 72.34				
X_1 $\Delta Ku_r 25$	*2* 13.95	*1,2* 72.70			
X_3 $\lvert\Delta Al_r\rvert$	*3* 93.86	*1,3* 94.10			
		2,3 95.90	*1,2,3* 99.60		
X_4 $\lvert\Delta Di_r\rvert$	*4* 34.21	*1,4* 72.67	*1,2,4* 73.09		
		2,4 37.22	*1,3,4* 94.15		
		3,4 93.87	*2,3,4* 96.00	*1,2,3,4* 99.60	
X_5 $\lvert\Delta T_r\rvert$	*5* 0.18	*1,5* 75.74	*1,2,5* 79.22		
		2,5 16.75	*1,3,5* 96.77		
		3,5 96.73	*1,4,5* 75.91	*1,2,3,5* 99.61	
		4,5 37.20	*2,3,5* 97.43	*1,2,4,5* 80.18	
			2,4,5 42.28	*1,3,4,5* 97.24	
			3,4,5 97.24	*2,3,4,5* 98.13	*1,2,3,4,5* 99.63

Table XVI - Reductions of the sums of squares of rhyodacite maximum projection sphericity effected by all combinations of the independent variables

X_1 A_r	*1* 0.08				
X_2 Ku_r25	*2* 13.32	*1,2* 13.97			
X_3 Al_r	*3* 1.11	*1,3* 84.01			
		2,3 13.51	*1,2,3* 86.68		
X_4 Di_r	*4* 3.47	*1,4* 9.10	*1,2,4* 18.00		
		2,4 13.97	*1,3,4* 88.95		
		3,4 3.65	*2,3,4* 14.02	*1,2,3,4* 90.07	
X_5 T_r	*5* 2.23	*1,5* 3.46	*1,2,5* 18.48		
		2,5 15.55	*1,3,5* 93.26		
		3,5 2.42	*1,4,5* 9.45	*1,2,3,5* 96.43	
		4,5 3,68	*2,3,5* 15.63	*1,2,4,5* 19.76	
			2,4,5 15.58	*1,3,4,5* 94.17	
			3,4,5 3.87	*2,3,4,5* 15.63	*1,2,3,4,5* 96.57

Table XVII - Reductions of the sums of squares of rhyodacite Wadell sphericity effected by all combinations of the independent variables

X_1	1 8.30				
X_2 Ku_r25	2 7.57	1,2 13.82			
X_3 Al_r	3 16.13	1,3 74.15			
		2,3 20.49	1,2,3 74.39		
X_4 Di_r	4 16.19	1,4 16.20	1,2,4 18.83		
		2,4 18.82	1,3,4 78.72		
		3,4 18.72	2,3,4 21.73	1,2,3,4 78.73	
X_5 T_r	5 19.30	1,5 20.15	1,2,5 27.11		
		2,5 26.87	1,3,5 94.76		
		3,5 24.60	1,4,5 22.32	1,2,3,5 95.26	
		4,5 22.28	2,3,5 30.13	1,2,4,5 27.43	
			2,4,5 27.43	1,3,4,5 94.78	
			3,4,5 24.70	2,3,4,5 30.37	1,2,3,4,5 95.28

It is obvious that simple addition of individual explanations can only be expected when independent variables are completely independent of each other. Where this is not the case interaction between them gives rise to either redundancy (damping effect) or reinforcement (gestalt effect).

Examining table XV where changes in rhyodacite mean form are analysed in terms of five independent variables and comparing the sums of squares reductions for all pairs of independent variables we find that redundancy is characteristic of all combinations of variables X_1, X_2, X_3 and X_4 but the same four variables show reinforcement when combined with X_5. The table shows that variables X_1, X_2 and X_3 in combination explain 99.60% of the variance in ΔF_r while X_4 and X_5 do not add significantly to this percentage. X_3 ($|\Delta Al_r|$) alone explains 93.86% of the variance and in combination with X_1 (ΔA_r) the percentage rises to 94.10%. This combination indicates the importance of the dilution effect in affecting change in form. X_2 ($\Delta Ku_r 25$) adds another 5.50% indicating that breakage has some effect.

Taking into account factors X_1, X_2 and X_3 only we find that R = .998 and the multiple regression of ΔF_r on these independent variables gives the equation

$$E(\Delta F_r) = 5.738 - .286\Delta A_r + .093\Delta Ku_r 25 + .265|\Delta Al_r|$$

which explains 99.60% of the variance. The correlation is highly significant with a level of significance of less than .001.

Table XVI analyses changes in rhyodacite mean Maximum Projection sphericity in terms of five independent variables. When the sums of squares reductions for all pairs of independent variables are examined we find a remarkable example of reinforcement between variables X_1 (A_r) and X_3 (Al_r). As a result of simple additivity one would expect a percentage explanation of only 1.18% whereas they do in fact explain 84.01%. Some redundancy is observed where variable X_5 (T_r) is combined with either X_3 (Al_r) or X_4 (Di_r). X_1, X_3 and X_5 in combination explain 93.26% while the addition of X_2 (Ku_r25) raises the explanation to 96.43%. X_4 does not appear to be making a significant contribution and its inclusion in the multiple regression equation does not seem justified as it increases the % explanation by only 0.14%. As was the case with form changes the two dilution factors (X_1 and X_3) again explain the bulk of the variance but this time both mean sample weight (T_r) and the breakage index (Ku_r25) make a significant contribution.

Taking the four factors X_1, X_2, X_3 and X_5 into account we find that R = .982 and the correlation is highly significant ($p < .001$). The multiple regression of M_r on the four independent variables gives the equation

$$E(M_r) = 2367.83 - 11.620A_r - .208Ku_r25 - 1.328Al_r + 1.554T_r$$

which explains 96.43% of the variance.

The same five independent variables used in the anlaysis of mean Maximum Projection sphericity were also employed in the analysis of rhyodacite Wadell sphericity and the results shown in table XVII. Examining the sums of squares reductions for all pairs of independent variables we find once again strong reinforcement between X_1 (A_r) and X_3 (Al_r) which in combination explain 74.15% of the total variance of W_r while from simple addition of their individual percentages one would expect only 24.43%. X_4 (Di_r) and X_5 (T_r) show marked redundancy when combined with each other or with any of the remaining three variables. X_5 has a significant effect however, as in combination with X_1 and X_3 it explains 94.76% of the total variance. When X_2 (Ku_r25) is also included the percentage improves to 95.26% indicating that breakage has but a slight effect. As in the previous analyses X_4 does not make a significant contribution as it adds only 0.02% and can therefore be disregarded.

Taking into account factors X_1, X_2, X_3 and X_5 we find that $R = .976$, a correlation which is highly significant ($p < .001$). The multiple regression of W_r on the four independent variables produces the equation

$$E(W_r) = 1989.37 - 8.962A_r - .071Ku_r25 - 1.067Al_r + 1.954T_r$$

which explains 95.26% of the variance.

Similar analyses were carried out to investigate changes in mean shape of sandstone pebbles. To investigate changes in mean form (ΔF_s) the independent variables ΔA_s, ΔKu_s25, ΔD_s and $|\Delta T_s|$ were employed while changes in mean Maximum Projection sphericity (M_s) and Wadell sphericity (W_s) were examined in relation to the independent variables A_s, Ku_s25, D_s and T_s. The results of the three analyses are shown in tables XVIII, XIX and XX. Of the three only changes in mean sandstone form show a significant relationship with the four independent variables indicated above. Multiple correlation gives $R = .828$ which is probably significant ($p < .02$). Neither mean Maximum Projection sphericity nor Wadell sphericity of sandstone show significant multiple correlation with the independent variables. Their multiple correlation coefficients are .264 and .592 respectively with Wadell sphericity approaching significance at $.05 < p < .10$. Only changes in mean form (ΔF_s) need therefore be considered.

When single independent variables are looked at the change in breakage index (ΔKu_s25) shows the greatest reduction of

Table XVIII - Reductions of the sums of squares of sandstone form effected by all combinations of the independent variables

X_1 ΔA_s	*1* 40.43			
X_2 $\Delta Ku_s 25$	*2* 47.30	*1,2* 50.65		
X_3 ΔD_s	*3* 9.66	*1,3* 48.22		
		2,3 55.72	*1,2,3* 58.65	
X_4 $\lvert \Delta T_s \rvert$	*4* 20.62	*1,4* 41.87	*1,2,4* 51.03	
		2,4 48.59	*1,3,4* 62.75	
		3,4 58.54	*2,3,4* 68.50	*1,2,3,4* 68.59

Table XIX - Reductions of the sums of squares of sandstone maximum projection sphericity effected by all combinations of the independent variables

X_1 A_s	*1* 0.91			
X_2 Ku_s25	*2* 0.63	*1,2* 5.86		
X_3 D_s	*3* 0.14	*1,3* 4.86		
		2,3 3.76	*1,2,3* 6.59	
X_4 T_s	*4* 0.08	*1,4* 1.33	*1,2,4* 6.57	
		2,4 1.28	*1,3,4* 4.92	
		3,4 0.14	*2,3,4* 4.06	*1,2,3,4* 6.96

Table XXI - Reductions of the sums of squares of sandstone Wadell sphericity effected by all combinations of the independent variables

X_1 A_s	*1* 6.43			
X_2 Ku_s25	*2* 17.87	*1,2* 18.64		
X_3 D_s	*3* 9.73	*1,3* 12.53		
		2,3 18.22	*1,2,3* 18.93	
X_4 T_s	*4* 18.76	*1,4* 19.91	*1,2,4* 34.52	
		2,4 24.17	*1,3,4* 22.98	
		3,4 18.82	*2,3,4* 34.11	*1,2,3,4* 35.09

the sums of squares explaining 47.30% of the total variance (cf. ΔF_r). Considering the effects of pairs of independent variables the pairs X_1X_2, X_1X_4 and X_2X_4 show a marked degree of redundancy while reinforcement is shown by the combination X_3X_4 which has the highest percentage reduction of the sums of squares and explains 58.54% of the variance of ΔF_s.

Taking three independent variables into consideration the highest percentage reduction is given by the combination $X_2X_3X_4$ which accounts for 68.50% of the variance. The addition of variable X_1 does little to improve the percentage explanation indicating that changes in area of outcrop between stations do not have any significance as an independent variable when the other three factors are taken into account. Using the independent variables X_2, X_3 and X_4 in multiple correlation regression it is found that R = .828 which is probably significant ($p < .02$). Multiple regression analysis produces the equation

$$E(\Delta F_s) = 25.413 - .112\Delta Ku_s25 - .586\Delta D_s - 1.147\ |\Delta T_s|$$

which explains 68.50% of the variance.

The relatively low percentage explanations for the shape characteristics are not unexpected as for reasons outlined earlier sandstone in the study area cannot be regarded as a very satisfactory lithology for the kind of multivariate approach used.

This was also the principal reason why the tedious procedure of measuring Al_s and Di_s was not carried out.

Returning to our three analyses of mean shape parameters of rhyodacite we observe that the explanations of ΔF_r, M_r and W_r not only give rise to highly significant values of R but also show a consistent pattern. The very high reduction of the sums of squares with ΔF_r may be due to several factors.

Some independent variables such as changes in area of outcrop (A) may not always cause a change in the same direction in the dependent variable. When sphericities are being considered a change in A between two sample stations may in one case cause an increase in sphericity while in another the reverse may be true depending on the shape characteristics of the material derived from the additional outcrop. The effect of A on mean sample sphericity may therefore be underestimated. When relating ΔA to ΔF, only the magnitudes of the changes are considered and the same problem does not arise.

Another factor that may be responsible in part for the very high reduction of the squares with ΔF_r is that the values of ΔF_r are those of chi-square obtained by a comparison between adjacent samples of numbers of pebbles in the ten form classes. The grouping of the original data into classes may have disposed of some of the error variance due to the limited size of the sample.

In all three cases the two parameters indicative of the dilution process (ΔA_r and ΔAl_r; A_r and Al_r) account for most of the change observed. In no case was mean distance from source a significant factor but variations in the rate of breakage and changes in mean size seem to have some influence on changes in mean shape between stations. The latter seems to confirm to some extent the findings of Sneed and Folk (1958) referred to earlier that even within a narrow size range particle size has a significant effect on sphericity and form.

Examination of the predictor equations shows that the change in form between stations is directly proportional to the change in breakage index and the magnitude of the change in altitude. However, rather surprisingly it bears a negative relationship to the change in area of outcrop. This may be the result of the very strong positive correlation between ΔA_r and $|\Delta Al_r|$.

The predictor equations for both M_r and W_r show that increases in the area of outcrop, mean altitude of outcrop and amount of breakage all bear a negative relationship to the two sphericity parameters. However, the size parameter bears a positive relationship in both cases indicating that the larger particles tend to be more spherical. This is in contrast to Sneed and Folk (1958) who found that larger pebbles tended to be characterized by lower sphericity values.

Roundness Variations

Multiple correlation regression analysis is not used to explain variations in mean roundness between samples. It has been suggested earlier that while changes in roundness for sandstone appear to be largely due to abrasion, variation in mean roundness of rhyodacite pebbles is mostly due to breakage. The breakage index (Ku25) used in the explanation of changes in mean pebble shape cannot be used as a parameter in multivariate analysis aimed at explaining variations in mean roundness as by definition it is based on the same measurements of r which are used to calculate the Kuenen, Kaiser and Cailleux roundness indices. Until an independent measure of breakage is found a complete quantitative evaluation of changes in mean roundness between sample localities cannot be attempted.

CHAPTER VI

CONCLUSION

Investigation of the relationships between the lithology of the basin and the lithological composition of samples after the manner of Tricart (1959) has confirmed the Q ratio as a useful indicator of the relative contributions made to the bedload by different rock types in the size class studied. However, the relationship between ΔQ_{ℓ} and ΔQ_0 which was considered by Tricart to give significant information on the physical behaviour of different rock types appears to have no real meaning and illustrates the problems involved in dealing with variables based on percentage values.

Studies concerned with the changes in shape and roundness of sedimentary particles during transport in a fluvial environment are numerous but many earth scientists seem to have been pre-occupied with changes only in relation to distance travelled downstream and have expressed their surprise when such changes do not seem to follow a distinct trend. Roundness has frequently been measured by the use of visual comparison charts and, as has been shown by Folk (1955), this method is likely to produce considerable operator error. The wholly quantitative parameters devised by Cailleux, Kuenen and others are to be preferred although the limitations of measurements restricted to the plane of maximum projection are fully recognized.

One of the aims of the thesis has been to determine the extent to which roundness measures within a sample are related to particle size and shape. In a study concerned with processes it is desirable that such a relationship be minimized. From this point of view Kuenen roundness appears to be the most satisfactory measure. Factor analysis, contrary to expectations, has not proved very satisfactory in assessing the various roundness parameters although it must be realized that the analysis was restricted to one sample of each lithology. Assessment from a correlation matrix showing the relationships of parameters within samples is both simpler and more satisfactory.

In the determination of shape the use of form seems to have been somewhat inhibited firstly by the problem of demonstrating significant changes between samples as illustrated by the work of Sneed and Folk (1958) and secondly by the anticipated dificulty of relating form, expressed in terms of two parameters, to other variables. In this study use of chi-square is made to demonstrate changes between samples and as a single parameter measuring the magnitude of change between two stations. As such it can be readily correlated with other variables, as long as it is remembered that only magnitude of change is being considered.

This has some advantages as some variables, for example ΔA (change in area of outcrop between two stations), taken as a measure of dilution, can affect form changes between pairs of samples that are opposed in direction depending on the nature of the material being added. The influence of such a factor can be seriously under-estimated when used in the explanation of sphericity where sign is taken into consideration. The effects on multiple correlation regression analysis are most clearly seen in the case of sandstone, a rather inhomogeneous rock type, but are also apparent, although less marked, in the analysis of rhyodacite.

The simultaneous analysis of pebble samples from two distinct lithologies has other advantages particularly when, as is the case here, they behave in such radically different ways. For example, shape and roundness sorting, if it occurs, may reasonably be expected to affect both lithologies in a similar manner and the fact that their behaviour is strikingly different is a good indication that, in the present case study at least, it is not a significant process.

Studies in particle morphogenesis have frequently confined themselves to rock types that crop out at only one locality along the river in order to avoid dilution effects. However, only in a minority of cases do such situations occur in nature. The present study has set out deliberately to deal with a situation where outcrop patterns are complex and dilution effects must be considered.

Apart from dilution three other processes may influence changes in shape and roundness between stations. They are breakage, abrasion and sorting. In addition variations in mean sample size were considered as a possible influence following observations by Sneed and Folk (1958) in their study that, even when confined to a restricted range, particle size has a substantial effect on variations in shape.

The use of multiple correlation regression analysis and its adaptation by Chorley (1964) using matrices of reductions of the sums of squares proves to be an efficient way of analysing the relative influences of different factors. Some striking examples of reinforcement and redundancy are observed underlining the danger of relying uncritically on simple correlation regression techniques in the initial exploration of a complex of relationships.

Multiple regression produces predictor equations which in the case of rhyodacite explain a very high percentage of the variations in mean form and sphericity between samples allowing surprisingly accurate prediction. Dilution factors appear to be the dominant influence on shape but variations in mean size and the rate of breakage has some effect.

In the case of sandstone only mean form changes are significantly related to parameters indicative of processes and mean size. Reasons for this appear to be the strongly anisotropic nature of weaknesses in sandstone, the unsatisfactory state of geological mapping of this lithology and the fact that material identified as sandstone comes from rocks differing widely in age, nature and degree of metamorphism.

In any rock with strongly anisotropic weaknesses, pebble shape is influenced in such a manner that planes of weakness tend to become parallel to the maximum projection plane and also tend to promote breakage parallel to this plane. Under such conditions breakages will not be reflected in measurements of the radius of curvature of the sharpest corner in the maximum projection plane (ra) so that any roundness measures based on ra will not indicate the full extent of breakage. In contrast, in a more isotropic rock, such as the rhyodacites dealt with in this study, breakage tends to occur parallel to the minimum projection plane and roundness measures involving ra will reflect much more accurately the extent of breakage.

A lesson to be learnt from this thesis is that if a relationship is sought between changes in pebble morphometry and environmental factors the rock type sélected for study should be massive and as free as possible from closely spaced planes of weakness and should not be subject to significant chemical weathering in the area of study. Moreover, if a distinctive and abundant rock type is selected, geological boundaries are likely to be more accurately mapped enabling better measurement of areas of outcrop. In the catchment basin of the Tambo River only rhyodacite meets all these requirements reasonably well.

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SUPPLEMENT TO M.Sc. THESIS, 1972

PEBBLE MORPHOMETRY OF THE TAMBO RIVER, EASTERN VICTORIA

ALBERT GOEDE

Some additional explanations and minor corrections are included in this supplement following the suggestions received from the two examiners for which the writer acknowledges his gratitude.

Throughout the thesis the term 'explanation' is used in a statistical sense to indicate the reductions of the sums of squares achieved by either simple or multiple regression analysis. Unless specifically implied it does not indicate explanation in terms of processes or causes.

<u>page 4</u> (to replace first seven lines of second paragraph)

The purpose of the study is to evaluate several techniques for measuring the geometry of river gravels, to use these techniques to quantify changes in gravel characteristics downstream and to try to ascertain the causes of the changes in geometry. An assessment is made of the relative importance of these causes in relation to rhyodacite and sandstone pebbles.

Practical considerations (see page 50) restrict the study to one size class of pebbles with long axes between 32 and 64 mm. It is realized that the results obtained for this class cannot be applied to the entire bedload.

page 50 - last sentence of paragraph beginning with "(iv)" to be reworded as follows:

Following factor analysis the Cailleux index was replaced by the Kaiser index as it has been shown (p. 49) that the Kaiser and Kuenen indices are the least dependent on both size and shape.

page 51 - last line

The location of the sample point on the gravel bar was determined by the abundance of pebbles in the size class being studied. There is a danger that this produces a biased sample if morphological characteristics vary across the bar. However, the alternative would have been to collect a few pebbles from many points which produces another problem - how to collect the pebbles objectively. For this reason, and the one stated on page 49, the procedure of point sampling has been adopted.

page 62 - third line

The statement that "Rhyodacites yield more material per unit area of catchment than any other rock type" does not apply to the bedload as a whole but only to that portion in the size range considered.

page 74, 75

It may be argued that since there are few significant changes in pebble form and sphericity between stations the subsequent work concerned with processes contributing to such changes loses much of its value. However, the significance of the changes is probably underestimated by the use of non-parametric tests (chi-square and Kolmogorov-Smirnov) required by the nature of the data, which are not suitable for use with more powerful parametric tests. Grouping of data into classes for application of non-parametric tests may also have partially masked differences between samples. The relatively high correlation coefficient ($r = .639$) between ΔF_s and ΔF_r, while not significant at the 5% level due to the small number of samples (page 74), gives at least an indication that the magnitudes of form changes in rhyodacites and sandstones are related. Such a correlation is not to be expected if differences in form (and hence sphericity) are due to chance variations between stations.

page 76

On this page it is suggested that abrasion is not a significant factor in explaining form changes and that in the case of sandstone this can easily be demonstrated in the field. The writer states that sandstone pebbles derived from conglomerate beds in the Upper Devonian Mount Tambo Group are characterized by a reddish ferruginous surface coating which persists for tens of miles downstream from the source. He suggests that since a long distance of transport is required to remove a thin surface coating abrasion would appear to be a slow process.

However, an alternative explanation, which was not previously considered, is that such pebbles were transported in larger boulders of conglomerate which do occur in the river load, and that the ferruginous skins remain on pebbles because they have only recently been released from the boulders.

Even if this alternative explanation is true it is still likely that abrasion is not a significant factor in explaining form changes and this is supported in the case of sandstones by the fact that the correlation of distance downstream (D) with mean Kuenen roundness values gives a correlation coefficient of .842. This indicates that a long distance of transport is required for such pebbles to reach their maximum roundness from which we may conclude that abrasion is a slow process. Since much more abrasion is required to change shape significantly than roundness it is unlikely that abrasion is a significant factor in changing shape. This is further confirmed in Chapter V where multiple correlation regression has shown that for rhyodacites distance from source (Di_r) makes little or no contribution towards explaining changes in form and sphericity between stations. Also form changes in sandstones appear to be only slightly influenced by distance downstream (D).

page 78

It is found that dilution by new gravel from tributaries accounts for a significant amount of the statistical explanation of variations in form and sphericity of the rhyodacites. It is considered surprising by one of the examiners that dilution does not also affect roundness. This is probably because, as indicated on page 103, rhyodacite pebbles appear to "quickly reach a limiting roundness after which there is a dynamic balance between abrasion tending to increase roundness and other factors tending to decrease it".

page 124-126

The statement made earlier about the use of the term 'explanation' is of critical importance here where the writer uses multiple correlation regression analysis to assess the extent to which variations in abrasion and breakage indices account for variations in mean Kuenen roundness of both rhyodacites and sandstones. No causative explanation of variations in mean roundness is intended. It has been shown in an earlier chapter that changes in mean roundness are very largely due to abrasion and breakage (page 105). The aim of the analysis is simply to see if the variation in mean roundness can validly be split into two independent components, Ku75 and Ku25, to provide separate measures for abrasion and breakage respectively. For such a split to be made without significant loss of information the two components together should account for nearly all the variation in mean roundness. Since multiple correlation regression analysis 'explains' 95.49% of the variation in mean roundness of sandstone and 96.58% in the case of rhyodacite this aim appears to have been achieved.

APPENDIX

The appendix summarizes most of the information obtained from computer processing of the sample data. The Algol programme, U876-PEBBLE ANALYSIS, for use with the University of Tasmania's Elliott 503/PDP-8L computer was written by N.K. Chick, assisted by the writer, when the former was employed as a research assistant. The measures of mean, standard deviation and kurtosis used are the moment measures.

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Rhyodacite Samples - Mean axial dimensions (mm)

Sample No.	L	I	S
1	43.50	29.36	17.91
2	44.84	30.47	18.62
3	42.06	27.99	17.42
4	46.02	31.61	18.83
5	43.18	30.82	20.71
6	43.46	30.41	19.71
7	44.59	30.80	17.91
8	43.43	30.51	18.27
9	46.68	33.66	20.63

Rhyodacite Samples - Frequency distributions of form.

Form Class	Sample No.								
	1	2	3	4	5	6	7	8	9
Compact	2	5	4	3	11	3	1	1	3
Compact platy	8	7	9	10	6	10	3	8	10
Compact bladed	12	16	11	8	30	23	13	13	15
Compact elongated	11	4	11	8	16	19	8	9	16
Platy	21	15	12	26	12	11	19	23	20
Bladed	37	45	56	49	46	51	58	57	51
Elongated	30	34	31	29	21	17	20	23	19
Very platy	1	4	1	5	1	2	4	0	3
Very bladed	23	15	10	8	5	9	20	14	12
Very elongated	5	5	5	4	2	5	4	2	1

Rhyodacite Samples - Frequency distributions of Kaiser roundness

Class	Sample No. 1	2	3	4	5	6	7	8	9
0 - 50	0	1	1	0	0	0	1	1	0
50 - 100	11	8	13	0	5	4	4	3	12
100 - 150	15	17	21	16	15	21	19	16	18
150 - 200	15	16	28	17	21	24	16	30	24
200 - 250	20	23	22	21	20	19	17	22	26
250 - 300	25	20	27	28	26	30	17	17	20
300 - 350	17	16	14	21	9	16	19	19	21
350 - 400	18	21	7	18	21	9	23	13	7
400 - 450	7	15	7	13	15	12	11	7	6
450 - 500	9	7	6	5	8	7	9	8	7
500 - 550	7	3	3	5	3	3	5	7	2
550 - 600	3	1	0	3	0	3	4	1	4
600 - 650	2	1	1	2	1	0	3	4	0
650 - 700	0	0	0	1	3	2	1	1	3
700 - 750	1	0	0	0	2	0	1	1	0
750 - 800	0	1	0	0	1	0	0	0	0
800 - 850	0	0	0	0	0	0	0	0	0
850 - 900	0	0	0	0	0	0	0	0	0
900 - 950	0	0	0	0	0	0	0	0	0
950 - 1000	0	0	0	0	0	0	0	0	0

Rhyodacite Samples - Frequency distributions of Kuenen roundness.

Class	Sample No. 1	2	3	4	5	6	7	8	9
0 - 50	0	0	1	0	0	0	0	0	0
50 - 100	5	5	10	0	2	2	3	2	10
100 - 150	8	7	10	8	9	9	11	6	8
150 - 200	12	15	12	10	15	22	9	15	15
200 - 250	15	17	28	17	15	20	14	29	26
250 - 300	16	16	17	20	19	15	16	15	21
300 - 350	17	14	22	15	21	21	19	15	17
350 - 400	23	23	14	17	8	12	6	14	16
400 - 450	10	11	12	24	19	16	26	16	11
450 - 500	8	12	6	10	12	9	12	10	6
500 - 550	12	8	9	9	9	9	11	8	7
550 - 600	8	7	3	6	7	8	8	8	5
600 - 650	7	6	2	7	5	3	6	5	0
650 - 700	3	6	1	4	2	2	4	2	2
700 - 750	3	2	2	0	4	0	1	3	5
750 - 800	3	0	0	1	2	0	3	0	0
800 - 850	0	1	1	2	0	1	1	0	1
850 - 900	0	0	0	0	0	1	0	1	0
900 - 950	0	0	0	0	0	0	0	1	0
950 - 1000	0	0	0	0	1	0	0	0	0

Rhyodacite Samples - Frequency distributions of Wadell sphericity

Class	Sample No. 1	2	3	4	5	6	7	8	9
0 - 50	0	0	0	0	0	0	0	0	0
50 - 100	0	0	0	0	0	0	0	0	0
100 - 150	0	0	0	0	0	0	0	0	0
150 - 200	0	0	0	0	0	0	0	0	0
200 - 250	0	0	0	0	0	0	0	0	0
250 - 300	0	0	0	0	0	0	0	0	0
300 - 350	0	0	0	0	0	0	0	0	0
350 - 400	0	1	0	0	0	1	0	0	0
400 - 450	1	2	0	1	0	1	0	0	1
450 - 500	6	4	8	3	4	3	1	2	12
500 - 550	17	12	12	20	4	6	18	10	14
550 - 600	30	22	24	21	17	25	29	24	29
600 - 650	17	39	46	31	20	24	28	31	33
650 - 700	32	24	23	32	37	27	33	31	30
700 - 750	24	22	18	22	24	29	27	35	16
750 - 800	14	13	11	12	20	19	9	11	11
800 - 850	8	7	6	5	15	10	4	5	4
850 - 900	1	2	1	3	7	5	0	1	0
900 - 950	0	2	1	0	2	0	1	0	0
950 - 1000	0	0	0	0	0	0	0	0	0

Rhyodacite Samples - Frequency distributions of Maximum Projection sphericity

Class	Sample No. 1	2	3	4	5	6	7	8	9
0 - 50	0	0	0	0	0	0	0	0	0
50 - 100	0	0	0	0	0	0	0	0	0
100 - 150	0	0	0	0	0	0	0	0	0
150 - 200	0	0	0	0	0	0	0	0	0
200 - 250	0	0	0	0	0	0	0	0	0
250 - 300	0	1	0	0	0	0	0	0	0
300 - 350	0	0	0	0	0	0	0	0	1
350 - 400	1	2	1	5	2	2	1	0	1
400 - 450	4	4	2	4	1	2	6	1	5
450 - 500	14	10	7	5	3	5	11	12	9
500 - 550	22	13	21	21	11	12	26	14	10
550 - 600	20	30	29	31	19	24	24	29	25
600 - 650	23	25	27	28	22	29	31	33	29
650 - 700	24	30	24	22	22	23	24	30	26
700 - 750	22	14	19	21	25	20	15	16	19
750 - 800	13	12	13	7	24	14	7	11	14
800 - 850	4	6	3	2	12	14	1	4	7
850 - 900	2	2	4	2	8	5	3	0	3
900 - 950	0	1	0	2	1	0	0	0	1
950 - 1000	1	0	0	0	0	0	1	0	0

Rhyodacite Samples - Kaiser roundness parameters

Sample No.	1	2	3	4	5	6	7	8	9
Mean	292.68	284.46	239.91	301.23	301.08	274.63	306.33	288.30	262.66
Minimum value	56.58	46.84	0	111.73	72.20	56.34	43.20	44.20	51.02
Maximum value	728.48	754.72	628.51	654.55	795.23	690.85	705.13	722.02	662.98
Standard deviation	135.82	127.14	117.23	120.09	143.18	127.13	139.76	137.52	131.81
Skewness	1.2×10^6	1.0×10^6	9.9×10^5	1.1×10^6	2.7×10^6	1.6×10^6	1.1×10^6	2.2×10^6	1.9×10^6
Variance	18447.88	16164.97	13742.05	14420.96	20499.71	16161.23	19533.04	18911.49	17373.47
Kurtosis	9.8×10^8	8.7×10^8	6.0×10^8	6.3×10^8	1.7×10^9	9.0×10^8	1.0×10^9	1.2×10^9	1.1×10^9

Rhyodacite Samples - Kuenen roundness parameters

Sample No.	1	2	3	4	5	6	7	8	9
Mean	366.79	357.49	305.71	376.06	364.12	335.67	376.46	352.25	315.50
Minimum value	61.92	51.28	0	115.94	74.77	75.19	52.08	57.14	58.82
Maximum value	791.37	800.00	838.32	823.53	1000.00	873.36	821.11	934.58	845.07
Standard deviation	167.16	163.22	152.01	150.10	169.15	150.39	164.44	162.87	156.50
Skewness	2.0×10^6	1.5×10^6	2.6×10^6	1.8×10^6	3.6×10^6	2.4×10^6	1.4×10^6	3.6×10^6	3.3×10^6
Variance	27942.96	26639.56	23105.93	22530.04	28610.45	22617.96	27038.92	26525.85	24492.26
Kurtosis	2.0×10^9	1.7×10^9	1.9×10^9	1.5×10^9	3.0×10^9	1.7×10^9	1.9×10^9	2.5×10^9	2.1×10^9

Rhyodacite Samples - Wadell sphericity parameters

Sample No.	1	2	3	4	5	6	7	8	9
Mean	648.50	652.68	645.90	650.61	696.93	677.14	647.29	661.14	676.31
Minimum value	446.79	392.05	452.17	446.01	471.57	389.74	491.26	472.96	485.97
Maximum value	876.93	923.85	942.08	893.97	915.28	887.59	948.60	856.29	890.41
Standard deviation	92.64	95.56	88.23	91.40	95.56	94.63	82.47	79.10	82.64
Skewness	6.9×10^4	1.4×10^5	2.4×10^5	2.0×10^5	3.1×10^4	-1.3×10^5	1.9×10^5	-1.1×10^4	3.8×10^4
Variance	8581.25	9132.03	7784.49	8353.73	9130.86	8954.42	6800.60	6256.34	6830.19
Kurtosis	1.6×10^8	2.6×10^8	2.0×10^8	1.9×10^8	2.2×10^8	2.2×10^8	1.4×10^8	9.8×10^7	1.2×10^8

Rhyodacite Samples - Maximum Projection sphericity parameters

Sample No.	1	2	3	4	5	6	7	8	9
Mean	627.46	629.30	634.44	621.63	680.54	659.26	613.58	629.17	643.03
Minimum value	366.36	291.51	354.08	357.44	365.71	358.02	491.26	409.32	348.40
Maximum value	969.07	930.67	893.58	940.35	907.98	867.80	948.60	841.47	926.36
Standard deviation	111.45	110.73	99.39	109.17	109.82	108.60	82.47	91.63	112.31
Skewness	$-5.4\text{x}10^{5}$	$-9.0\text{x}10^{5}$	$-1.3\text{x}10^{5}$	$-8.6\text{x}10^{5}$	$-9.5\text{x}10^{5}$	$-7.7\text{x}10^{5}$	$1.9\text{x}10^{5}$	$-6.6\text{x}10^{5}$	$-1.3\text{x}10^{6}$
Variance	12420.85	12261.58	9877.85	11918.59	12060.94	11793.59	6800.60	8396.41	12613.50
Kurtosis	$4.0\text{x}10^{8}$	$4.8\text{x}10^{8}$	$2.9\text{x}10^{8}$	$4.6\text{x}10^{8}$	$4.2\text{x}10^{8}$	$3.8\text{x}10^{8}$	$1.4\text{x}10^{8}$	$1.8\text{x}10^{8}$	$4.8\text{x}10^{8}$

Sandstone Samples - Mean axial dimensions (mm).

Sample No.	L	I	S
1	42.59	28.87	17.03
2	42.65	29.20	17.71
3	41.18	27.51	17.27
4	44.94	31.61	17.89
5	42.55	28.48	18.30
6	42.84	29.29	19.30
7	44.14	30.45	16.73
8	44.50	30.67	18.51
9	46.28	33.33	19.53
10	43.17	30.07	19.70

Sandstone Samples - Frequency distributions of form

Form Class	Sample No. 1	2	3	4	5	6	7	8	9	10
Compact	2	0	4	2	5	6	3	1	2	3
Compact platy	5	7	8	8	9	9	10	4	13	9
Compact bladed	20	24	21	20	16	28	11	14	12	25
Compact elongated	7	11	8	7	14	15	5	18	9	13
Platy	13	12	6	18	9	12	20	20	25	13
Bladed	43	40	49	41	39	32	41	46	47	38
Elongated	24	29	30	17	31	25	18	19	19	35
Very platy	4	9	2	6	3	2	8	5	6	1
Very bladed	23	13	16	24	15	11	26	15	14	10
Very elongated	9	5	6	7	9	10	8	8	3	3

Sandstone Samples - Frequency distributions of Kaiser roundness

Class	Sample No. 1	2	3	4	5	6	7	8	9	10
0 - 50	1	2	0	0	0	0	1	2	2	5
50 - 100	1	5	7	3	4	5	5	8	2	13
100 - 150	16	17	15	7	14	9	12	13	11	11
150 - 200	12	13	7	13	16	7	16	7	8	11
200 - 250	28	18	25	20	16	10	12	16	14	17
250 - 300	27	29	24	21	22	21	15	15	14	13
300 - 350	20	22	22	14	12	17	14	14	20	16
350 - 400	13	9	15	22	22	18	11	18	17	20
400 - 450	10	12	12	12	12	20	17	15	10	11
450 - 500	2	10	8	11	7	13	12	11	15	11
500 - 550	9	3	7	15	9	8	11	10	15	11
550 - 600	4	4	4	4	8	8	14	7	6	3
600 - 650	3	1	0	1	4	5	6	9	8	5
650 - 700	2	2	3	2	0	5	2	2	4	1
700 - 750	1	3	1	0	1	2	2	1	2	2
750 - 800	1	0	0	1	2	1	0	0	0	0
800 - 850	0	0	0	2	1	1	0	0	1	0
850 - 900	0	0	0	1	0	0	0	1	0	0
900 - 950	0	0	0	0	0	0	0	1	1	0
950 - 1000	0	0	0	1	0	0	0	0	0	0

Sandstone Samples - Frequency distributions of Kuenen roundness.

Class	Sample No. 1	2	3	4	5	6	7	8	9	10
0 - 50	0	0	0	0	0	0	0	1	0	4
50 - 100	2	5	4	0	2	3	5	8	4	10
100 - 150	6	9	9	4	7	7	6	7	2	11
150 - 200	9	9	8	9	8	6	9	7	11	10
200 - 250	15	14	12	11	14	6	12	7	9	7
250 - 300	25	14	9	17	14	10	6	8	10	11
300 - 350	16	21	23	15	17	13	20	16	15	13
350 - 400	12	18	21	16	10	13	11	9	11	8
400 - 450	21	16	17	13	14	14	9	18	17	17
450 - 500	9	8	14	13	12	10	10	13	11	12
500 - 550	8	9	6	16	16	14	12	13	11	16
550 - 600	10	12	3	6	8	16	13	11	10	5
600 - 650	4	6	12	11	9	9	10	8	10	9
650 - 700	2	2	5	8	6	11	7	6	12	9
700 - 750	5	4	3	3	5	6	12	7	6	5
750 - 800	1	2	2	3	3	4	5	3	4	1
800 - 850	1	0	2	0	1	3	1	4	3	1
850 - 900	3	1	0	1	3	2	0	2	3	1
900 - 950	1	0	0	1	0	3	2	1	0	0
950 - 1000	0	0	0	3	1	0	0	1	1	0

Sandstone Sample - Frequency distributions of Wadell sphericity

Class	Sample No. 1	2	3	4	5	6	7	8	9	10
0 - 50	0	0	0	0	0	0	0	0	0	0
50 - 100	0	0	0	0	0	0	0	0	0	0
100 - 150	0	0	0	0	0	0	0	0	0	0
150 - 200	0	0	0	0	0	0	0	0	0	0
200 - 250	0	0	0	0	0	0	0	0	0	0
250 - 300	0	0	0	0	0	0	0	0	0	0
300 - 350	0	0	0	0	0	0	0	0	0	0
350 - 400	0	0	0	0	1	0	2	2	0	0
400 - 450	2	1	2	2	0	3	3	1	0	0
450 - 500	7	7	5	9	7	7	11	7	5	6
500 - 550	15	11	16	19	17	15	19	11	10	8
550 - 600	29	27	21	20	23	17	24	13	17	11
600 - 650	29	33	31	32	20	16	25	31	29	36
650 - 700	27	18	25	18	31	29	27	43	32	32
700 - 750	22	30	27	23	23	24	16	25	27	17
750 - 800	8	11	15	15	14	20	13	9	22	22
800 - 850	7	10	7	11	11	15	6	6	6	14
850 - 900	3	2	1	1	2	4	3	2	1	3
900 - 950	1	0	0	0	1	0	1	0	1	1
950 - 1000	0	0	0	0	0	0	0	0	0	0

Sandstone Sample - Frequency distributions of Maximum Projection sphericity

Class	Sample No. 1	2	3	4	5	6	7	8	9	10
0 - 50	0	0	0	0	0	0	0	0	0	0
50 - 100	0	0	0	0	0	0	0	0	0	0
100 - 150	0	0	0	0	0	0	0	0	0	0
150 - 200	0	0	0	0	0	0	0	0	0	0
200 - 250	0	0	0	0	0	0	0	0	0	0
250 - 300	0	0	0	0	0	0	0	0	0	0
300 - 350	0	3	1	1	0	0	2	2	0	0
350 - 400	4	2	3	2	1	5	9	6	0	0
400 - 450	8	3	2	10	5	3	7	6	8	3
450 - 500	12	13	11	14	11	8	17	12	11	6
500 - 550	19	16	16	25	11	12	18	10	18	13
550 - 600	21	18	19	21	25	18	34	20	25	19
600 - 650	26	21	22	26	23	15	19	34	21	20
650 - 700	24	27	27	15	24	24	18	18	28	32
700 - 750	19	27	30	18	25	30	12	16	22	22
750 - 800	9	10	10	13	9	19	11	15	9	20
800 - 850	5	9	6	2	9	12	0	9	5	12
850 - 900	3	1	3	2	6	3	2	1	3	3
900 - 950	0	0	0	1	1	1	1	1	0	0
950 - 1000	0	0	0	0	0	0	0	0	0	0

Sandstone Samples - Kaiser roundness parameters

Sample No.	1	2	3	4	5	6	7	8	9	10
Mean	307.89	301.52	307.60	354.69	333.60	371.62	356.82	353.78	375.52	312.78
Minimum value	49.88	47.73	50.38	97.56	55.40	57.55	48.08	0	46.95	0
Maximum value	788.95	715.27	723.98	968.72	809.25	808.71	744.99	906.80	911.68	733.33
Standard deviation	140.99	144.39	137.79	159.10	156.87	157.72	166.73	175.08	167.92	166.20
Skewness	2.5×10^6	2.0×10^6	1.5×10^6	4.0×10^6	2.5×10^6	1.2×10^6	5.6×10^5	1.9×10^6	1.5×10^6	8.2×10^5
Variance	19877.60	20848.07	18986.26	25313.56	24607.42	24874.82	27798.33	30654.52	28198.42	27622.77
Kurtosis	1.4×10^9	1.5×10^9	1.2×10^9	2.9×10^9	1.9×10^9	1.7×10^9	1.6×10^9	2.7×10^9	2.3×10^9	1.8×10^9

Sandstone Samples - Kuenen roundness parameters

Sample No.	1	2	3	4	5	6	7	8	9	10
Mean	387.82	373.51	388.72	436.33	422.16	464.89	442.77	435.42	452.91	385.76
Minimum value	60.98	52.49	56.98	102.83	62.11	88.89	61.16	0	52.49	0
Maximum value	921.66	855.61	839.69	1000.00	960.00	919.54	942.03	962.57	987.65	894.31
Standard deviation	177.03	168.17	169.70	190.23	190.17	195.11	200.73	206.97	198.91	201.62
Skewness	4.5×10^6	1.8×10^6	1.7×10^6	5.1×10^6	2.8×10^6	7.8×10^5	7.7×10^5	1.5×10^6	1.4×10^6	3.3×10^5
Variance	31340.83	28282.83	28798.87	36188.19	36166.20	38066.80	40290.89	42837.58	39565.61	40649.85
Kurtosis	3.3×10^9	2.2×10^9	2.3×10^9	4.7×10^9	3.5×10^9	3.5×10^9	3.5×10^9	4.6×10^9	3.7×10^9	3.6×10^9

<u>Sandstone Samples</u> - Wadell sphericity parameters

Sample No.	1	2	3	4	5	6	7	8	9	10
Mean	643.55	653.40	650.98	647.08	655.54	670.74	632.62	652.89	668.17	678.69
Minimum value	415.09	437.99	438.58	403.54	367.05	407.71	352.45	370.75	468.09	451.44
Maximum value	932.93	868.62	852.61	858.27	906.69	877.07	909.19	881.37	907.72	919.17
Standard deviation	97.42	93.23	93.02	98.89	102.03	107.82	107.34	91.51	86.24	94.72
Skewness	2.9×10^{5}	5.9×10^{4}	-3.2×10^{4}	1.3×10^{4}	5.1×10^{4}	-3.6×10^{5}	1.0×10^{5}	-3.0×10^{5}	-5.3×10^{4}	4.4×10^{4}
Variance	9490.58	8691.88	8651.98	9779.04	10410.43	11626.19	11522.83	8374.12	7438.00	8971.66
Kurtosis	2.6×10^{8}	1.7×10^{8}	1.8×10^{8}	2.1×10^{8}	2.8×10^{8}	3.1×10^{8}	3.6×10^{8}	2.4×10^{8}	1.5×10^{8}	2.0×10^{8}

Sandstone Samples - Maximum Projection sphericity parameters

Sample No.	1	2	3	4	5	6	7	8	9	10
Mean	617.47	632.08	638.12	604.48	647.37	660.65	587.57	625.09	625.44	666.69
Minimum value	352.40	323.78	322.13	302.14	382.45	364.01	323.27	307.67	404.53	424.72
Maximum value	872.74	858.32	883.13	900.33	921.76	914.65	913.95	919.59	870.24	875.20
Standard deviation	113.10	115.26	108.98	120.58	112.23	120.49	127.15	124.31	113.94	104.05
Skewness	-1.0×10^{6}	-1.5×10^{6}	-7.7×10^{5}	-1.5×10^{6}	-2.2×10^{5}	-1.2×10^{6}	-1.8×10^{6}	-1.7×10^{6}	-1.4×10^{6}	-6.3×10^{5}
Variance	12792.57	13285.33	11877.02	14539.38	12596.14	14518.18	16166.21	15452.94	12982.44	10826.48
Kurtosis	4.3×10^{8}	5.4×10^{8}	4.2×10^{8}	5.2×10^{8}	4.1×10^{8}	5.9×10^{8}	6.8×10^{8}	7.2×10^{8}	4.2×10^{8}	2.8×10^{8}

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LIST OF SYMBOLS

A - area of outcrop above a station (km^2)

Al - mean altitude of outcrops at a sample station (metres)

B - number of bladed pebbles in a sample

C - mean Cailleux roundness of sample

D - distance downstream from station 1 (km)

Di - mean distance from outcrops at a sample station (km)

E - number of elongated pebbles

Δ F - magnitude of form change between adjacent stations (chi-square)

I - mean length of intermediate axis of a sample (mm)

Ka - mean Kaiser roundness of sample

Ku - mean Kuenen roundness of sample

Ku25 - Kuenen breakage index

Ku75 - Kuenen abrasion index

L - mean length of long axis of a sample (mm)

M - mean Maximum Projection sphericity of a sample

P - number of platy pebbles in a sample

Q - the ratio Q_ℓ/Q_0

Q_ℓ - percentage content of a particular lithology in a sample of 200 pebbles

Q_0 - percentage area of the catchment over which a particular lithology outcrops

ra - radius of curvature of sharpest corner of pebble in the maximum projection plane

S - mean length of short axis of a sample (mm)

T - mean pebble weight of a sample (grams)

W - mean Wadell sphericity of a sample

The following additional symbols are used in conjunction with some of the above variables:

X* - actual value for an individual pebble

$\bar{X}$ - mean value for a particular lithology from all sample stations

X_r - indicates value for rhyodacite

X_s - indicates value for sandstone

$|X|$ - indicates modulus of value

Δ X - change in value between two adjacent stations