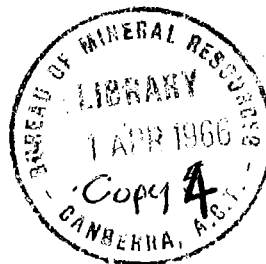019095

COMMONWEALTH OF AUSTRALIA

DEPARTMENT OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES
GEOLOGY AND GEOPHYSICS

RECORD

1966/1

THE STAIRWAY SANDSTONE
A
SEDIMENTOLOGICAL STUDY
BY
P J COOK

Sympo   ast

THE STAIRWAY SANDSTONE

- A SEDIMENTOLOGICAL STUDY

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P.J.Cook

Record 1966/1

C O N T E N T S

ILLUSTRATIONS

FIGURES

ABSTRACT

The Stairway Sandstone is an Ordovician formation of the Amadeus Basin of Central Australia. It can be divided into a lower unit of coarse grained super-mature orthoquartzites; a middle unit of siltstones, claystones (mainly illite) and phosphorites, grading into carbonates then "red-beds" to the south-east; and an upper unit mainly of fine grained mature orthoquartzites. The heavy mineral assemblage of the formation is one typically associated with orthoquartzites - almost exclusively well rounded tourmalines and zircons.

Detailed textural analyses of the arenites gave values for the mean and median diameters, standard deviation, skewness and kurtosis which suggest that the coarse sands were deposited in a beach or shallow water marine environment and the fine sands in a shallow marine shelf or lagoonal environment.

The isopachous maps show the Amadeus Basin to be a basin with an eroded northern margin of deposition, for the thickest part of the Stairway Sandstone is abruptly cut off in the vicinity of the Macdonnell Ranges. Lithofacies studies suggest that the basin had a north-west to south-east trending axis. Cross-bedding studies indicate the palaeocurrents flowed from the south-east, parallel to the axis, except in the middle Stairway where the currents assumed a more north-easterly trend. Other cross-bedding studies suggest the presence of high energy zones at right angles to the main palaeocurrent direction.

The physico-chemical conditions during Stairway Sandstone times are postulated from the mineralogy, textures and sedimentary structures of the sediments. These suggest a low average rate of sedimentation (in the order of 0.1 mm. per annum), fairly uniform conditions in the

lower and upper Stairway, current velocities with a range of from 1 to 30 cms./sec., fairly warm conditions, normal salinities (except in the Mount Charlotte embayment), pH values of from about 7.0 to 8.0 and Eh values of about -0.2 (reducing conditions).

The environment of deposition of the Stairway Sandstone is delineated by means of the detailed graphic log. It is possible to establish that the overall Stairway Sandstone sequence is regressive-transgressive. From the basic sedimentation units it is possible to recognise six composite sedimentation units (A, B, C, D, E, F) which together make up a compound sedimentation unit which can be related to a sedimentological model. It is found that two modern environments - the barrier-lagoon environment and the intertidal flat environment and a more hypothetical environment - the epeiric sea - are compatible with the compound sedimentation unit.

The phosphorites of the formation are considered in some detail and ten types of phosphatic material are recognized, some of which are thought to be primary precipitates whilst others have replaced carbonates etc. The main concentration of phosphorites appears to have taken place during winnowing. It is thought that upwelling currents were probably the main source of the phosphorites. The idea of upwelling currents is compatible with a palaeogeographic picture of the Ordovician Amadeus Basin situated within the torrid zone, and probably within a desert belt. The connection to the open sea was to the west. Sediments were derived mainly from distant plutonic and sedimentary sources located to the south in the more tropical climatic zone.

There are several economic implications of the sedimentological study. Various potential mineralogical marker horizons are suggested

for detailed stratigraphic correlation. The formation is considered to be
an excellent petroleum or natural gas prospect and it is possible to
indicate areas where the best prospects of stratigraphic traps are
believed to lie. Finally, it is suggested that in order to find economic
phosphate deposits it is necessary to find zones where winnowing occurred
- possibly the southern margin of the basin. Alternatively rich primary
phosphorites undiluted by terrigenous sediments may be found to the north-
west of the basin.

CHAPTER 1
INTRODUCTION

General

This sedimentological study is the product of two years work resulting partly from the author's investigations in his capacity as a geologist of the Bureau of Mineral Resources, Geology and Geophysics, Canberra, and partly from independent investigations carried out at the Australian National University under the supervision of Dr.K.A.W.Crook.

The author has been involved in the study of the geology of the southern part of the Northern Territory since 1961, and of the Stairway Sandstone in particular since 1963. A total of three field seasons, each of approximately five months duration, together with laboratory investigations for a total period of about 8 months, have given ample opportunity to study the Stairway Sandstone in detail.

These studies have included the compilation and use of the graphic log, thin section studies (both textural and mineralogical), detailed heavy mineral studies, the measurement of detailed stratigraphic sections, and crossbedding studies. All these studies have been used to build up an integrated picture of the provenance, environments of deposition and the palaeogeography of the Stairway Sandstone. In addition, the origin of pelletal phosphorites has been investigated in some detail because of its economic significance.

Investigations were carried out on both surface and sub-surface samples. Surface samples are referred to by a prefix related to the name of the 1:250,000 sheet area from which they were collected - specimen LA 188 was collected from the Lake Amadeus Sheet area (see

FIG. I

LOCALITY MAP
AMADEUS BASIN
CENTRAL AUSTRALIA

REFERENCE

Superficial mesozoic sediments

Western limit of removal of Stairway Sandstone below the Mereenie unconformity

Igneous and metamorphic rocks and metasediments

Road

Railway

AP2 Diamond Drill Hole

LOCALITY MAP

MOUNT RENNIE	MOUNT LIEBIG	H/BERG	ALICE SPRINGS
BLOODS RA.	LAKE AMADEUS	HENBURY	RODINGA
PETERMANN RANGES	AYERS ROCK	KULGERA	FINKE

fig.1). Sub-surface core samples were obtained from four diamond drill holes AP1, AP2, AP3 and AP4 (see fig.1). They are numbered by using the drill hole number as a prefix. The second set of numbers is the number of the sedimentation unit (see Chapter 7) and the third set of numbers is the distance in inches from the top of the sedimentation unit. Hence, specimen AP1/762/13 is a sample collected from a point 13 inches below the top of sedimentation unit 762 in the AP1 core.

The Amadeus Basin

The Stairway Sandstone is one of the rock units of the Amadeus Basin, a large sedimentary basin in central Australia, stretching from about longitude 128°E in Western Australia, east to about longitude 135°E in the Northern Territory and from Alice Springs in the north to near the South Australian border in the south (Fig.1). The basin is approximately 500 miles long and 170 miles wide and covers an area of about 60,000 square miles.

The sediments of the Amadeus Basin range in age from Adelaidean (upper Proterozoic) to Upper Palaeozoic and are mainly of the miogeosynclinal type. They have a total thickness of approximately 30,000 feet. These sediments have been fully described by Wells, Forman and Ranford, (1965(a), (b)); Wells, Stewart and Skwarko, (1966); Ranford, Cook and Wells, (1966); and Wells, Ranford, Stewart, Cook and Shaw, (1966). Sedimentation was interrupted by two major orogenies, the Petermann Ranges Orogeny of Late Proterozoic to Early Cambrian age (Forman, 1966) and the Alice Springs Orogeny of Late Palaeozoic age (Forman, Milligan and McCarthy, 1966). The Lower Palaeozoic of the Amadeus Basin is divided into the Pertaoorrta Group, the Larapinta Group (Cambro-Ordovician) and the Mereenie Sandstone (?Ordovician).

The Larapinta Group is made up of four formations :-

Stokes Formation	Upper Ordovician
Stairway Sandstone	Middle Ordovician
Horn Valley Siltstone	Lower Ordovician
Pacoota Sandstone	Upper Cambrian to Lower Ordovician

These four formations are marine sediments probably deposited under fairly shallow conditions, and are described by Cook, (1966).

Previous Investigations of the Stairway Sandstone

The Larapinta Group was first defined by the Horn Expedition of 1892 (Tate and Watt, 1896), and was originally called the Larapintine Series. Chewings (1935), was the first to use the name "Stairway" and he refers informally to the unit as the Stairway Ridge Beds or the Stairway Quartzite. The formation was formally named the Stairway Greywacke by Prichard and Quinlan (1962), and defined as being "The formation of quartz greywacke and quartz sandstone which at Ellery Creek conformably overlies the Horn Valley Formation and is there followed unconformably by the Mereenie Sandstone. It consists of 60 percent of fine grained and medium grained quartz greywacke, usually rather silty, and about 40 percent of cleaner quartz sandstone".

Wells, Forman and Ranford, (1962) renamed the formation the Stairway Sandstone. The Stairway Sandstone has been described from various areas of the Amadeus Basin by Wells, Forman and Ranford (1962); Wells, Ranford and Cook (1963); Ranford and Cook (1964); Wells, Stewart and Skwarko, (1964); and Wells, Ranford, Stewart, Cook and Shaw (1965). It has been referred to briefly by Stelck and Hopkins, (1962); Rameft, (1963) and Haites, (1963). It is also described in various unpublished company

PLATE 2

DISTRIBUTION OF THE
STAIRWAY SANDSTONE
AMADEUS BASIN
CENTRAL AUSTRALIA

REFERENCE

Superficial mesozoic sediments

Western limit of removal of
Stairway Sandstone below the
Mereenie unconformity

Igneous and metamorphic rocks
and metasediments

Outcrop of Stairway Sandstone

Area where Stairway Sandstone is
present subsurface

Alice Springs

Lake Neale

Lake Amadeus

Finke River

LOCALITY MAP

W.A.
N.T
QLD
S.A
N.S.W
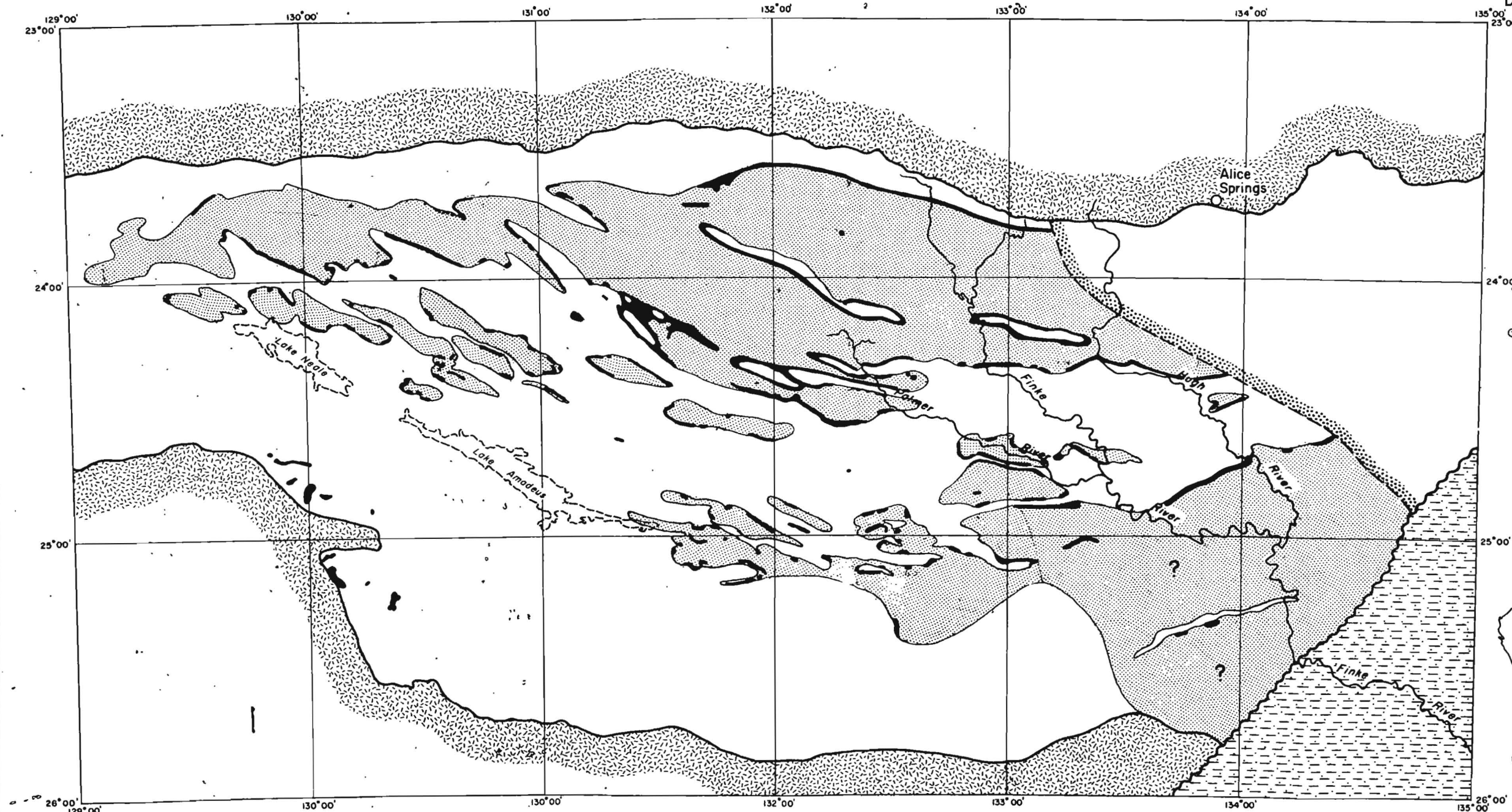
Scale

16   8   0   16   32 miles

reports - Gillespie, (1959); Taylor, (1959); Weegar, (1959); Leslie, (1960); Hopkins, (1962); McNaughton, (1962); and Haites, (1963).

Cook, (1963), recorded the presence of phosphorites in the Stairway Sandstone. Crook, (1964), also discussed the phosphorites, and Barrie, (1964), gave the preliminary results of a drilling programme in the Stairway Sandstone.

General Stratigraphy of the Stairway Sandstone

The Stairway Sandstone crops out sporadically throughout much of the Amadeus Basin (Fig.2). Although it has an outcrop area of only 600 square miles or possibly even less, it is estimated to underlie an area of at least 20,000 square miles.

The palaeogeologic map (Fig.3) shows that in the northern half of the Amadeus Basin the Stairway Sandstone rest conformably on the Horn Valley Siltstone. To the south it disconformably overlies the Cambrian Pertaoorrta Group and unconformably overlies Upper Proterozoic sedimentary rocks. Further south and west (e.g. Petermann Range), the Stairway Sandstone rests unconformably on igneous and metamorphic rocks of the Musgrave Block. In most areas the Stairway Sandstone is conformably overlain by the Stokes Formation but in the eastern part of the basin it is overlain unconformably by the Mereenie Sandstone (Fig.3).

The Stairway Sandstone ranges in thickness from 1840 feet in the Idirriki Range to 100 feet or less on the southern margain of basin. The isopachous map (Fig.12) clearly demonstrates that the present limits of the Amadeus Basin are markedly different from the original limits of deposition of the Stairway Sandstone. At the maximum development of the Stairway Sandstone seas the margins

PALAEOGEOLOGIC MAP
OF THE PRE-STAIRWAY
SANDSTONE SURFACE

AMADEUS BASIN
CENTRAL AUSTRALIA
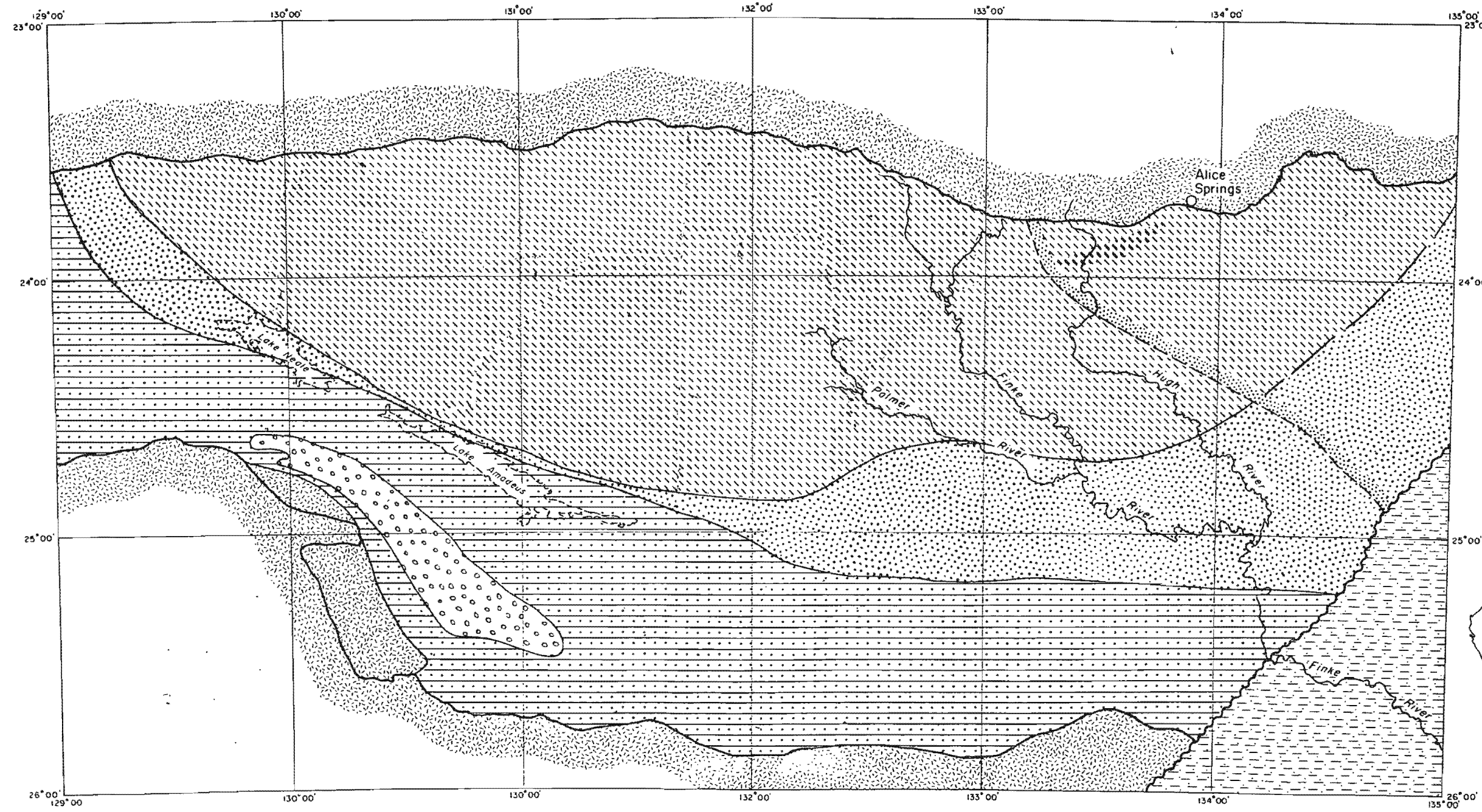
REFERENCE

Superficial mesozoic sediments

Western limit of removal of
Stairway Sandstone below the
Mereenie unconformity

Igneous and metamorphic rocks
and metasediments

Ordovician
(Horn Valley Siltstone)

Cambrian (Pertaoorrta Group)

Cambrian (Mount Currie conglomerate
& Ayers Rock arkose)

Upper Proterozoic
(Winnall Beds, Inindia Bed,
Bitter Springs limestone, Heavitree
Quartzite and equivalents)

LOCALITY MAP

Scale
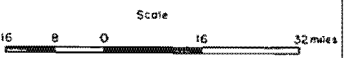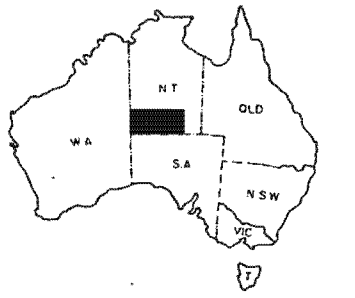
stretched well beyond the present limits of the basin.

The Stairway Sandstone is Middle Ordovician in age with an estimated range of possible upper Llanvirnian to Llandeilian (J.G.Tomlinson, pers.comm.) - equivalent to an interval of about 20 million years. Tomlinson (appendix in Wells, Ranford and Cook, 1963) records a number of fossils from the Stairway Sandstone, including trilobites, brachippods, peleycypods, gastropods, nautiloids, various trace fossils and sponge spicules. Some of the macrofossils are notable for the size they attain; the author found a trilobite in the Johnny Creek area with a pygidium more than 1 foot across. Several specimens of nautiloids several feet in length have also been found in the northern part of the Amadeus Basin. Jones (pers. comm.) has found a number of species of microfossils at various intervals within the formation. In spite of this wealth of palaeontological material it has so far proved possible to erect only one time-line within the formation. This divides the formation into what Tomlinson (pers.comm.) refers to as the Early Larapintan (equivalent to the upper part of the Pacoota Sandstone, the Horn Valley Siltstone and the lower and middle parts of the Stairway Sandstone) and the Late Larapintan (equivalent to the upper part of the Stairway Sandstone, the Stokes Formation and the lower part of the Mereenie Sandstone). The Stairway Sandstone is therefore a rock unit and not a time-rock unit.

The Stairway Sandstone has been divided on lithological grounds into lower middle and upper units which extend over much of the basin. Fig.4 shows 31 representative stratigraphic columns across the basin and correlation lines have been drawn for the three rock units. Such a correlation diagram is subject to severe limitations when there is

COLUMNAR SECTIONS   STAIRWAY SANDSTONE
AMADEUS BASIN.

PJ COOK 1965

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no fossil control, and it is fully realized that later fossil evidence may completely invalidate many of the correlations. However, the three units are recognisable in most areas as mappable units. The three units should strictly be referred to as for instance "The lower unit of the Stairway Sandstone" - however, from here on the units are informally referred to as the lower Stairway, the middle Stairway and the upper Stairway.

The lower Stairway is the most uniform of the three units, both in lithology and thickness. The thickness ranges from about 80 feet in the south (the Mount Charlotte area) to about 200 feet in the north (the Idirriki Range area). The unit is predominantly a white or grey, fine to very coarse grained sandstone. It is well rounded and sorted, pebbly in places, thin to massively bedded, ripple marked and cross-bedded (fig.41). The basal sandstone is remarkable for the presence of up to 20% of pyrite ooliths in places (generally weathered out, or in the form of limonite). The lower Stairway Sandstone contains a great variety of bedding plane markings (fig.42), tracks and trails (many of which are of an indeterminate nature) and one of the sandstones has a very characteristic texture referred to by Ranford, Cook and Wells (1966) as a "ropey texture" (fig.40, appendix). The lower unit is frequently strongly silicifed; it is well exposed and commonly forms very prominent escarpments (fig.39, appendix).

The middle Stairway ranges in thickness from less than 100 feet in the south to about 700 feet in the north. It is lithologically the most varied of the three divisions. It is predominantly a lutaceous interval, with siltstones, mudstones, and claystones which are grey and green at the surface but black sub-surface. The

lutites are sandy and micaceous in places, laminated, easily weathered and very poorly exposed. They are interbedded with thin, very fine grained, grey and white sandstones, and grey, brown or black pelletal and nodular phosphorites. In areas to the south-east (Seymour Range) thin yellow, or brown (grey or white at depth) dolomites and limestones are fairly common. Further to the south-east red and red-brown poorly sorted sandstones and lutites are extremely common; in the Mount Charlotte area these "red-beds" make up the whole of the middle Stairway Sandstone (fig.16). Fossils are fairly common in the middle interval; "chewing" and "churning" by infauna is particularly common (fig.43,appendix).

The upper Stairway ranges in thickness from less than 100 feet to 1,000 feet. It is made up predominantly of white and grey, very fine grained sandstones which are cross-bedded in places and may crop out fairly prominently when silicified. Interbeds of lutite, though generally minor, may form a fairly high percentage of the upper division in places. The lutites are green at the surface and black, grey or grey-green at depth; they are generally very poorly exposed. Interbeds of pelletal and nodular phosphorites are present but not very common. Fossils and trace fossils such as Diplocraterion (fig.43) and Cruziana are very common.

Summary

The Amadeus Basin is a large Upper Proterozoic - Palaeozoic basin in central Australia. The lower Palaeozoic of the basin is divided into the Pertaoorrta Group, the Larapinta Group and the Mereenie Sandstone. The Stairway Sandstone is one of the members of the Larapinta Group, and is of middle Ordovician age. It crops out over a large area of the basin and has a maximum thickness of

1840 feet. On lithological grounds the formation may be divided into three units; a lower coarse sandstone;a middle phosphatic lutite unit (grading laterally into carbonates and "red-beds"; and an upper fine sandstone with minor silts.

CHAPTER 2

PETROGRAPHY OF THE STAIRWAY SANDSTONE

There are four basic rock types present in the Stairway Sandstone:-
quartz arenites, lutites, phosphorites and carbonates. There is some
overlap between these four types (e.g. sandy limestones). However,
only the basic types will be discussed separately. The phosphatic
sediments are dealt with later, in Chapter 8. All petrographic
determinations were estimated . Petrographic descriptions of
approximately 200 specimens are summarized in Table 1,(appendix).

Arenites

The vast majority of the arenits fall into the orthoquartzite class
of Folk (1961) or the quartzose arenite class of Crook (1960). The
arenites are for the most part remarkable "pure" with little or no
chert, feldspar, or rock fragments. A very few fall into the sub-
arkose field of Folk, (1961); even fewer fall into the feldspathic
sub-labile arenite field of Crook, (1960).

The basic philosophy behind the "metamorphic" pole of Folk (1961)
is that this represents a metamorphic provenance and implies moderate
tectonism. On this basis there is some justification for including
"composite" quartz in this class. Similarly, the "rock fragment" or
"labile" pole of Crook (1960) includes chert because of its relative
instability. The author's observations on the quartz types within
the Stairway Sandstone suggest that composite quartz is less stable
than other forms of quartz. Composite quartz is, for instance,
apparently more common in the southern part of the basin where it
is nearer the source area; in addition, in many specimens the
distinction between a composite grain and a stretched metaquartzite

FIG 5

QUARTZ TYPES

C

P   U
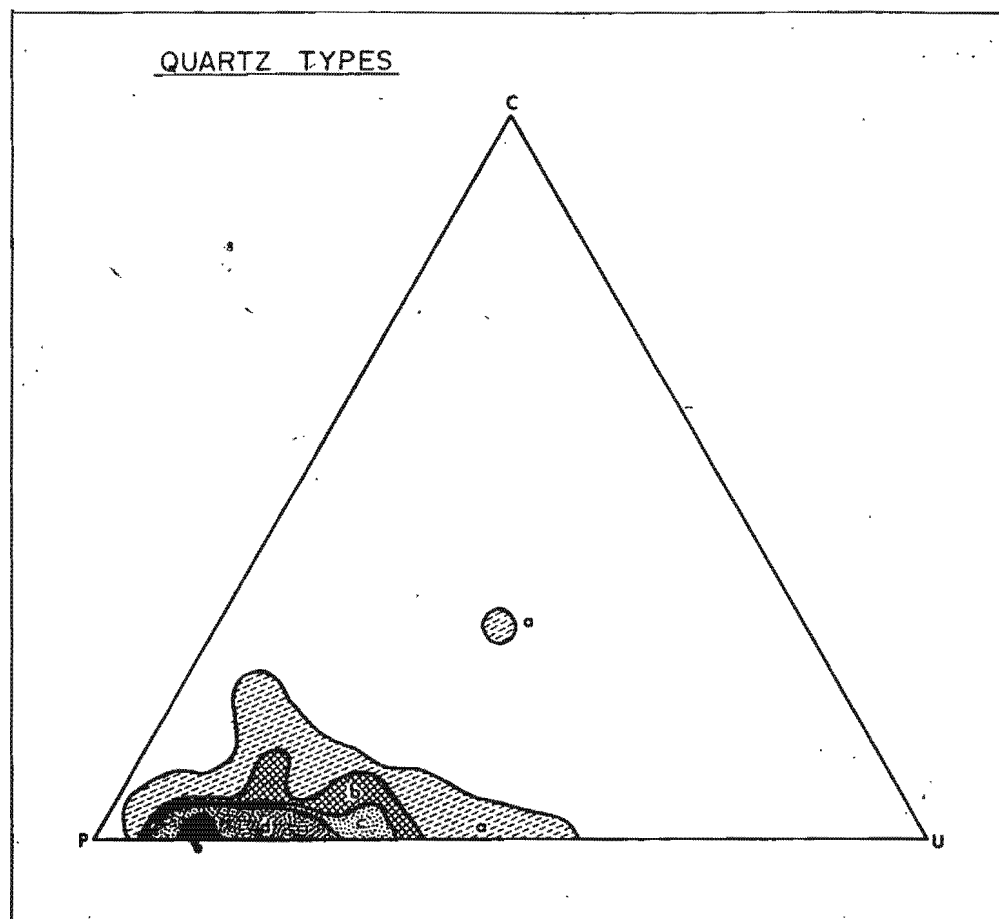
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Fig.5

QUARTZ TYPES WITHIN THE ORTHOQUARTZITES OF THE STAIRWAY SANDSTONE

Reference
Poles   P pole — plutonic or common quartz

             U pole — undulose quartz

             C pole — composite quartz

Relative concentration of points

             Blank areas — no points whatsoever

                         a — less than 1 point per unit area

                         b — 1 to 2 points per unit area

                         c — 2 to 4 points per unit area

                         d — 4 to 8 points per unit area

                         e — 8 to 16 points per unit area

grain is somewhat arbitrary. Blatt, (1963,1964), Blatt and
Christie (1963) and Greensmith (1963), have also noted this apparent
instability of composite quartz. If composite grains were to be
included with rock fragments then 10 - 20% of the specimens would
fall into the lithic sub-labile arenite field of Crook (1960) or
the sub-greywacke field of Folk (1961). A very small number of
specimens with over 25% composite grains would fall into lithic
labile arenite or greywacke field. However, despite the
advantages of this approach, it is proposed to avoid confusion
by following the accepted procedure and including composite quartz
grains with "normal" quartz. Rock types are named in accordance
with the scheme suggested by Folk (1961).

a) Orthoquartzite (0 - 5% feldspar, 0 - 5% metamorphic rock
    fragments and 95 - 100% of quartz-excluding metaquartzite).

The majority of the Stairway Sandstone arenites fall into this
class. The essential minerals assemblage is extremely uniform,
and for instance over 50 percent of the orthoquartzites contain less
than 1% feldspar. The quartz is mainly "common" (straight to slightly
undulose extinction) or "undulose" (strongly undulose extinction).
"Composite" quartz forms only a small percentage of the total quartz
(see Figs. 5 and 6). Chert and metaquartzite are present (Fig.44)
but rare, and no examples of reworked quartz grains are known. The
heavy mineral assemblage is also uniform, representing a typical
supermature assemblage of extremely well rounded tourmaline and zircon.

Both the lower and upper Stairway in diamond drill hole AP1 are
composed predominantly of siliceous mature orthoquartzites. There are
however important differences between the two (see table 1, appendix).

fig 6

MINERALOGICAL VARIATION OF ORTHOQUARTZITES IN AP1
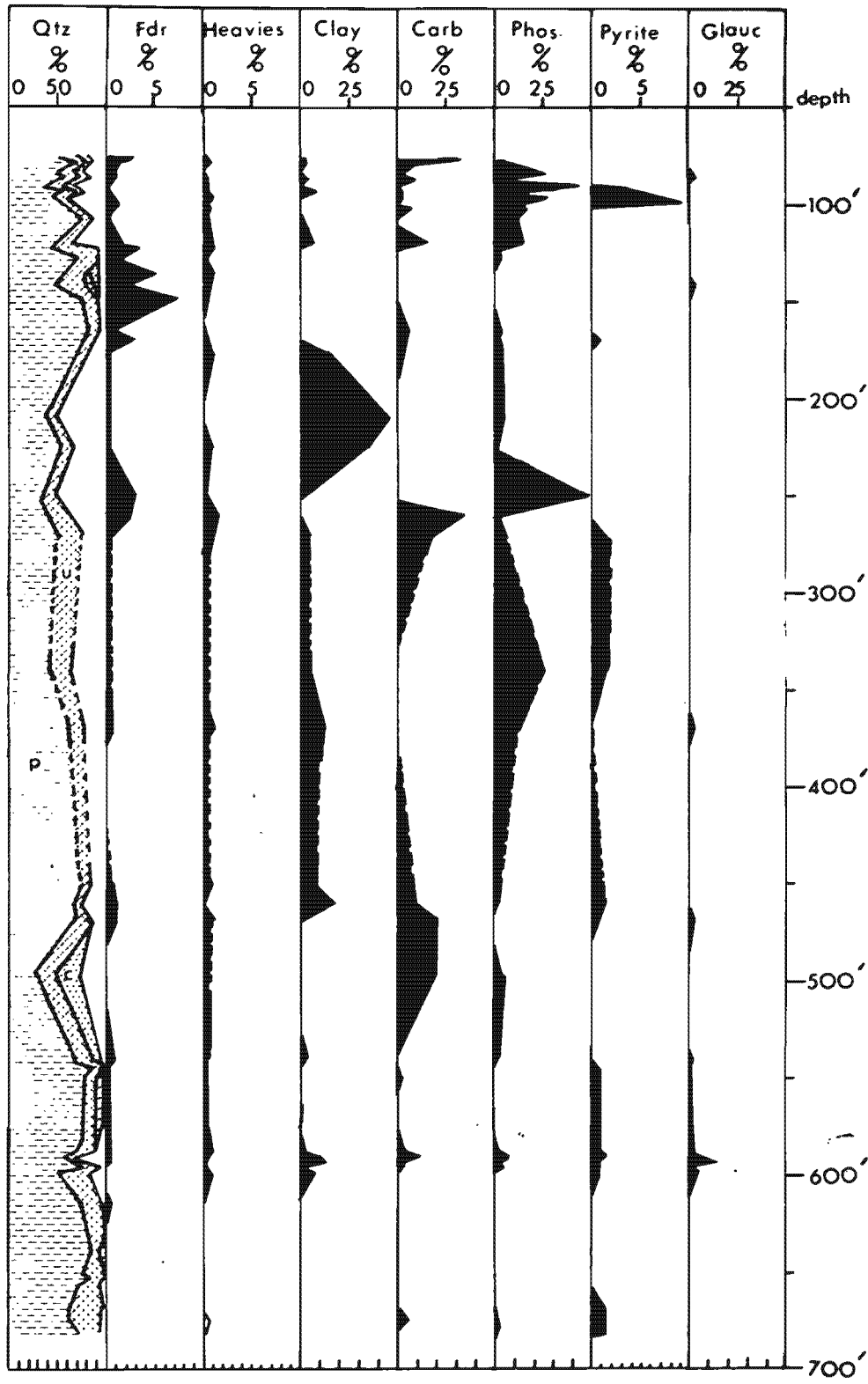
The lower orthoquartzites have a modal grain size of about $1\emptyset$ to $2\emptyset$, and are quite commonly bimodal, with a secondary mode of $3\emptyset$ to $4\emptyset$. The grains (particularly the coarse ones) are very round (Fig.45) and generally well sorted. Where the sands are bimodal, the individual modes are well sorted (Fig.45). The feldspar content is extremely low and out of 20 specimens in the lower Stairway of AP1 only one contained more than 1% feldspar. Heavy minerals are very rare or absent. Quartz cement is very common in many of the arenites. Six (out of 20) specimens have significant quantities of clayey matrix (see Table 1, appendix) and several specimens have carbonate cements. Phosphate and pyrite (as cement and discrete particles) are fairly common. Glauconite is present in 7 out of 20 specimens and forms 10 - 15% of the rock in one specimen (AP1/754/6.).

The upper orthoquartzites are generally unimodal, with a grain size of $3\emptyset$ to $4\emptyset$. The grains are angular to sub-angular and the sorting moderate. Chert is present in many of the specimens. The feldspar content is generally in the range 2 - 3%; the heavy mineral content is in the range 0 - 1%. Clay, carbonate, phosphate, pyrite and glauconite are either all absent or present in small quantities only.

The orthoquartzites of the phosphatic parts of the Stairway Sandstone (i.e. the middle Stairway and the uppermost transitional Stairway) are very fine grained sub-mature to immature orthoquartzites. Their grain size ranges from $1\emptyset$ to $4\emptyset$ and bimodality is fairly common. Grains are subangular and sorting is moderate. The feldspar content is in the range 1 - 2%. Clay, carbonates and phosphate are all

common.　Pyrite is comparatively common in the middle part of the Stairway Sandstone (1 - 2%) and is common in places in the uppermost transitional part of the Stairway Sandstone.

The considerable mineralogical variation within the orthoquartzite group is shown in Fig.6.　It is possible to divide the Stairway Sandstone mineralogically, into much the same three units which have been recognised in the field.

The siliceous cements are a very common feature of the Stairway Sandstone orthoquartzites, and the overgrowths are in optical continuity with the grains.　In places they may be replacing clay or carbonate cement (although the thin sections were not examined under a universal stage to confirm this), but generally there is little sign of replacement and the quartz appears to be pore filling.　The siliceous cement has been found to considerably limit porosities in the potential reservoir rocks of the StairwaySandstone and therefore it is important to know when silicification took place.　Considerable silicification of many of the Amadeus Basin sediments is thought to have occurred during the Tertiary era, but this is unlikely to be the cause of the Stairway Sandstone silicification, as the formation is found to be　just as strongly silicified at depths of several thousand feet as it is at the surface.　It appears that there are several likely causes of the silicification.　It is due to regional silicification during the Alice Springs Orogeny, or to sub aerial exposure and weathering of the Stairway Sandstones shortly after deposition or it is due to the environment of deposition or it is the result of post-deposition solution pressure.

There is little evidence of sub-aerial exposure of the sands -

such a thing may indeed have occurred but there are no clear diastems or faunal breaks as proof. The second alternative has more to commend it. It is known that waters with a high silica content are present in humid tropical areas (Krumbein and Garrells, 1952), and there is evidence that the climate during Stairway Sandstone times was in part tropical. The mineralogy of the Stairway Sandstone orthoquartzites suggests that they may be what Krynine (1941) calls "first-cycle orthoquartzites". Such rocks are acknowledged to be the product of intense chemical decay and destruction and the conditions producing this intense chemical weathering also gave extremely high concentrations of silica alkalis in the sea-water to produce the authigenic or early diagenic silicification. Such silicification is extremely common in many of the classic orthoquartzites (e.g. theGatesburg and Potsdam of North America). However if silicification occurred in response to the environment of deposition then it occurred in some cases as a later stage diagenesis for in places phosphatic overgrowths on quartz are themselves overgrown by silica.

The third alternative is the most widely accepted explanation for silica cementation. Solution of quartz will take place at a sufficiently high pressure, so that the silica is mobilized then later redeposited in some more favourable part of the sandstone. Heald (1956) found that there was no relationship between faulting and cementation but considered that pressure solution occurred during structural deformation or if there was sufficient overburden.

Siever (1959, 1962) agrees with Heald's conclusion and further asserts that it is impossible for the cementing silica to have come

from sea-water.   Heald and Anderegg (1960) found that interstitial argillaceous material may considerably inhibit cementation due to solution pressure resulting from deformation or overburden.   Towe (1962) maintains that considerable quantities of silica may be dissolved by the action of alkaline solutions obtained from the loss of potassium from illite.

A regional analysis of the variation in intergranular porosity in the Stairway Sandstone would establish the validity or otherwise of the post-depositional solution pressure theory.   If porosity was found to decrease from south to north then this would suggest the theory is correct though whether the silicification would be due to the Alice Springs Orogeny or the increase of overburden to the north cannot be established.

Conclusions:

The lack of recognisable reworked grains or chert suggests that the lower Stairway orthoquartzites have a granitic provenance (Folk, 1961).   However, the abundance of "common" (non-undulatory) quartz is considered by Blatt and Christie (1963) to be strong evidence of reworking of grains from a sedimentary source area.   Up to 10% chert in some of the upper orthoquartzites indicates that the provenance for the upper Stairway was definitely mixed - both granitic and sedimentary.

The lack of feldspar suggests that the source area was intensely weathered, i.e. a humid tropical climate.   Alternatively the sediments were subjected to very prolonged abrasion or are the product of reworked orthoquartzites.   The increase in feldspar content in the upper Stairway orthoquartzites suggests that the climate may have

become more arid than it was in lower Stairway Sandstone times.

The coarseness of the grains together with the high degree of rounding and sorting of the basal orthoquartzite compared with the higher orthoquartzites suggests a very much more vigourous depositional environment or one in which the rate of sedimentation was slow so that the "rounding mechanism" (probably a beach environment) was able to keep pace with sedimentation.

The presence of bimodality within the orthoquartzites suggests that mixing of sediments formed in environments of different energy levels has occurred. Folk (1961) suggests that this type of thing commonly occurs in the neritic zone when for instance the sand grains on a sand bar are blown into a lagoon and mixed with the finer sediments being deposited there.

b) Sub-arkose (5 - 25% Feldspar; 0 - 5% metamorphic rock fragment; 95 - 75% quartz).

Very few of the Stairway Sandstone arenites occur within the subarkose group. An example is AP1/122/11, which is a very fine grained siliceous immature subarkose.

The few subarkoses are in the very fine-grained sand range and are subangular and moderately to poorly sorted.

The quartz of the subarkose group is predominantly of the plutonic or undulose variety; there is however an indication that the percentage of chert is higher in the subarkose than in the orthoquartzite (see table 1, appendix). Heavy minerals are very minor and allochemical minerals (clays, carbonates etc.) are absent. The feldspar is predominantly microcline together with minor indeterminate feldspar. Generally the feldspar is finer grained than the quartz and in some

cases it is better rounded. The feldspar grains are fresh in all the slides inspected.

Conclusions:

The predominance of microcline suggests that the source area was plutonic. A fairly arid climate is suggested by the unweathered stage of the feldspar and by the degree of rounding relative to that of the quartz.

c) "Red Arenite" ("Red-beds")

The sediments of this group are very fine grained sandy or silty immature orthoquartzites but because of their distinctive red colour they are dealt with separately.

The grain size ranges from $3\emptyset$ to $5\emptyset$; the grains are angular and sorting is moderate to poor (Fig. 46, appendix). The quartz types are the normal assemblage for orthoquartzites. It is thought that within the "red arenites" the percentage of composite quartz and chert is slightly less than in adjacent non-red sediments. Feldspar is generally absent but rarely makes up 2% of the rock. Heavy minerals are present only in very minor amounts. Pyrite, glauconite, phosphate and carbonate are absent, but clay is always present forming 5 - 20% of the total rock. It is the ferruginous clay matrix which imparts the red colour to the sediments. Generally, quartz grains are not in contact and each grain is coated by red ?limonitic clay (Fig.47, appendix). There are however examples of quartz grains in contact with other quartz grains, and with no red matrix between them but with an overall red coating round the group of grains.

Observations made on the AP2 and AP3 cores further complicate the picture as in several places the "red-beds" have a markedly

gradational boundary with white sandstones. Therefore the possibility
of ancient circulating iron-rich ground waters cannot be ignored.
However the distinct areal distribution of the "red-beds" and their
presence at depth are contrary to this hypothesis.

Conclusions:

The source area was probably composed of both granitic and
sedimentary rocks. The form of the red matrix implies that the red
colour probably results from lateritic weathering in the source area.
There is however some evidence to suggest that part of the red-matrix
may result from a paralic type of depositional environment. The
poor rounding and sorting imply a very tranquil type of environment
such as a lagoon, or relatively short-lived transport from the source
area, or both.

Lutite

This term is applied to all terrigenous sediments which contain
50% or more of silt and/or clay.

(a) Siltstone

These do not differ markedly in mineralogy from the orthoquartzites
and may be considered as orthoquartzite-type siltstones. The only
differences are of grain size $(4\emptyset$ to $8\emptyset)$, the sub-angular form of the
grains, a slightly higher percentage of feldspar, and the very much
higher percentage of clay matrix in siltstone (Fig.48, appendix).
The detrital grains may also be less well sorted and rounded.

Conclusions:

There is no difference in provenance or climate between the
orthoquartzites and the siltstones. The lower textural maturity of
the siltstone is due to the environment of deposition being less

vigorous than that in which the orthoquartzites were deposited. The relatively high percentage of clay matrix suggests that the environment was either fairly deep neritic or lagoonal.

(b) Claystone

Claystones may form as much as 10 - 20% of the total thickness of the formation, but few thin sections were available for examination. 5 - 10% detrital quartz of very fine sand or silt size is commonly present in the claystone - the quartz types being the usual assemblage of plutonic (common) and undulose quartz with only very minor composite quartz and chert. Feldspar and heavy minerals are present in the claystones. Fine flakes of mica are common. Glauconite is absent and pyrite is rare. Phosphatic material varies from 0 to 5%. The percentage of carbonate is generally low, except in a few specimens. The carbonate (calcite, dolomite or siderite) may be authigenic. Fig.49 (appendix) is an example of a sideritic claystone, with patches of ?authigenic siderite about .05 mm. across. No clay minerals were positively identified from microscopic examination, but Crook (1964) has shown that the dominant clay mineral is illite (70 - 100%), with minor kaolinite (0 - 30%) and chlorite (0 - 12%).

Conclusions:

The sand and silt grains within the claystone indicate that the provenance was predominantly igneous or sedimentary and the climate humid tropical. This is supported by the presence of kaolin which is generally regarded as forming in areas of intense weathering. Chlorite may be indicative of a lagoonal or near-shore environment.

Present-day illite is most commonly found in an arid environment (Jackson, 1958). It is however of uncertain value as an environmental indicator as it is also formed by the transformation of montmorillonite. Hurley (1959) has also shown that much of the illite in Recent sediments has been obtained from the reworking of ancient sediments.

Carbonates

Calcite, and dolomite are known to occur as thin interbeds within the Stairway Sandstone but are not common. Siderite is only known in claystones (see Fig.49, appendix). Both the limestones and dolomites may contain significant amounts of terrigenous material. The quartz grains are generally in the size range very fine sand to coarse silt. The quartz is predominantly the usual plutonic and undulose varieties and is angular to sub-round and moderately sorted. Feldspar and heavy minerals form a very minor part of the terrigenous fraction, but clays may form from 0 - 20% of the rock. 1 - 2% of phosphate and pyrite are commonly present and the phosphate content may be as high as 10%. Glauconite is absent.

(a) Limestone

The limestones are mainly micrites and biomicrites but clayey micrites (e.g. AP1/184/0)and ?dismicrites (e.g. AP1/74/1) are known. The fossils which may form quite a high percentage of the biomicrite are predominantly brachiopods, gastropods and pelecypods. They are generally present as large fragments or whole fossils, with few signs of severe fragmentation. In places, it is clear that dolomite is replacing the calcite.

(b) Dolomite

Following the classification of Folk (1961) the dolomites range

from aphanocrystalline to coarsely crystalline dolomites. The name may in addition be qualified by one or other of the prefixes "clayey", "phosphatic" or "sandy". Some of the dolomite crystals show an extremely well developed rhombic form (Fig.50, appendix). Fossils are absent.

Conclusions:

It would appear that much of the dolomite has formed by the replacement of calcite - this is supported by the texture of the dolomites and by the lack of fossils (possibly destroyed during dolomitization). Some of the finer grained varieties may however be primary.

The mineralogical assemblage of the terrigenous material indicates the usual igneous or mixed provenance and humid tropical weathering.

The predominantly microcrystalline form of the calcite and the ?primary dolomite suggests that the rock was once a microcrystalline ooze, forming in a very quiet area. Folk (1961) considers that the four environments where this type of sedimentation occurs are in shallow protected lagoons; on broad shallow platforms to the lee-side of barriers; in moderately deep water in geosynclines; and in areas of organic baffling. The fossil content implies that the first or second suggestions are the more likely. The fact that the limestone beds are very thin and commonly alternate with arenites further suggests that the lagoonal environment is the most likely.

Summary

Three basic rock types are dealt with - quartz arenite, lutite, and carbonate (phosphorites are left until later). The arenites are predominantly super mature orthoquartzites, apart from some of those

of the middle Stairway which may be sub-mature to immature. The orthoquartzites are strongly silicified - perhaps due to early diagenesis but more probably due to late stage pressure solution. Arkoses are present but rare - they are generally fine grained and the feldspar is most commonly microcline. "Red-beds" are also known - they are red limonitic slightly clayey sandstones. The lutites are either "orthoquartzite-type" of siltstones, or claystones made up predominantly of illite with minor kaolinite and chlorite. The carbonates are limestones or dolomites, or rarely siderite.

The arenites suggest that the climate was tropical or subtropical but hot arid in part. There was possibly some lateritic weathering in the source area. The provenance is predominantly plutonic (granitic) or mixed granitic-sedimentary. There is strong evidence of reworking of sedimentary rocks during upper Stairway times. The quartz arenites may have been laid down under fairly vigorous conditions but the lutites and carbonates appear to have been laid down in a very quiet environment.

CHAPTER 3

HEAVY MINERAL STUDIES

General

The methodology of the heavy mineral studies is given in the appendix. Heavy mineral counts were made at regular intervals of AP1.
throughout the Stairway Sandstone/ In addition to the mineralogy it was also noted whether grains were rounded, angular or euhedral. The percentage of each heavy mineral was expressed as a percentage of the whole heavy mineral content. It was also initially intended to consider the variation of the total heavy mineral assemblage as a percentage of the whole rock but this proved impossible because of the high percentage of contaminating heavy authigenic minerals such as pyrite, dolomite and phosphate.

Results

The percentages of angular and euhedral grains proved to be so small in most cases (2% or less) that it was impossible to separate them out on the graphical presentation of the results (Fig.7).

In all, the presence of five heavy minerals was noted in the Stairway Sandstone - tourmaline, zircon, apatite, garnet and rutile - but of these only tourmaline and zircon are abundant. The other three minerals generally make up ohly 1 - 2% of the heavy mineral assemblage.

Tourmaline occurs as six distinct types - brown, green, blue, grey, pink and colourless. The brown and green forms are by far the commonest. Zircon occurs in three forms - clear, brown and purple, of which the clear and brown types are the commonest.

fig 7

VARIATION OF HEAVY MINERAL ASSEMBLAGE WITH DEPTH

MINERAL REFERENCE

A	Brown
B	Green
C	Blue
D	Grey
E	Pink
F	Colourless

TOURMALINE

G.	Colourless
H.	Brown
I.	Purple

ZIRCON

| J | | APATITE |

| K | | GARNET |

| L | | RUTILE |

Depth in Feet

Relative Percentages of Heavy Minerals

0%   100%

TO ACCOMPANY RECORD 1966/1

AUS 1/98
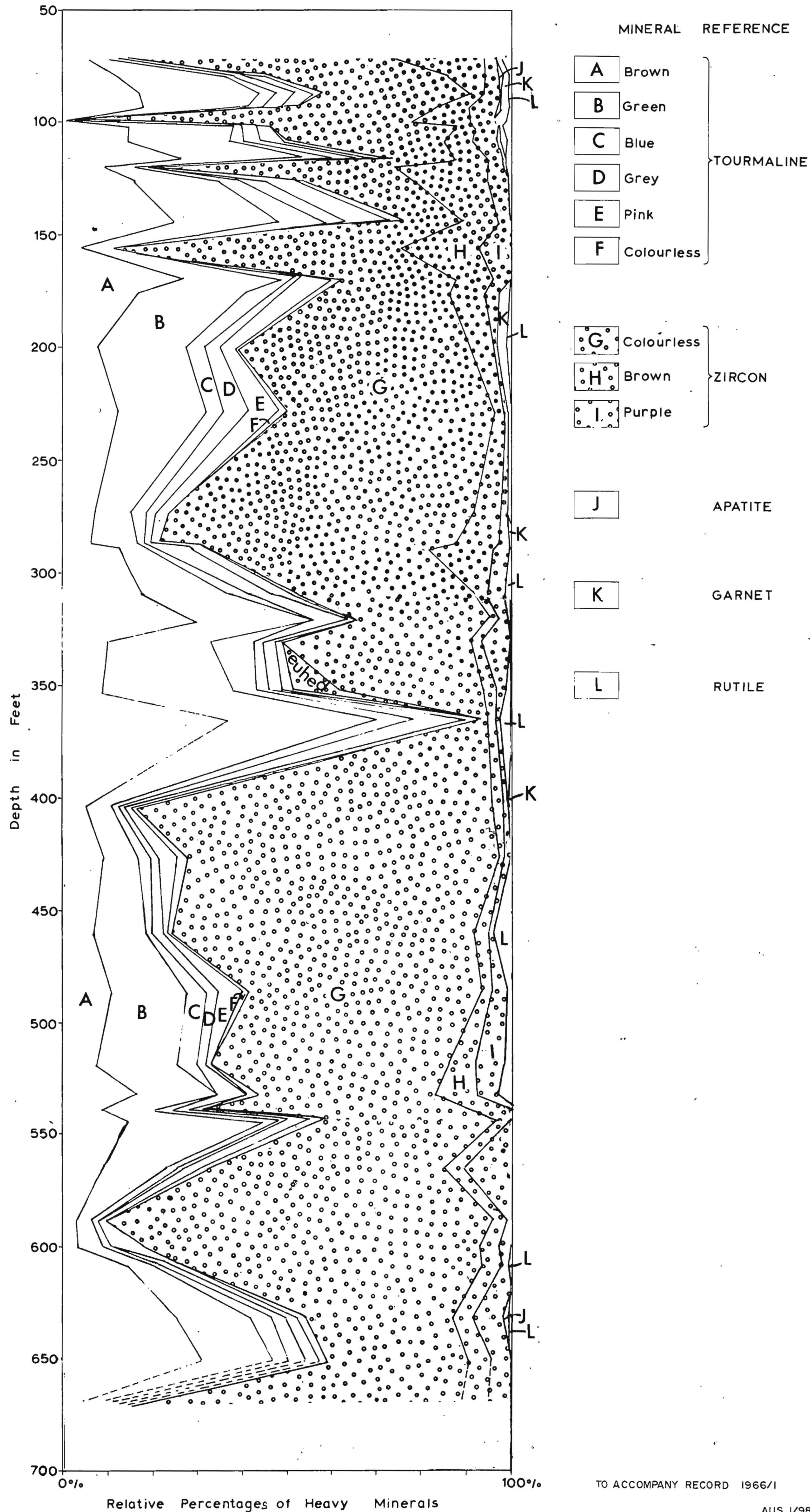
The vertical variation in the ratio of tourmaline to zircon is marked by extreme variations commonly occurring within a very small vertical distance (Fig.7). It was also observed that the diameter of the tourmaline is commonly twice or three times that of the zircon (Fig.51, appendix) - a reflection on the differing hydraulic properties of the two minerals (tourmaline is tabular) and the specific gravities (tourmaline is 3.1, zircon is 4.5). Both tourmaline and zircon show an extremely well rounded habit throughout (Figs.52-53, appendix). Authigenic tourmaline and zircon forming as overgrowths on detrital grains have been previously described (Krynine, 1946; Awasthi, 1961) and one or two such overgrowths were noted in the Stairway Sandstone (e.g. spec. AP1/640/0). Many of the tourmaline and zircon grains contained a variety of inclusions, but no quantitative study of the inclusions was undertaken.

Interpretation of the heavy mineral data

The extremely high degree of rounding shown by the heavy mineral grains is a feature commonly shown by super-mature orthoquartzites and suggests either extreme prolonged abrasion (and/or chemical action) of an acid igneous source area or reworking of older sedimentary rocks. However, the occurrence of extremely well developed euhedral zircon, together with extremely well rounded zircon at about 350 feet in AP1 (see Fig.7) can only be satisfactorily explained by having a mixed provenance with the euhedral grains being derived from a primary plutonic (?granitic) source area and the well rounded grains being derived from sedimentary rocks (probably sandstones).

The considerable vertical variation shown in the tourmaline: zircon ratio together with the extremely restricted nature of the

fig 8

Graph to illustrate the lack of correlation between modal grain size and heavy minerals
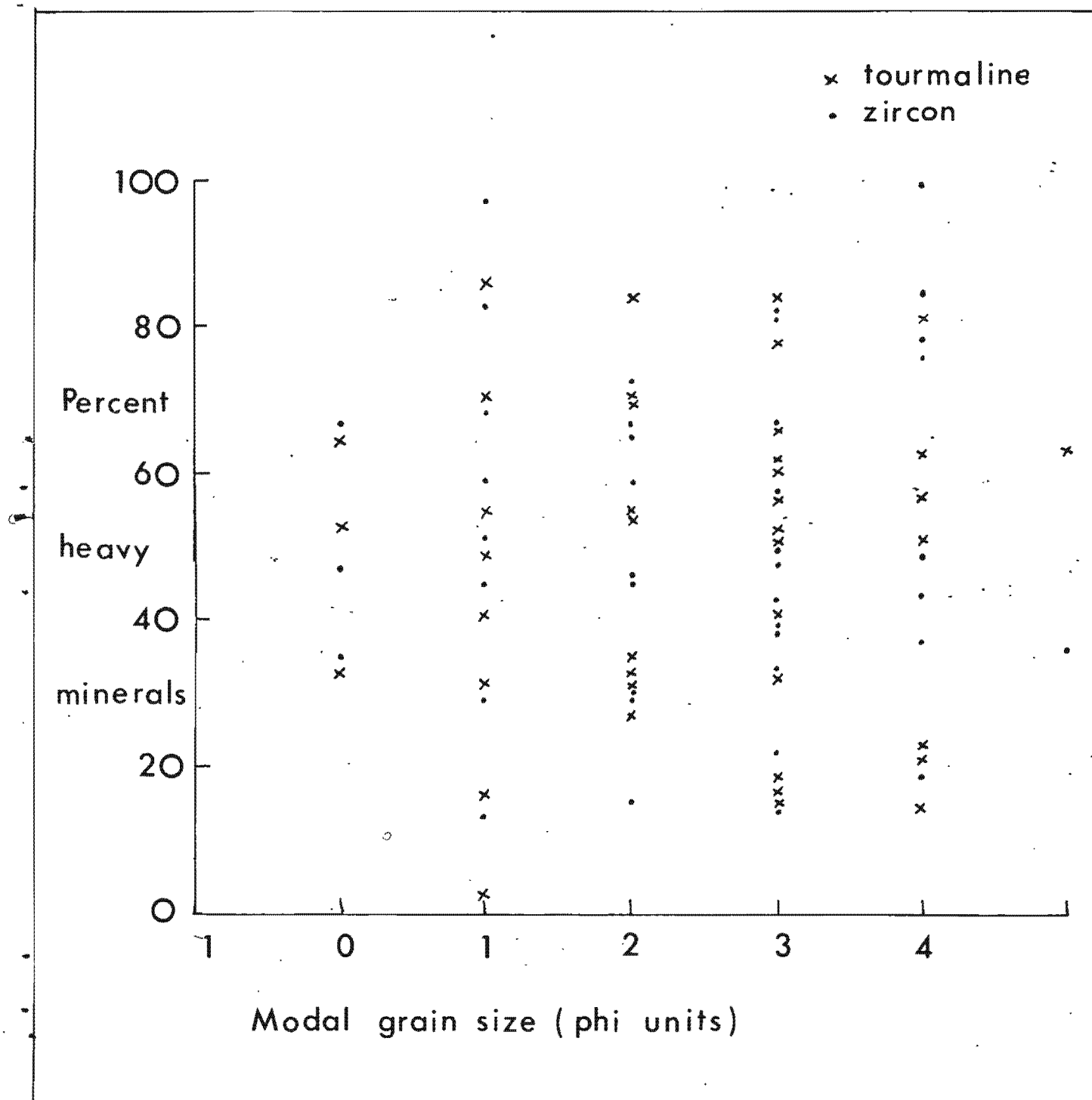
heavy mineral assemblage make it unlikely that heavy mineral studies will be of any great value for correlation purposes within the Stairway Sandstone. The form of the tourmaline:zircon graph (Fig.7) may be of some value in environmental interpretation however. R.L.Folk (pers.comm.) has suggested that the type of variation in the tourmaline and zircon percentages shown by the Stairway Sandstone is commonly a reflection of the dependency of the heavy minerals on grain size, i.e. a plot of modal grain size of the whole rock against percentage of tourmaline or zircon gives a straight line relationship. This however has been found not to be the case in the Stairway Sandstone and there is no correlation between grain size and the tourmaline:zircon ratio (Fig.8). The variation is therefore probably dependent on one or more of the following factors:- (i) a change in the source area - perhaps merely by a slight change in the river drainage pattern; climatic changes which will selectively remove one or other of the heavy minerals: (ii) progressive erosion of successive layers of rocks, some of which are rich in tourmaline whilst others are rich in zircon: (iii) the heavy mineral assemblage may be related to the strand line position so that any variation is a reflection of a transgression or regression. Bruckner and Morgan (1964) found that the distribution of heavy minerals on the inner part of the West African continental shelf is related to their specific gravity (and also presumably to their hydraulic behaviour). Regression or transgression in this area would result in laterally adjacent heavy mineral assemblages becoming also vertically adjacent. This could have happened during Stairway Sandstone sedimentation. Because of the relative paucity of heavy mineral determinations, it is not

possible to substantiate this hypothesis for Fig.7 cannot be compared with Fig.26 to see if there is any correlation between regression transgression and tourmaline/zircon. Such a comparison would only be possible by carrying out heavy mineral counts for each of the sedimentation units.

There is however a striking similarity between the form of the heavy mineral plot (Fig.7) and the plot of the vertical distribution of the number of sedimentation units per ten feet (Fig.23). This similarity may be a reflection of the environmental sensitivity of the heavy mineral assemblage.

Summary

The Stairway Sandstone has a typical supermature heavy mineral assemblage made up predominantly of well rounded tourmaline and zircon. The heavy mineral studies are of little value for correlation purposes but they do suggest the weathering of a mixed plutonic-sedimentary source area. The relative proportions of tourmaline and zircon may be dependant on a variety of factors but it is suggested that the position of the strand line may be the most important single factor.

CHAPTER 4

DETAILED TEXTURAL ANALYSES

General

Eighteen detailed textural analyses of 12 thin sections from
AP1 were carried out using Packham's (1955) method. The various
percentiles ($\emptyset_{95}$, $\emptyset_{84}$, etc.) were obtained and the values for
mean diameter (Mz), standard deviation ($d_.$), skewness (sk_1) and
kurtosis (K_g) calculated by the method of Folk and Ward (1957).
Details of the method are given in the appendix. The percentiles
and the textural parameters are tabulated in Tables 2 to 4 (appendix).
Some analyses (those on AP1/51/2, AP1/112/70, AP1/601/0 and AP/755/0)
were made as part of the investigations into the origin of phosphorites
and these analyses are discussed in more detail in the chapter on
phosphorites.

The cumulative frequency curves (plotted on probability paper)
for the 18 analyses are shown in Fig.9. There are three main
textural groupings: the group on the extreme left of the graph
(i.e. the very coarse grained end) is composed of counts of
phosphatic pellets, with the exception of AP1/648/6 (a coarse sand
which occurs near the top of the lower Stairway). The middle group
of sediments comprises mainly the coarse basal sands plus the coarse
sands associated with phosphorites. The group on the extreme right
of the graph (the fine end) is made up of fine and very fine grained
upper Stairway sands, very fine grained middle Stairway sands and
fine and very fine grained sand within phosphatic pellets.

The discussion on the significance of the textures is here for
the most part limited to the non-phosphatic sediments. The shape

CUMULATIVE FREQUENCY CURVES

Fig 9

grain size (phi)

cumulative percent
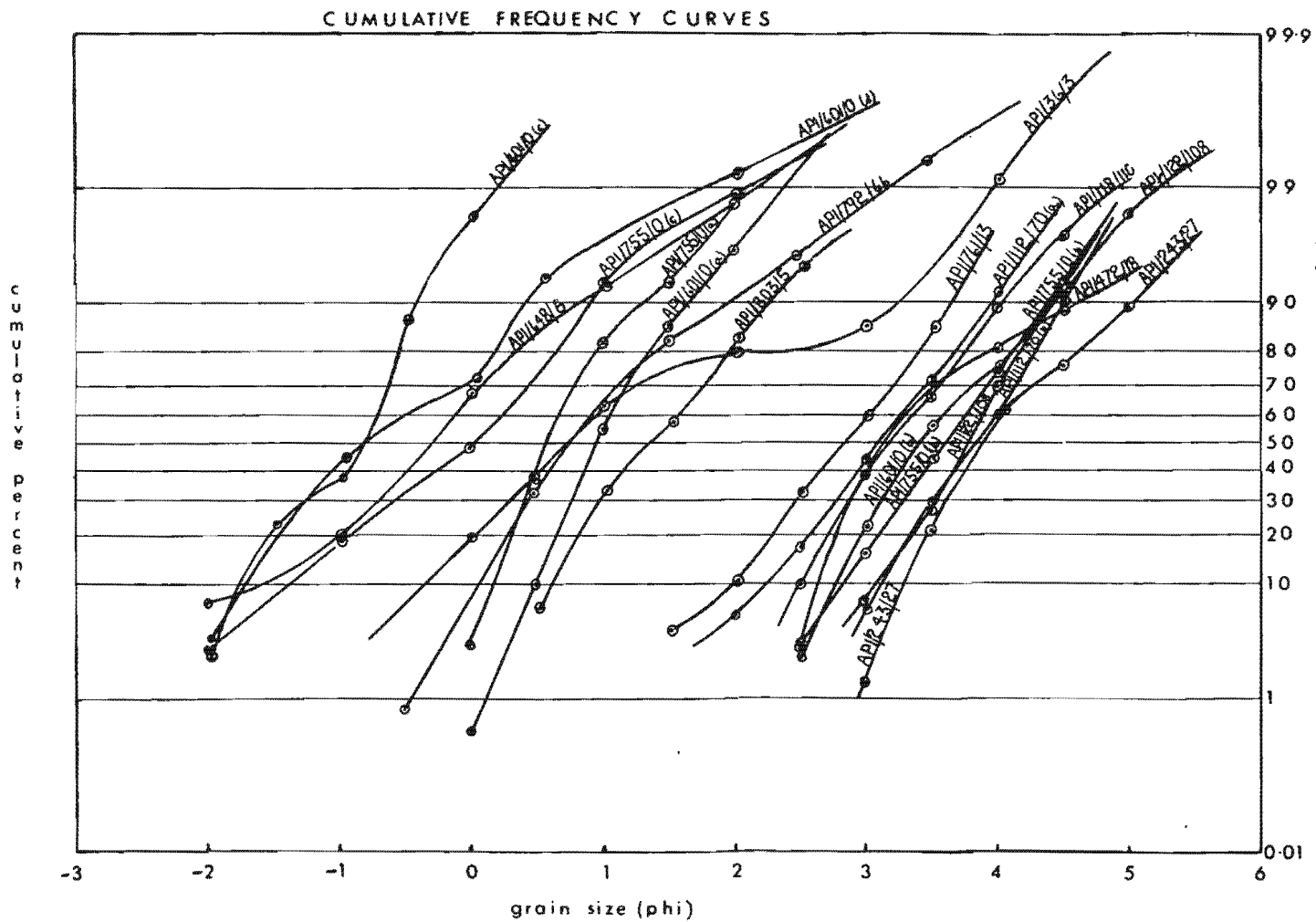
of the curves may be to some extent environmentally significant.
Doeglas (1946) suggests that there are 3 basic shapes of cumulative
frequency curves which are diagnostic of the environment but as his
plots are arithmetic the shapes of the curves cannot be compared with
those in Fig.9, which is a logarithmic plot.   It is therefore necessary
to look at the actual values of the parameters (see Table 3) as
calculated by the equations suggested by Folk and Ward (1957).

Mean diameter (Mz)

$$Mz = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3}$$

Both the mean and median diameters of the lower Stairway sands
are in the very coarse sand range, whilst the middle and upper
Stairway sands are in the very fine sand range. This suggests that
very much more vigorous conditions prevailed in lower Stairway times
than was the case in middle or upper Stairway times.

Standard Deviation (d_1)

$$d_1 = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6}$$

Standard deviation is a measure of the sorting of a sediment.
The results obtained for the Stairway Sandstone vary from $d_1 = 0.54\phi$
to $d_1 = 0.99\phi$ and indicate that all the sands fall into the moderately
to moderately well sorted range of Folk and Ward (1957).   There
appears to be a tendency for the finer sands to be slightly better
sorted than the coarser sands.   The most poorly sorted specimen
(AP1/648/6) occurs near the top of the lower Stairway.   Friedman
(1962) has shown that the environment of deposition of moderately
sorted coarse sand may be river, beach or continental shelf and

that the environment of deposition of moderately well sorted very fine sands may be river, beach, lagoon or continental shelf below wave base.

Skewness (Sk_1)

$$Sk_1 = \frac{\phi_{16} + \phi_{84} - 2\phi_{50}}{2(\phi_{84} - \phi_{16})} + \frac{\phi_5 + \phi_{95} - 2\phi_{50}}{2(\phi_{95} - \phi_5)}$$

Skewness is an indication of the assymmetry of curve and therefore also of the "tails" of the curve. The sands have a range in skewness of -0.05 to +0.47. The coarse basal sands have near symmetrical skewness (with the exception of AP1/792/66 which is fine skewed). The very fine sands of the upper Stairway are also near symmetrical but the sands of the middle Stairway are strongly fine skewed.

The fact that most of the sands are near symmetrical implies that the environment in which they were deposited and acquired their textural characteristics was not later modified by winnowing or other processes, i.e. the textures were in effect acquired in situ. The strongly fine skewed sands in the middle Stairway suggest that some mixing of environments may have occurred to produce a bimodal sediment.

Kurtosis (Kg)

$$Kg = \frac{\phi_{95} - \phi_5}{2.44(\phi_{75} - \phi_{25})}$$

Folk (1961) states that most sediments have kurtosis values in the range 0.85 to 1.4. It is found that the range of the Stairway sands is 0.90 to 1.33. Most of the sands are mesokurtic. The lower sands range from platy-kurtic to leptokurtic; the middle and upper sands are mesokurtic or leptokurtic. The mesokurtic form

fig 10A

fig 10B

SKEWNESS

STANDARD DEVIATION

KURTOSIS
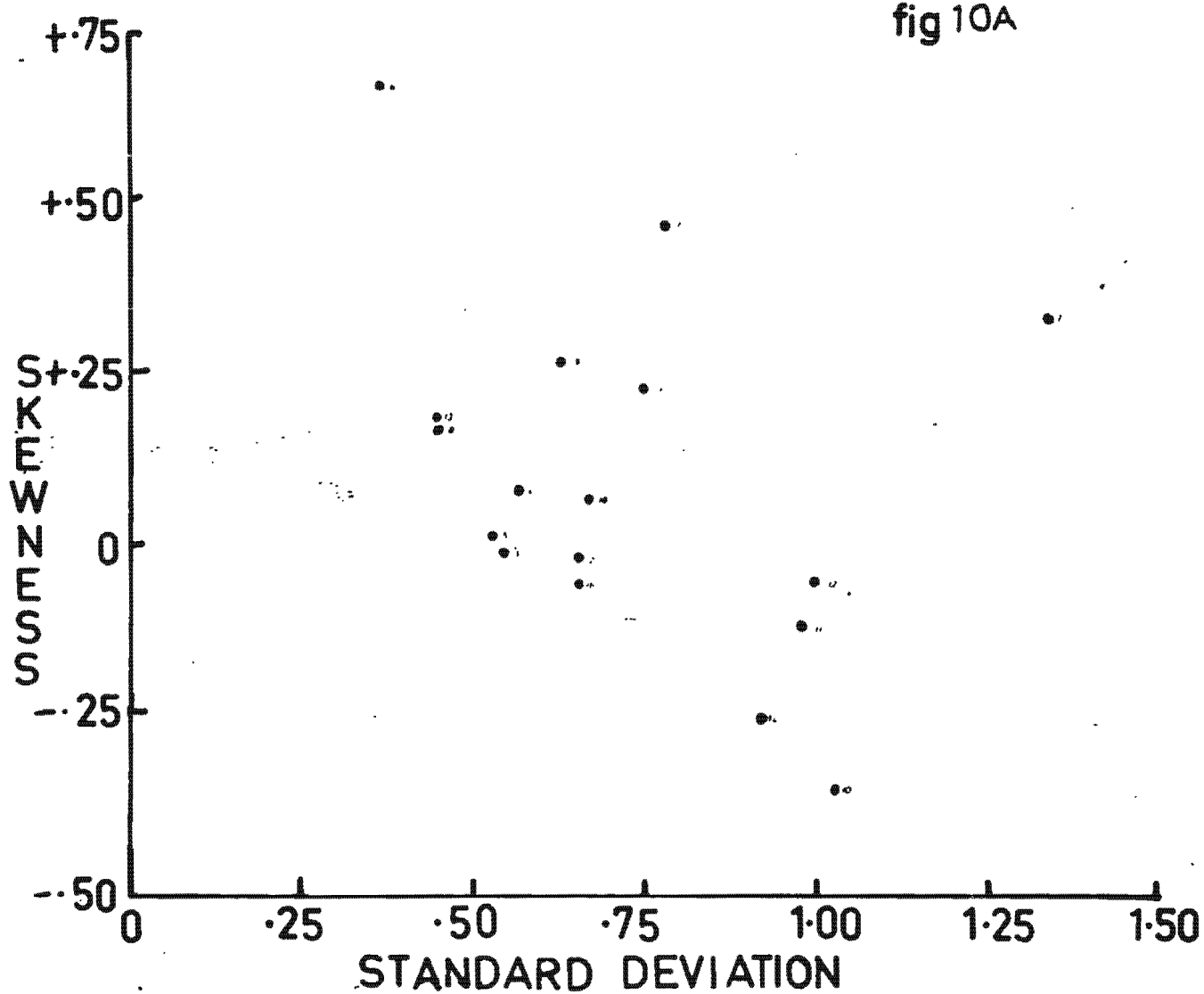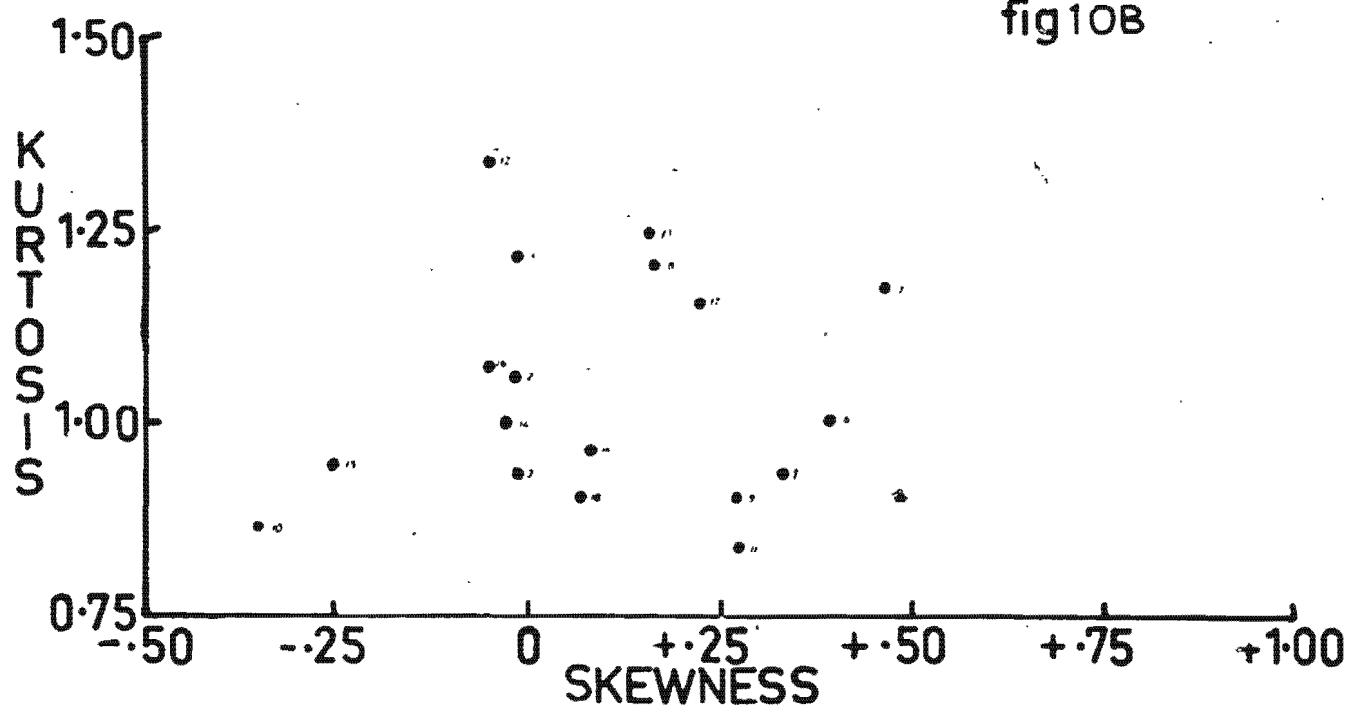
SKEWNESS

of many of the sediments supports the conclusion already obtained
from the skewness that the sediments acquired their textures in
the environment in which they were finally deposited. The textures
were not inherited from an earlier environment (as appears to be
the case with some of the sands associated with the phosphorites).
The strongly fine skewed - leptokurtic combination shown by
AP1/472/18 suggests that the coarser sands in this specimen
acquired their sorting in a slightly higher energy environment
than the one in which they are now found.   However, the lack of
any extreme skewness or kurtosis values in the Stairway Sandstone
suggests that any mixing has occurred between similar environments
(and probably geographically adjacent environments). Such mixing
as has occurred has been the result of coarse high energy sediments
being brought into a finer grained lower energy environment.   There
is no evidence of the reverse having occurred. Winnowing might have
produced some of the leptokurtic values.

Determination of environment from the textural parameters

Mason and Folk (1958) have shown that it is possible to
distinguish between beach and dune environments by plotting
skewness against kurtosis.   Friedman (1962) distinguished between
beach and river sands by using a plot of standard deviation against
skewness.

Both of these plots were applied to the Stairway Sandstone
(Fig.10)[x] but in neither case can any environmental significance
be ascertained.   There appears to be no obvious grouping of
[x] The points on the plots are identified by the numbers 1 to
18. The specimen number equivalents are given in Tables
2 - 3 (appendix).

fig IIA

fig IIB

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AUS 1/102.
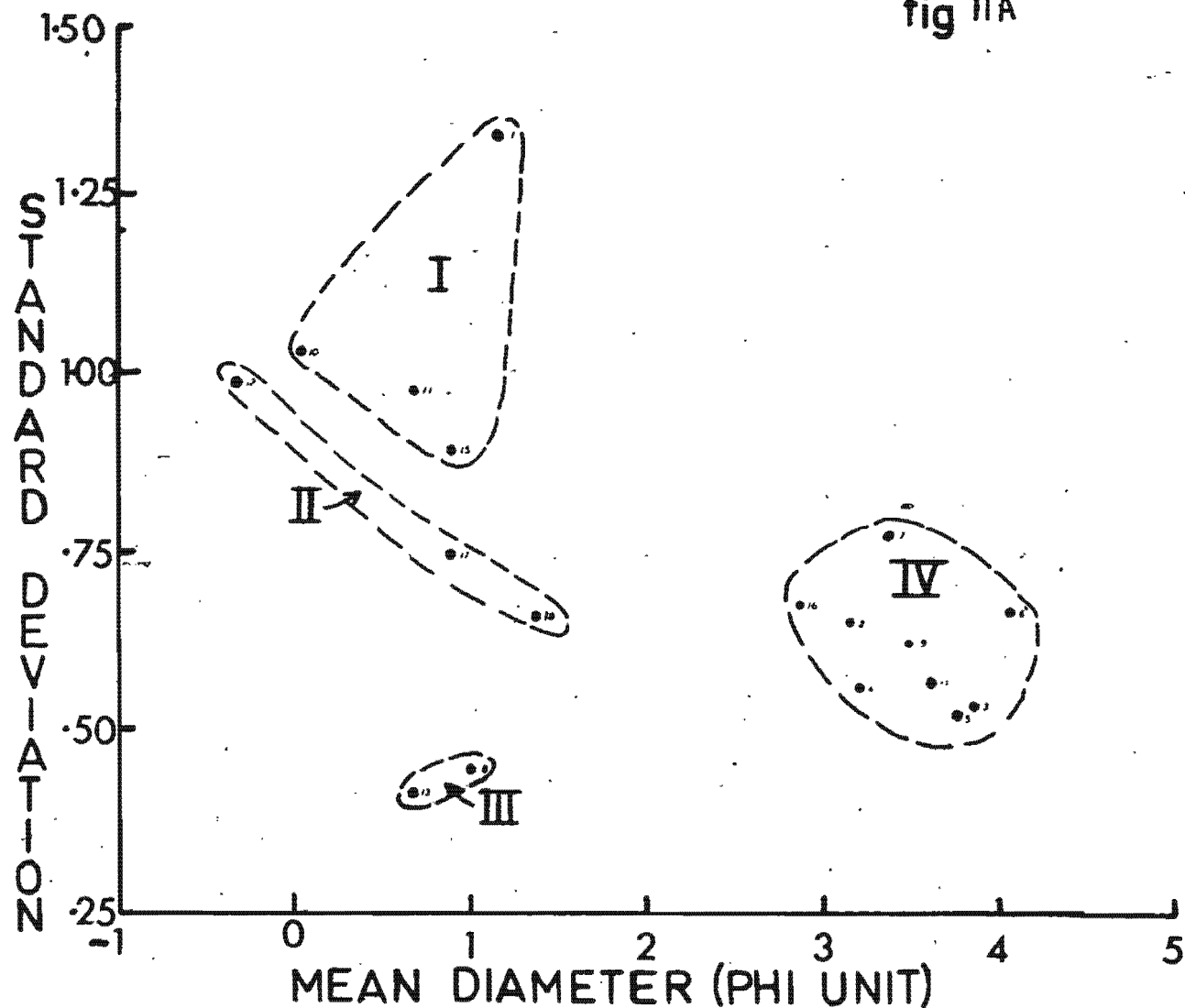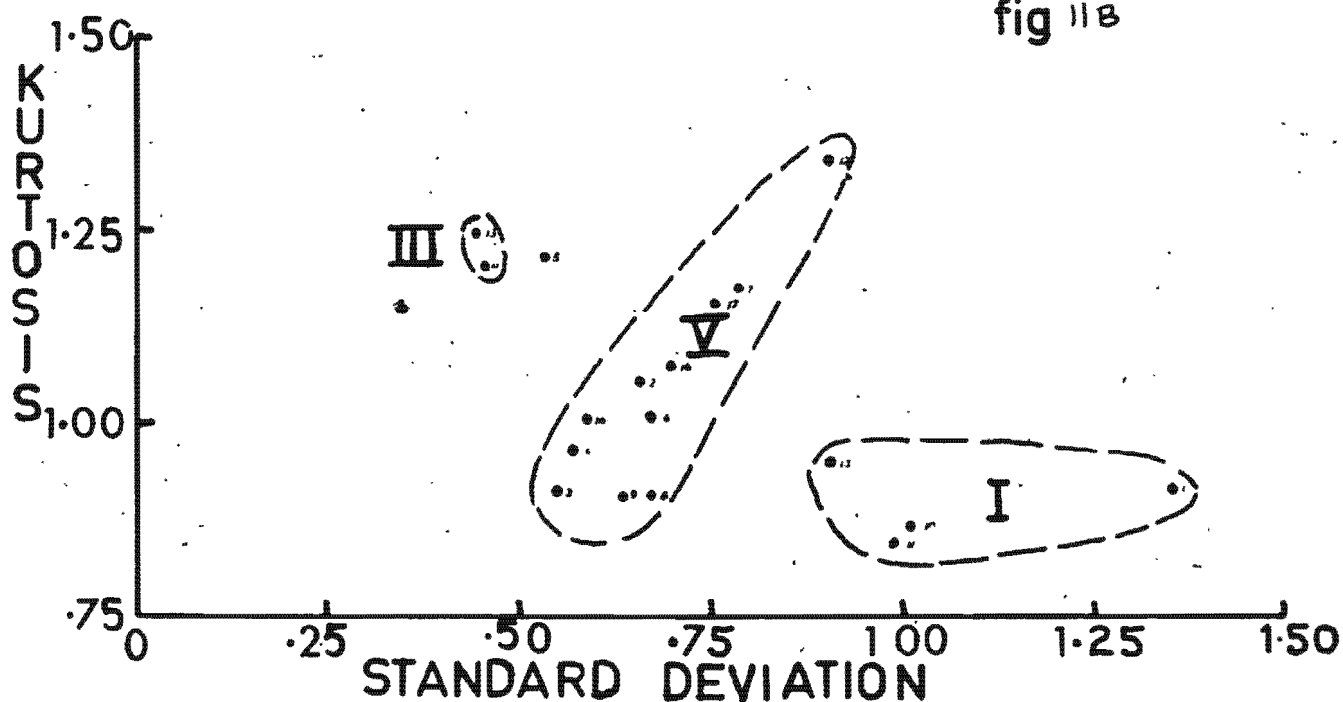
points according to stratigraphic position, presence or absence of phosphate, or grain size. No pre-existing plots are known to the author which distinguish between two or more shallow marine environments by size analysis and which could be used for the Stairway Sandstone. However, a definite separation of points is achieved by plotting standard deviation against kurtosis (Fig.11B) and standard deviation against mean diameter (Fig.11A). Two fields (I and III) are common to both plots but Fields II and IV are unique to the standard deviation-mean diameter plot and Field V is unique to the standard deviation-kurtosis plot.

Standard deviation against kurtosis produced a 3-field separation (Fig.11B). Field I is the field of phosphatic pellets (both pellets counted alone and pellets plus detrital quartz). Field III is the field of coarse grained sands associated with but outside the phosphatic pellets. Field V is the field of non phosphatic sands plus the very fine sands found within phosphatic pellets.

The implication of this is that fairly similar environmental processes produce the non-phosphatic sediments, but that the processes producing the textures of the phosphatic pellets, and the coarse sands associated with the pellets are rather dissimilar. The position of Field V between Fields I and III may be significant. It may indicate that the textures of Fields I and III were produced by modification of Field V by for instance winnowing or reworking.

Standard deviation against mean diameter gives a 4-field separation. Field I is again the field of phosphatic pellets (both with and without detrital quartz) and III the field of

coarse sands in phosphatic sediments but outside the actual pellets. Field II is the field of the coarse sands of the lower Stairway and Field IV is the field of the very fine sands of the middle and upper Stairway and the very fine sands within the phosphatic pellets. Therefore whilst it is apparent from Field I that the coarse and fine sands are produced in much the same environment it is also evident from the existence of Fields II and IV that two different processes are acting within the same basic environment to produce the coarse and fine sands. Field IV appears to be the environmental field in which the phosphate is precipitated but the field is modified (either by transport or winnowing) to produce Field 1, the environment in which the phosphate pellets are concentrated. This is discussed in more detail later (Chapter 8).

Sahu (1964) has introduced the use of the discriminant function (Yu) into the determination of the depositional environment. Working with both ancient and recent sediments, Sahu has found that by substituting the Folk and Ward (1957) parameters into various equations it is possible to distinguish between aeolian, beach, shallow water marine, (down to depths of 300 feet), fluviatile and turbidity current environments.

To distinguish between beach and aeolian the equation used is:

(1) $Yu = 3.5688 (Mz) + 3.7016 (d_1^2) - 2.0766 (Sk_1) + 3.1135(K_g)$

for beach $Yu = -3.9073 \pm 0.519$

for aeolian $Yu = -1.7824 \pm 1.397$

Yu is less than -2.7411 for an aeolian environment and greater than -2.7411 for a beach environment.

To distinguish between beach and shallow water marine the equation used is:-

(2) $Yu = 15.6534 (Mz) + 65.7091 (d_1{}^2) + 18.1071 (Sk_1) + 18.5043 (K_g)$

for beach $Yu = 51.9536 \pm 4.869$

for shallow water marine $Y = 104.7536 \pm 14.300$

In addition, values for Yu above 65.3650 indicate a shallow water marine environment and below 65.3650, a beach environment.

To distinguish between shallow water marine and fluviatile:-

(3) $Yu = 0.2852 (Mz) - 8.7604 (d_1{}^2) - 4.8932 (Sk_1) + 0.0482 (K_g)$

for shallow water marine $Yu = -5.3167 \pm 2.190$

for fluvatile $Yu = 10.4418 \pm 3.149$

Values of Yu greater than -7.4190 indicate a shallow marine environment and values less than -7.4190 indicate a fluvial environment.

To distinguish between fluviatile and turbidity current, the equation used is:-

(4) $Yu = 0.7215 (Mz) - 0.4030 (d_1{}^2) + 6.7322 (Sk_1) + 5.2972 (K_g)$

for fluvatile $Yu = 10.7115 \pm 1.197$

for turbidity current $Yu = 7.9791 \pm 2.570$

Yu less than 9.8433 indicates turbidity current deposition and Yu greater than 9.8433 indicates fluvial deposition.

On substituting results from the Stairway Sandstone into these equations, it was found that all the sediments fell into the shallow water marine field, the beach field or the fluviatile field.   In addition, almost every sediment fell into the turbidity current field on substituting in equation 4.   As this is inconsistent with every other feature of the Stairway Sandstone, it must be concluded that

either the Stairway Sandstone is an exception to t he rule, or equation 4 is incorrect. Therefore, only substitutions in equations 1, 2 and 3 are regarded as being significant. The values obtained for Yu in Stairway Sandstone sediments and the environmental significance of the values, are given in Table 5 (appendix).

The majority of non-phosphatic sediments give values consistent with a shallow marine origin - this is particularly true for the very fine grained sands. One of the coarse basal sands (AP1/803/5) falls into both the shallow water marine field and the beach field and AP1/648/6 has a Yu value which indicates a fluviatile environment (the coarse sands associated with phosphatic sediments give Yu values for beach). Thus it is apparent that the coarse basal sands have some beach, shallow water marine (down to depths of 300 feet), and fluviatile characteristics. The fine sands of the middle and upper Stairway (and the fine sands within phosphatic pellets) exhibit shallow water marine characteristics only.

Summary

There are two main classes of sands - coarse sands and very fine sands.

The coarse sands occur in the lower Stairway Sandstone and are mainly moderately sorted, near symmetrical mesokurtic sands. The environment in which these sands were deposited and acquired their textures has undergone little or no subsequent modification. By combining the conclusions reached from Mason and Folk (1958), Friedman (1962) and Sahu (1964) it is apparent that the coarse sands

were probably deposited on a beach or shallow water marine environment with a few rare coarse sands being subjected to some fluviatile (or perhaps tidal channel) influence.

The fine sands of the middle Stairway are moderately or moderately well sorted, strongly fine skewed lepto-mesokurtic sands. This suggests that a mixing of sediments from two or more environments has occurred. Such a mixing commonly occurs in a lagoonal or bay environment.

The fine sands of the upper Stairway Sandstone are moderately well sorted, near symmetrical mesokurtic sands. There is no suggestion of any mixing of environments. The most likely environment for the fine sediments is shallow water marine lagoonal or shelf.

There are no major environment changes apparent between the coarse and the fine sediments - they represent 2 or 3 facets or microenvironments of the same overall macro-environment.

PLATE 12

ISOPACHOUS MAP WITH
PALEOCURRENT DIRECTIONS

STAIRWAY SANDSTONE
AMADEUS BASIN
CENTRAL AUSTRALIA

REFERENCE

Superficial mesozoic sediments

Western limit of removal of
Stairway Sandstone below the
Mereenie unconformity

Igneous and metamorphic rocks
and metasediments

——500—— Isopach (original thickness)

——400—— Isopach (original thickness-
data poor)

——300—— Isopach (inferred original thickness)

Current rose indicating the paleocurrent
directions. Figure gives the total
number of readings at each locality

Current rose scale
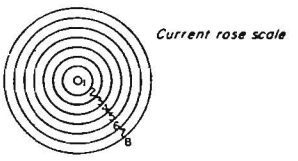
Mean current direction

LOCALITY MAP

Alice Springs

Lake Neale

Lake Amadeus

Palmer River

Finke River

Hugh River

Finke River

Scale
16   8   0   16   32 miles

AUS 1/103

To accompany Record no 1966/1
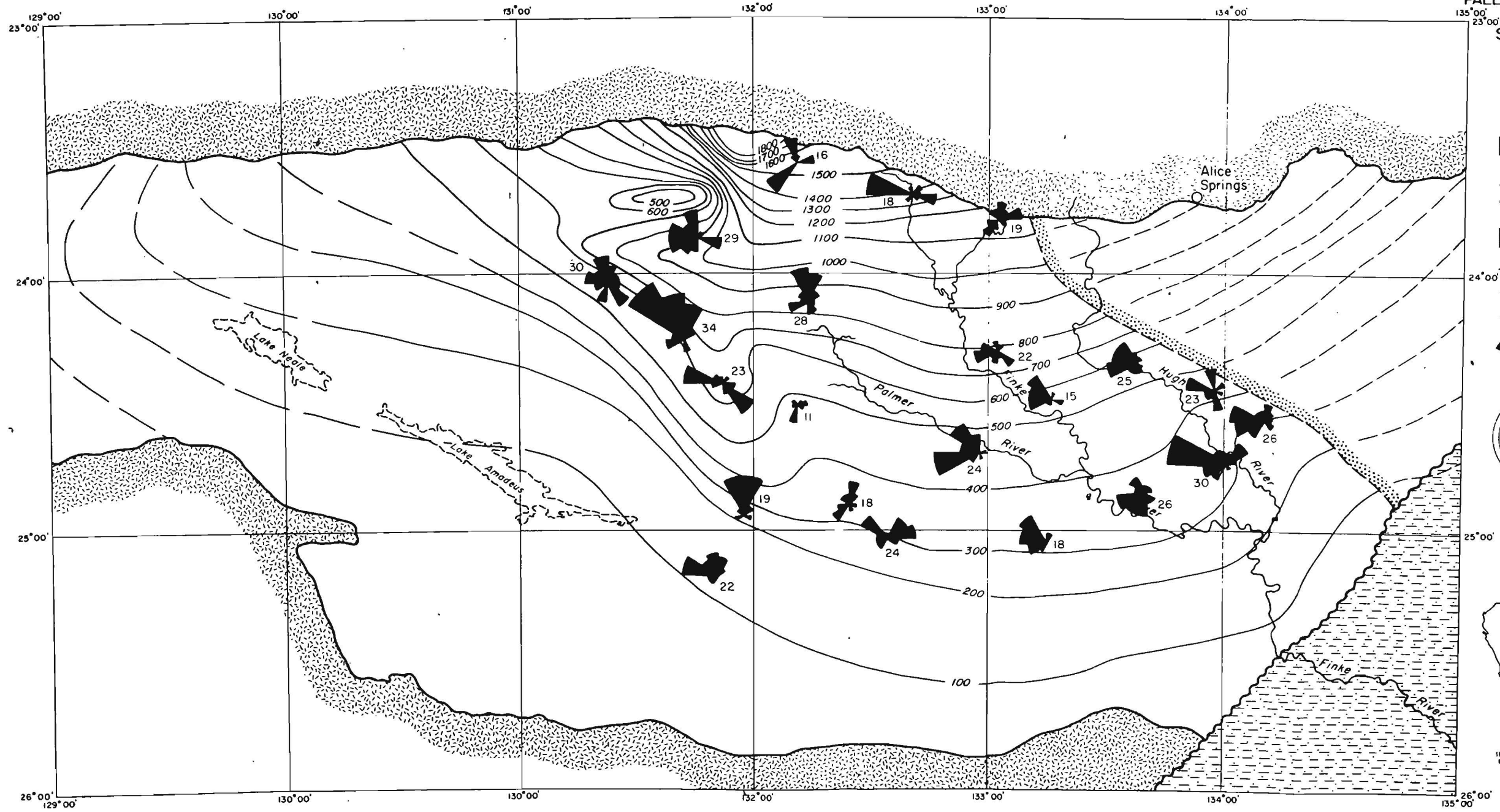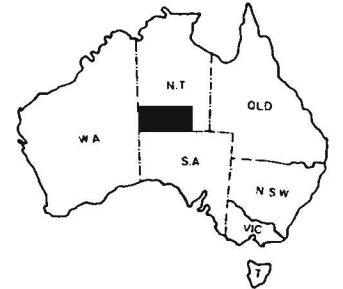
CHAPTER 5

PALAEOCURRENT AND RELATED BASINAL STUDIES IN THE STAIRWAY SANDSTONE

General

In order to understand fully the implications of palaeocurrent directions obtained from a study of cross-bedding, it is also necessary to consider maps of other current-induced properties of the Stairway Sandstone. Isopachous and lithofacies maps are particularly relevant; iso-set and iso-angle maps are also considered to be of value.

Isopach studies

The isopachous map on the whole of the Stairway Sandstone (Fig.12) shows a considerable thickening of the formation to the north with a marked cut-off on the Western Macdonnell Ranges (due to the Alice Springs Orogeny). In the eastern side of the basin, the formation has been removed by erosion subsequent to the pre-Mereenie Sandstone uplift, so that data is not now available from a considerable portion of the area in which the Stairway Sandstone was originally deposited.

It is impossible to derive the precise form of the Stairway Sandstone palaeoslope directly, but it is a reasonable assumption that the isopachs reflect approximately the palaeoslope. It therefore follows that the deepest Stairway Sandstone seas lie in the northern part of the basin. However, it is not impossible that the thick section in the north may also reflect a more rapid rate of subsidence.

Fig.13A shows the limits of the maximum extensions of the

Map showing successive limits of
Stairway sedimentation

Fig.13

A
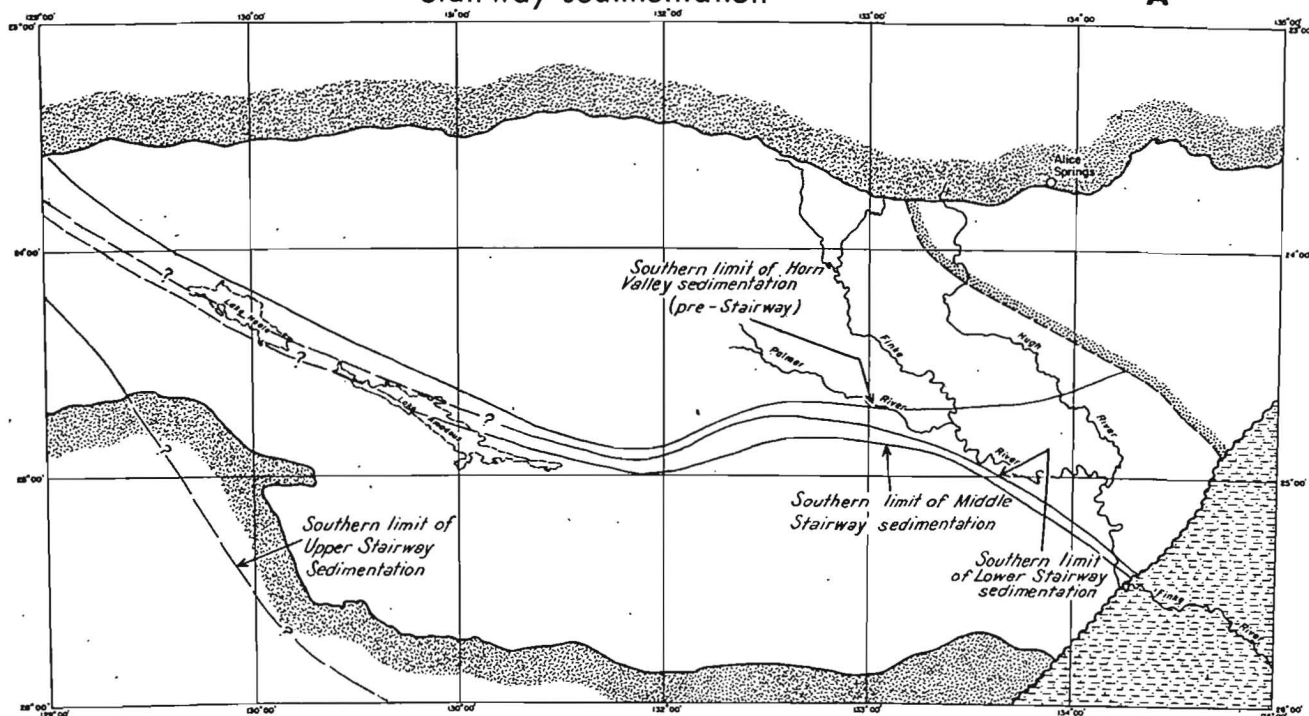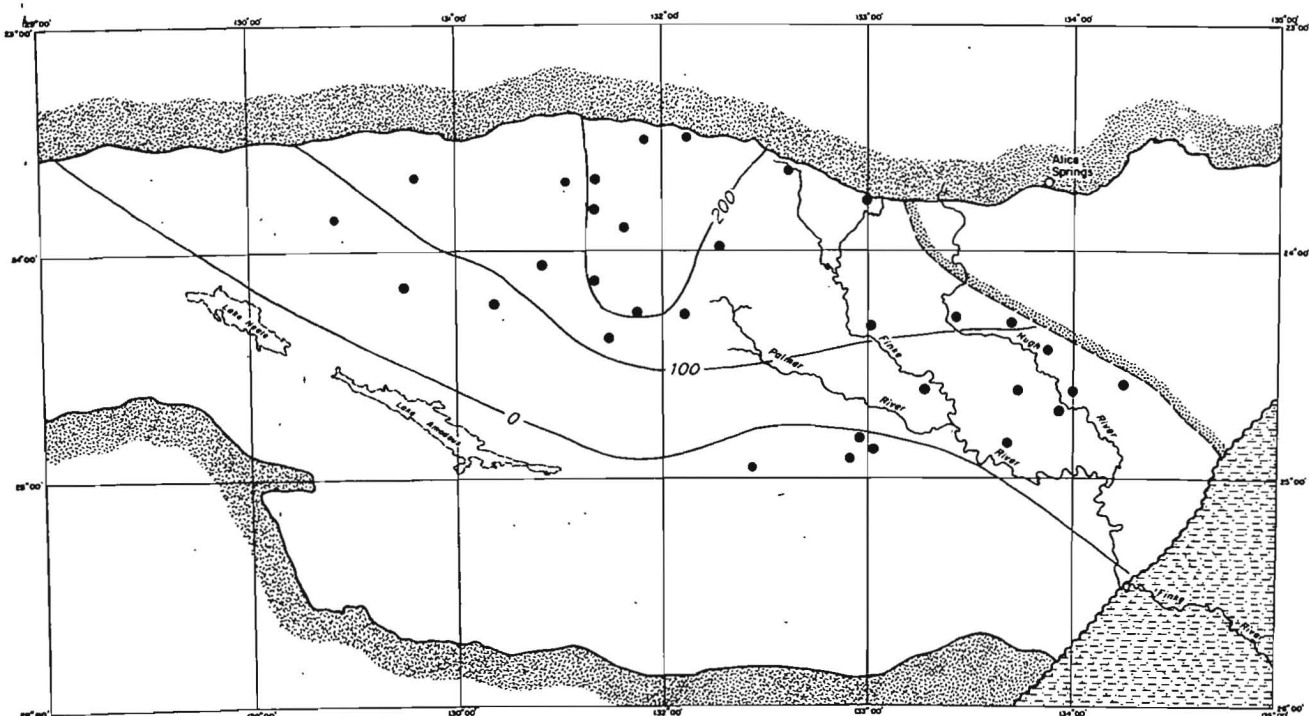
Isopachous map— Lower Stairway Sandstone

B

LOCALITY MAP

SCALE

16 8 0   16   32   48
MILES

Reference

Superficial mesozoic sediments

Western limit of removal of Stairway
Sandstone below the Mereenie unconformity

Igneous and metamorphic
rocks and metasediments

Isopach– thickness in feet

Locality with measured
thickness

To accompany Records 1966/1

AUS1/104

lower middle and upper Stairway seas and indicates that the
lower and middle seas were fairly restricted whereas the upper
Stairway sea was extremely widespread.

It is apparent from the lower Stairway isopachous map
(Fig.13B) that following the deposition of the Horn Valley Siltstone,
a large shallow embayment formed in the south-east part of the basin.
The extremely uniform thicknesses of the lower Stairway suggests
that the palaeoslope was probably extremely gentle and that the
lower sand body was of the "blanket" type with very uniform
conditions prevailing over a wide area.   The palaeoslope was at
the most (not allowing for differential subsidence) 1 foot per
mile and was probably considerably less (if subsidence is allowed
for).   These gradients are in the order of slopes found in ancient
epeiric seas (Shaw, 1964).

The isopachous map on the middle Stairway (Fig.14A) shows
a more complicated picture, with the suggestion of some sort of
stratigraphic thinning along a fairly definite line north through
the Seymour Range and the Chandler Range and then along a more
conjectural north-west line through the northern part of the James
Range.   Whether this thinning is merely due to non-deposition or
the development of a topographic high is uncertain.   This line
of thinning effectively divides up the Amadeus Basin into a
western basin with a fairly thick sequence of sediments and with
no evidence of restriction to the open sea;   a north-eastern
area in which there is also a considerable thickness of sediments;
and also a south-easterly embayment with a very thin sequence of
sediments.   The relation of the rock types to these sub-basins

Isopachous map — Middle Stairway Sandstone

Fig.14

A
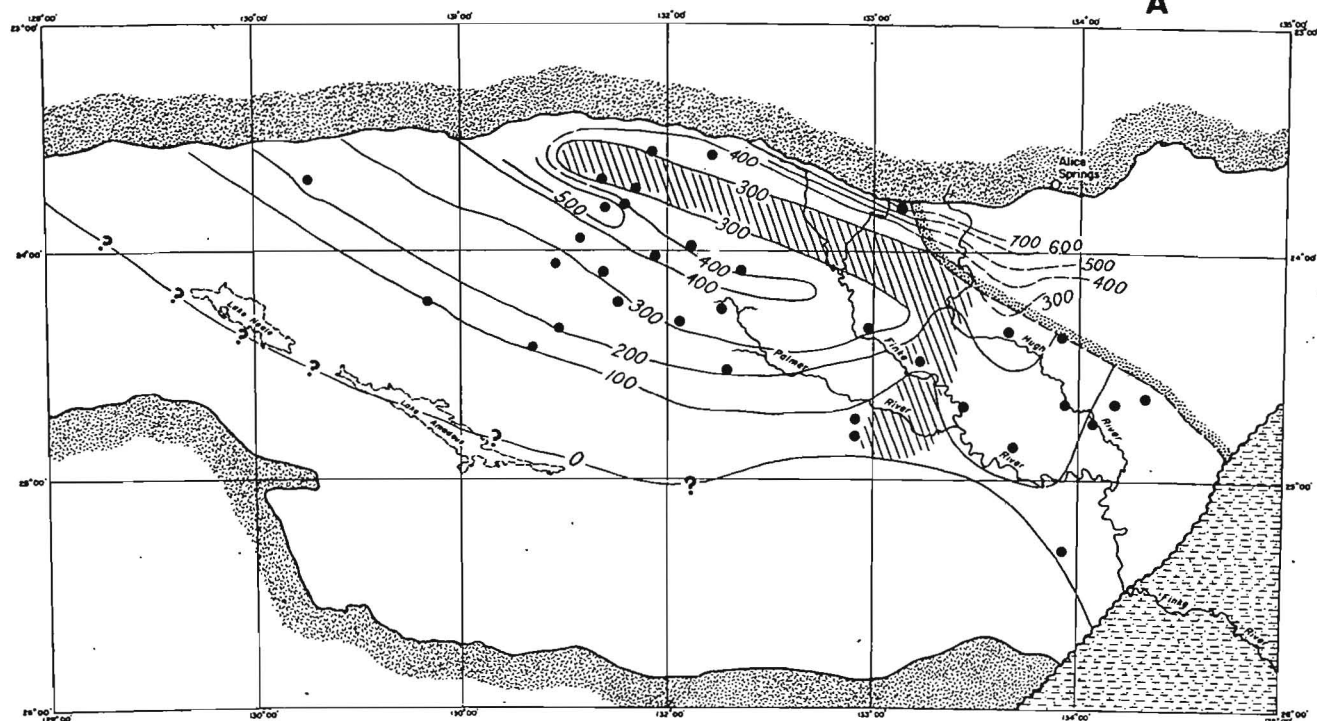
Isopachous map — Upper Stairway Sandstone
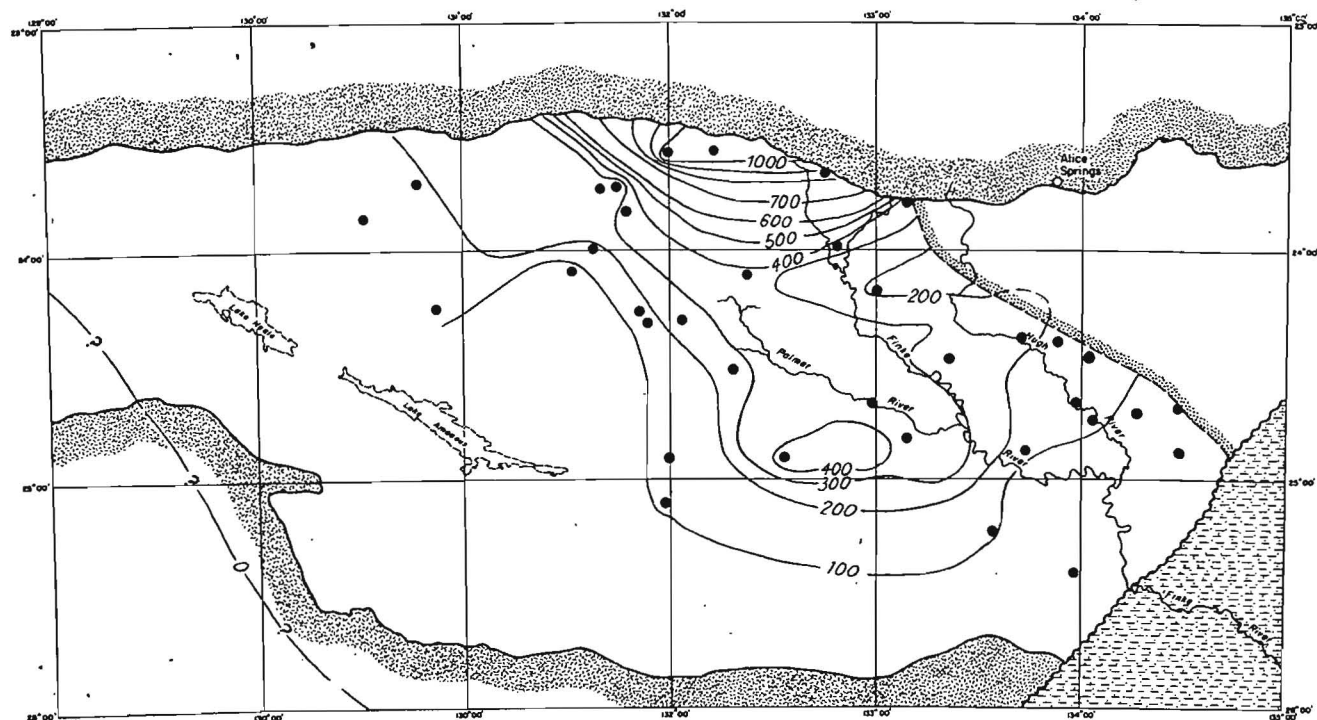
B

Reference

LOCALITY MAP

SCALE

16 8 0   16   32   48

MILES

:::::: Superficial mesozoic sediments

/// Western limit of removal of Stairway Sandstone below the Mereenie unconformity

::::: Igneous and metamorphic rocks and metasediments

/100 Isopach – thickness in feet

● Locality with measured thickness

To accompany Records 1966/1

is shown in Fig.16.   From this it is evident that the zone of middle
Stairway thinning is also the zone of maximum carbonate precipitation.
This may be due to the carbonates forming on a topographic high.   The
carbonates are not however reef limestones - they are mainly thin-
bedded finely crystalline dolomites.   Therefore this zone may also
be due to the fact that it was a zone of minimum terrigenous
sedimentation so that chemical precipitation was the predominant
sedimentation process.

The upper Stairway isopachous map (Fig.14B) shows little
relationshop to that of the Middle Stairway.   The sub-basin in the
southern part of the Amadeus Basin has been delineated from only a
few known thicknesses and in addition the stratigraphy in parts of
the southern margin of the basin (the Mount Sunday Range area) is a
little uncertain;   therefore too much significance should not be
attached to it at this stage.   It would appear however that some
thinning of sediments occurred along an east-west line running
through the middle of the basin.   There is a very definite thickening
of the upper Stairway on the northern margin of the basin so that
overall, the upper Stairway resembles the lower Stairway although
the sediments are both more widespread and thicker.

Lithofacies variations

The paucity of outcrop prevents anything more than a very
approximate lithofacies map being drawn up for the whole of the
Stairway Sandstone (Fig.15).   To some extent this gives a false
impression of Stairway Sandstone sedimentation for the map suggests
that the present northern margin of the Amadeus Basin was also the

LITHOFACIES MAP - STAIRWAY SANDSTONE
Sand shale ratio

Fig.15
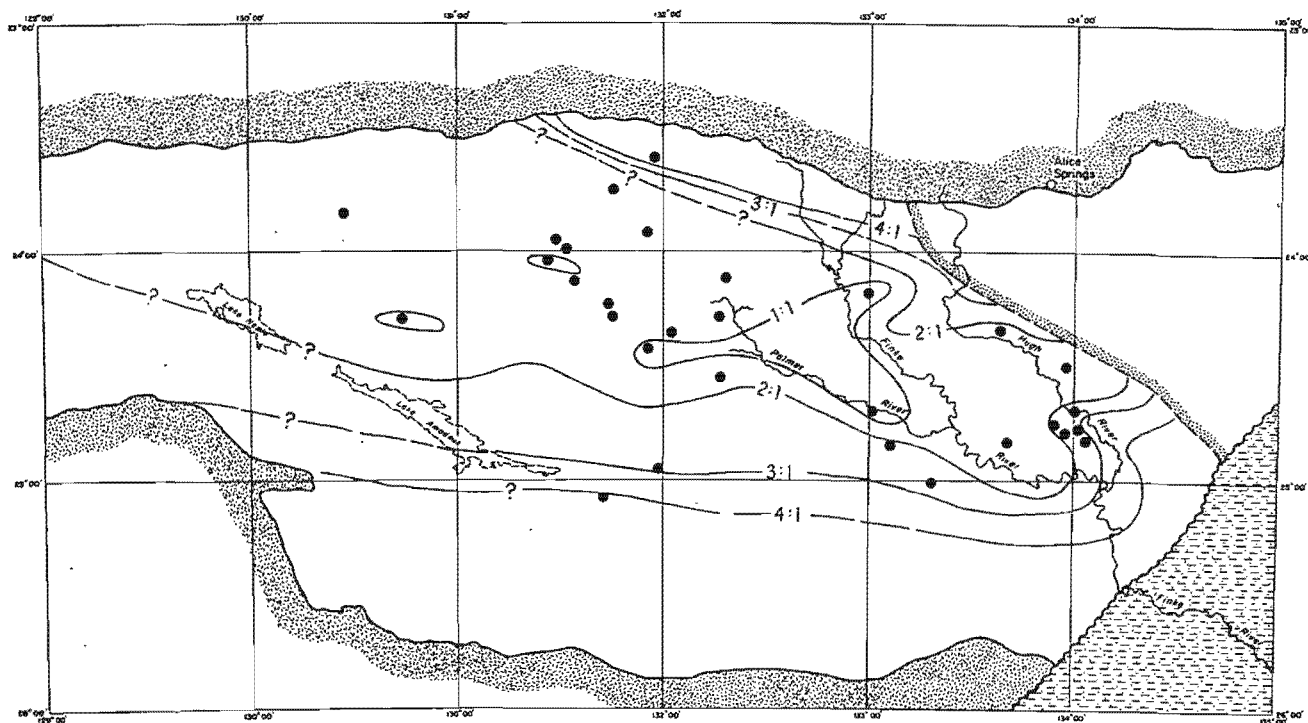
Alice Springs

Reference

Superficial mesozoic sediments

Western limit of removal of Stairway
Sandstone below the Mereenie unconformity

Igneous and metamorphic
rocks and metasediments

Isopleth - showing the
sand : shale ratio

Locality with measured
thickness

To accompany Records 1966/1

LOCALITY MAP

SCALE

16 8 0   16   32   48

MILES

AUS 1/106

Ordovician margin.   This has been shown not to be the case (see Figs.13-14). The high sand:shale[x] ratios in the northern part of the basin are entirely due to the considerable thickening of the upper Stairway Sandstone to the north.   The high sand:shale ratios on the southern margin are mainly a reflection of the absence of the predominantly silty middle Stairway.   Therefore any lithofacies interpretation based on Fig.15 must be treated with caution; it does however show that the most lutaceous part of the basin is in the middle. Source areas for the sediments may have been situated on all sides of the basin except to the north-west, where it appears that the basin was connected to the open sea.   The impression of a north-west to south-east embayment is strangthened by the form of the lithofacies map.   This form suggests that the palaeocurrent direction is in part parallel to the axis of the embayment or basin.

A very much more valuable picture would be obtained by drawing up lithofacies maps (both sand:shale and clastic to non-clastic) for the lower, middle and upper Stairway Sandstone, but this is at present impossible because of the lack of data.   Superficial examination of the lithofacies picture in these three units suggest that the lower and upper Stairway, whilst showing very little variation in sand:shale ratio, would nevertheless show progressive decrease of sand to the north and west. The middle Stairway Sandstone would show a marked increase in sand to the south-east and would show its highest proportion of non-clastics in the Seymour Range area (also the approximate area of the lowest sand:shale ratio for the whole of the Stairway Sandstone - Fig.15).

x   The term "sand-shale" is used because it is in general usage -
    it should not be taken as implying fissility in the lutites.

Fig 16

DISTRIBUTION OF MIDDLE STAIRWAY LITHOLOGIES
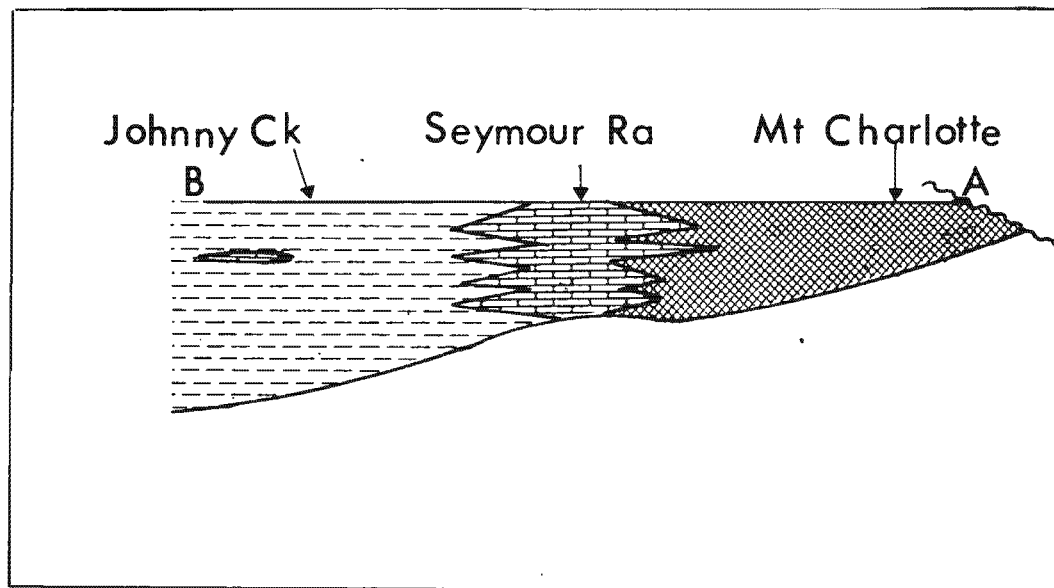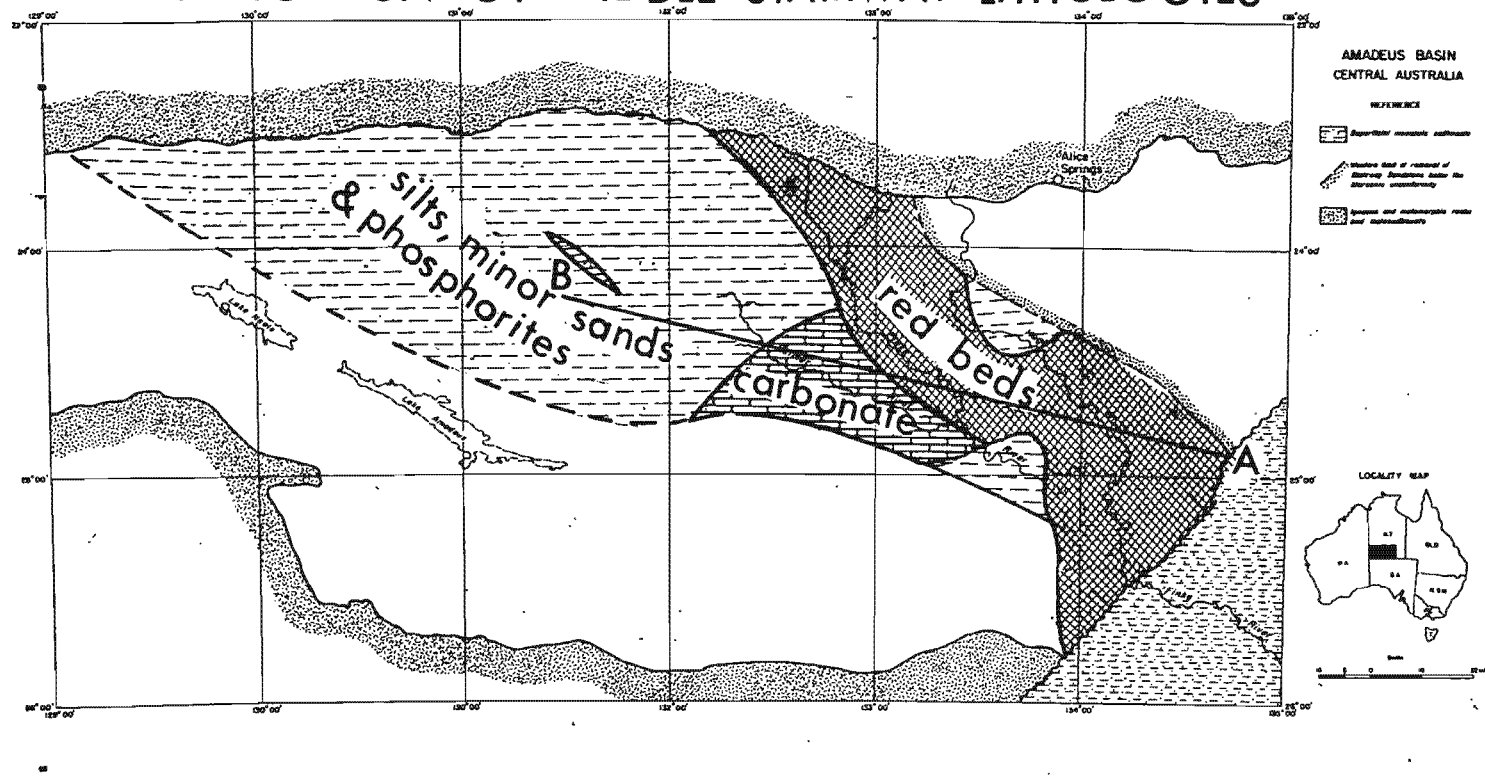
The distribution of the rock types within the middle Stairway Sandstone is shown in Fig.16, and it is apparent that there is a change from marine shales in the north-west to carbonates and paralic red-beds in the south-east.

Palaeocurrent studies

With the exception of the coarse sands in the lower Stairway Sandstone, cross-beds are both fairly rare and poorly developed. Therefore it is only possible to draw up a palaeocurrent map for the Stairway Sandstone as a whole.

Fig.12 shows that in general the trend indicates currents coming from the south-east.   This direction is particularly evident in the south-east and north-west parts of the basin;   in several places this south-east to north-west direction is parallel to the isopachs.   In the middle zone of the basin the current pattern becomes somewhat irregular and there is a fairly strong northerly component (and a minor southerly component in places).   This northerly component (i.e. current flowing from the south) would indicate currents flowing down the palaeoslope - this is commonly found to be the case in current studies (Potter and Pettijohn, 1963).   Reference to the isopachous maps of the lower and upper Stairway (Figs.13B and 14B) suggests that the currents from the south-east may have been strong and persistent in the areas with minimum palaeoslope gradient. These south-easterly currents were probably completely independent of the palaeoslope.   However, on moving into an area where the palaeoslope was steeper, their direction became modified and was more dependent now on the palaeoslope.

Fig.17 gives mean current rose diagrams of the palaeocurrents

fig 17

VARIATION OF CURRENT DIRECTION WITH STRATIGRAPHIC POSITION
AND GRAIN SIZE

LOWER

VERY FINE

MIDDLE

FINE

UPPER

MEDIUM

WHOLE
FORMATION

COARSE

reference

0% 5% 10% 15% 20% 25%
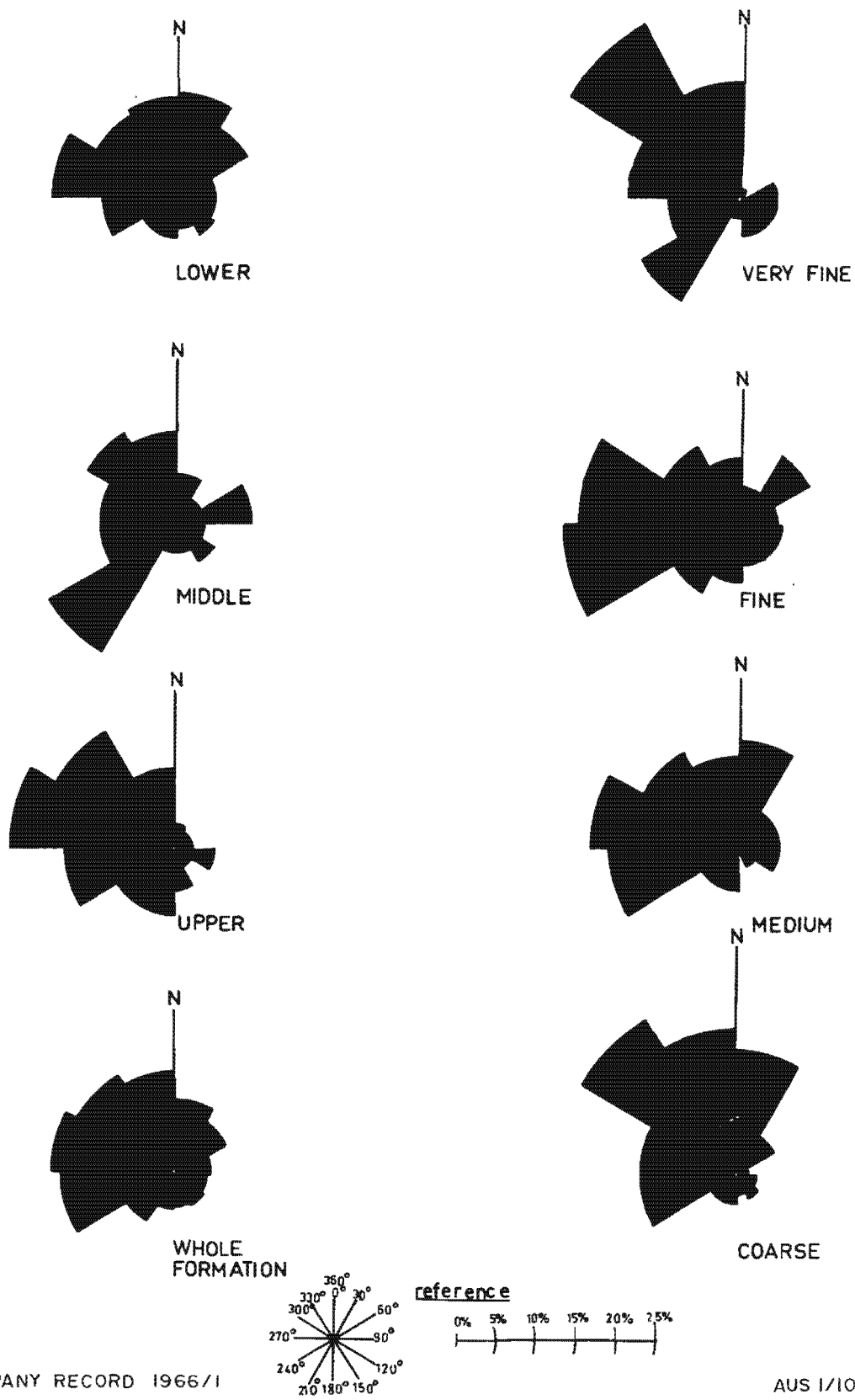
for the entire basin. All of the rose diagrams show a fairly wide spread of results (as is normally the case in shallow marine sediments). However it is evident that the mean current direction for the whole formation was from the south-east. The same south-easterly current is also seen in the lower and upper Stairway. By contrast the main current direction in the middle Stairway is from the north-east. This may indicate that to some extent the development of the thick sands of the lower and upper Stairway is dependent on the palaeocurrent direction. The presence of phosphate in the middle Stairway may also be dependent in part on the palaeocurrent; the north-easterly current may have been the phosphate-bearing one. Alternatively the north-easterly current may have been one which carried little terrigenous material so that there was no"dilution" of phosphate.

There is also a suggestion from Fig.17 that the size of detrital grains is in part dependent on the direction of the palaeocurrent, so that coarse and very fine sands show a palaeocurrent direction from the south-east whilst fine and medium sands generally show a current direction from the east (it may be relevant to note that bimodal sands generally have the modes very fine sand and coarse sand). This change of grain size with palaeocurrent direction may be due to the variation of current velocity with the direction or could be a reflection of the provenance, i.e. coarse and very fine sands are derived from the south-east whilst fine and medium sands are derived from the east.

Cross-bed Studies

Cross-beds were studied at a number of localities throughout the basin and in addition to the dip and azimuth of the cross-bed sets (necessary for the determination of palaeo-current directions) the type of cross-bedding, the thickness of the cross-beds and the grain size of the cross-bedded units were all noted (see Table 9, appendix).

The cross-beds are mainly of the curved tabular or straight tabular type (Crook, 1957), and cannot be regarded as environmentally significant except that they are of sub-aqueous origin. Similarly, the values obtained from the angle of inclination of the cross-beds cannot be regarded as being of environmental significance except the average value of 18° (range of 14° to 22° - see Table 6, appendix) indicates that they were formed in a sub-aqueous environment (McBride and Hayes, 1962).

The question of variation of palaeocurrent direction with grain size has already been mentioned; in addition cross-bedding is common to very common in the coarse grained sandstones, common in the fine to very fine grained sandstones, and probably rare in the medium grained sandstones.

The question of whether there is any variation of angle of inclination with grain size was not investigated. When an iso-angle[x] map is drawn up (Fig.18A) an interesting though puzzling pattern emerges in which there are three low angle zones (less than 20°) and two intervening high angle zones (greater than 20°). These zones trend approximately south-west to north-east, i.e. at right angles to the

x Isoangles are lines joining points of the same angle of inclination of the cross-beds.

Iso dip map – average values of dip of cross-beds throughout the Stairway Sandstone

Fig.18

A
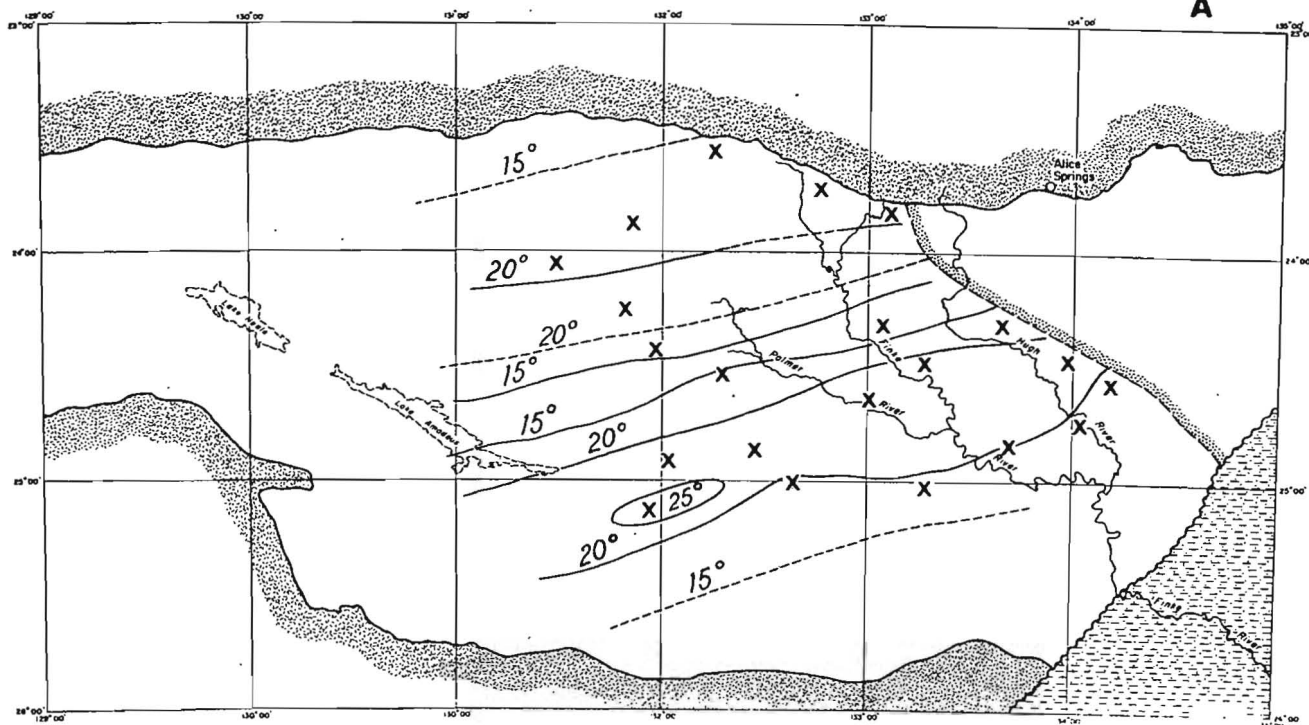
Iso set map – average values for cross-beds throughout the Stairway Sandstone

B

Reference

LOCALITY MAP

SCALE
16 8 0   16   32   48
MILES
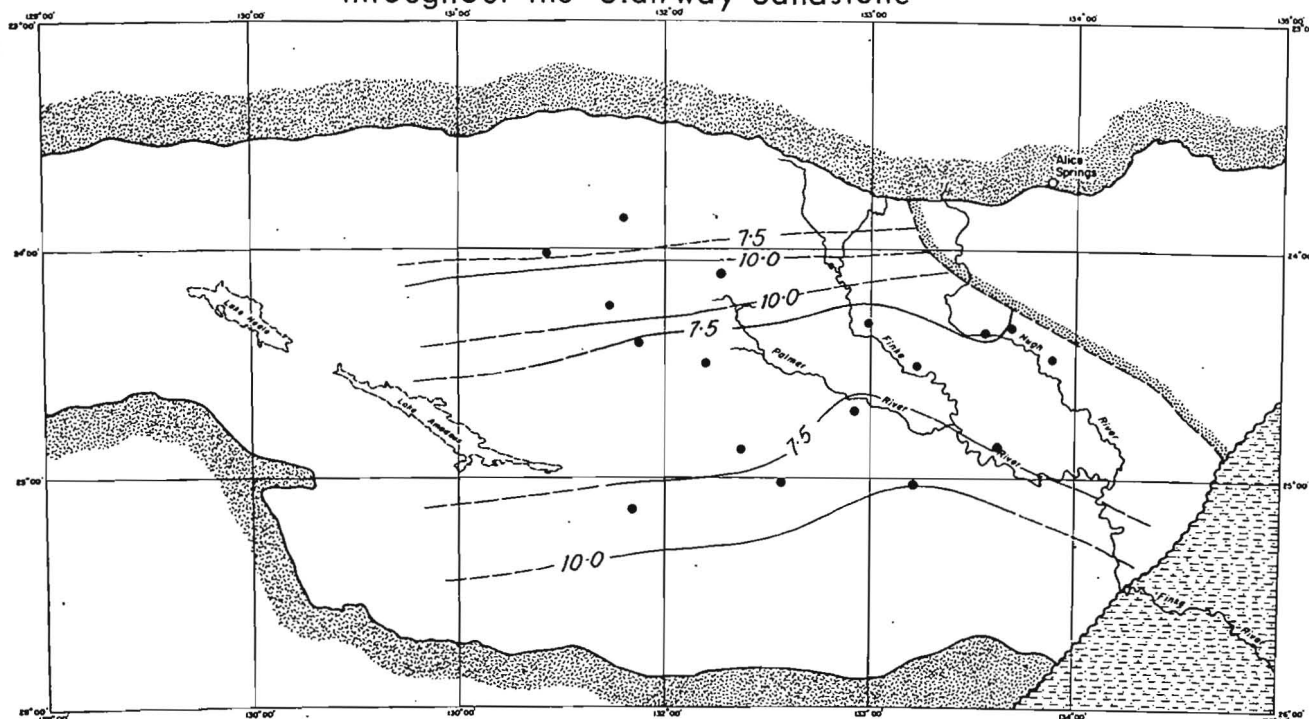
To accompany Records 1966/1.

	Superficial mesozoic sediments	**X**	Locality with measured cross-bed dip
Western limit of removal of Stairway Sandstone below the Mereenie unconformity		*7.5*	Iso set – thickness of cross-bed set in inches
	Igneous and metamorphic rocks and metasediments	•	Locality with measured thickness
15°	Iso-dip – dip of cross-bed in degrees		

AUS 1/109

palaeocurrent direction, and bear no relationship whatsoever to the isopachous map.

The explanation of this zonation may be that high angle zones correspond to a low energy environment whilst the low angle zones correspond to a high energy environment (Jopling, 1963). The reason for the change in energy may have been a function of sea-bottom topography but it is more likely to have been due to tides and currents. It may be feasible to apply this possible indication of high current activity to the phosphate search for the stronger the current, the greater the winnowing action and the greater the phosphate enrichment. Jopling (1963) has also shown that an increase in the dip of cross-beds can be related to an increase in the suspended load (probably due to an increase in velocity of the current) and also to a shallowing of the basin).

The thickness of cross-bed sets were also plotted up (Fig.18B - the isoset[x] maps), with the original idea that the sets would possibly show thickening towards the source area but this was not found to be the case. The isoset map on the Stairway Sandstone as a whole shows a distinct resemblance to the isoangle map except that the trend is more east-west. There is however no correlation between the thickness of the cross-bed set and the angle of inclination.

The lateral variation in thickness of cross-bed sets within both the lower and upper Stairway show a trend opposite to the expected one for both show a general thickening of the isosets

[x] Isosets are lines joining points with the same thickness of cross-bed set

ISO SET MAPS—STAIRWAY SANDSTONE

Cross-beds in the lower unit

Fig. 19

A
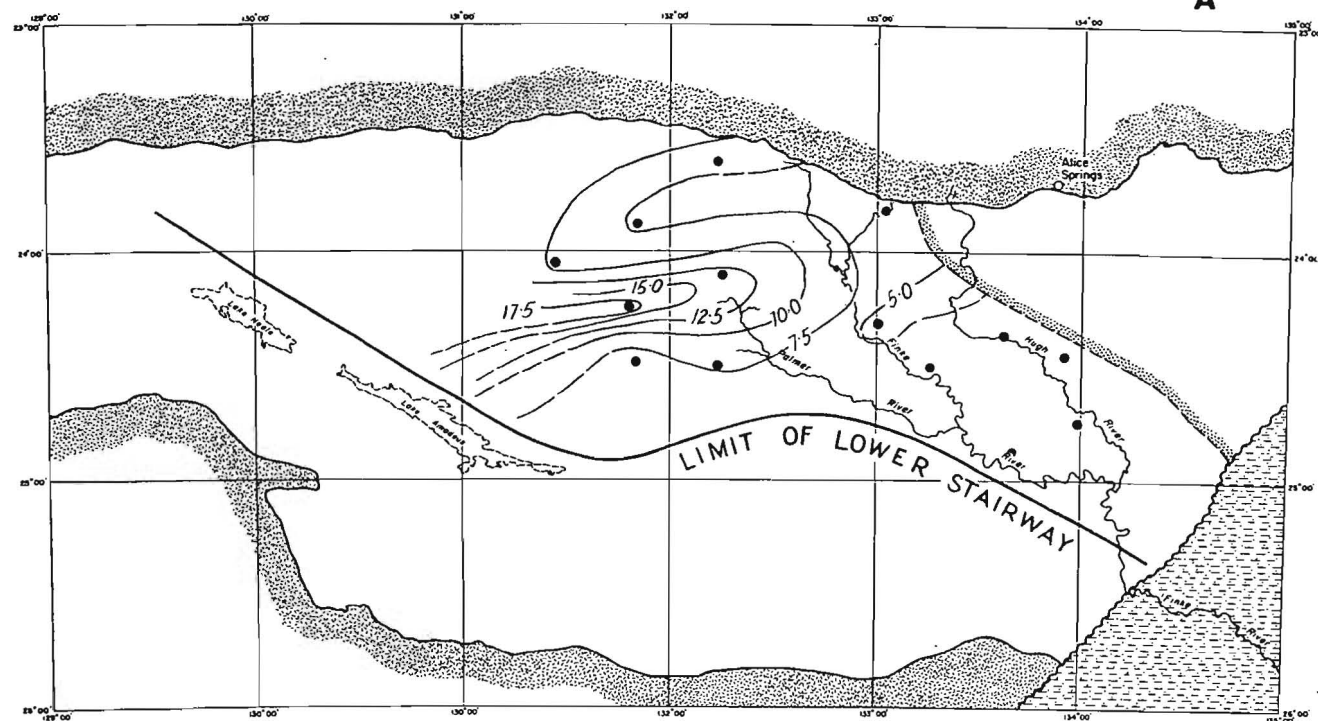
Cross—beds in the upper unit

B
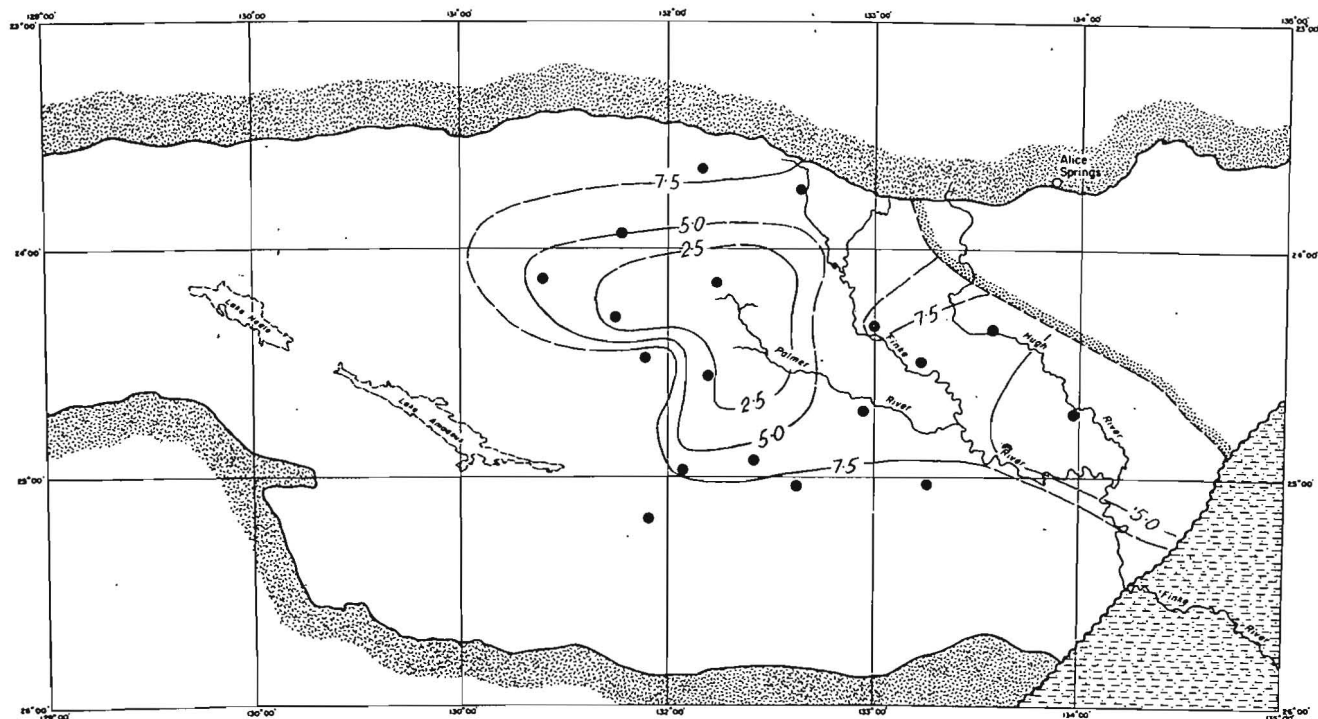
LOCALITY MAP

SCALE
16 8 0 16 32 48
MILES

Reference

Superficial mesozoic sediments

Western limit of removal of Stairway Sandstone below the Mereenie unconformity

Igneous and metamorphic rocks and metasediments

Isoset - thickness of cross-bed set in inches

Locality with measured thickness

To accompany Records 1966/1

AUS 1/110

to the west (Fig.19). The region with the thinnest isosets of the lower Stairway corresponds fairly well to the area of the lower Stairway embayment - perhaps a fairly low energy zone. The presence of the isoset minimum in the upper Stairway may be significant as this "depression" shows a fairly general sort of correlation with the zone of minimum sand:shale ratio (Fig.15) and may again be a reflection on a low energy zone so that cross-beds were poorly developed and lutites form a high percentage of the sequence.

When isosets are plotted for particular grain sizes there is somewhat less regional variation (Fig.20) suggesting that set thicknesses are in part dependent on grain size (or on the current velocity, which in turn influences the grain size). There are however a variety of other factors such as the duration of a current, the suspension load of the current or bottom topography which may influence the thickness of the sets. The majority of the sets of the fine and very fine grain sands are 5.0 to 7.5 inches thick whilst the coarse and very coarse sands have sets 10 to 15 inches thick. Apart from this variation there is also a very marked difference between grain size classes in that the isosets of fine sands thicken to the east whilst the coarse sands thicken to the west. This suggests that two distinct hydrodynamic systems were operative at various times throughout the Stairway Sandstone times, - one system produced cross-bedded coarse grained sands and the other system produced cross-bedded fine grained sands. This does not mean that the environments were necessarily very different; it is for instance possible in the same beach environment to get

ISO SET MAPS — STAIRWAY SANDSTONE

Fig. 20
A

Cross beds in fine and very fine grained sandstone

B
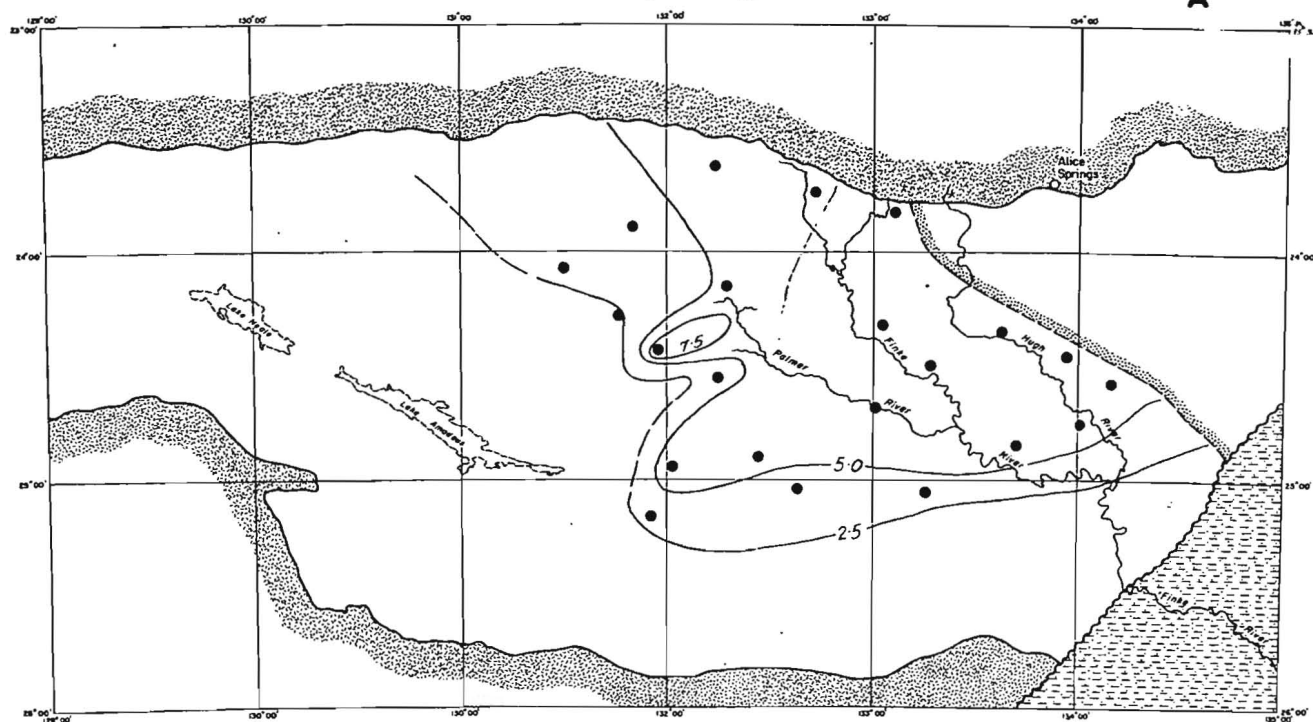
Cross beds in coarse and very coarse grained sandstone
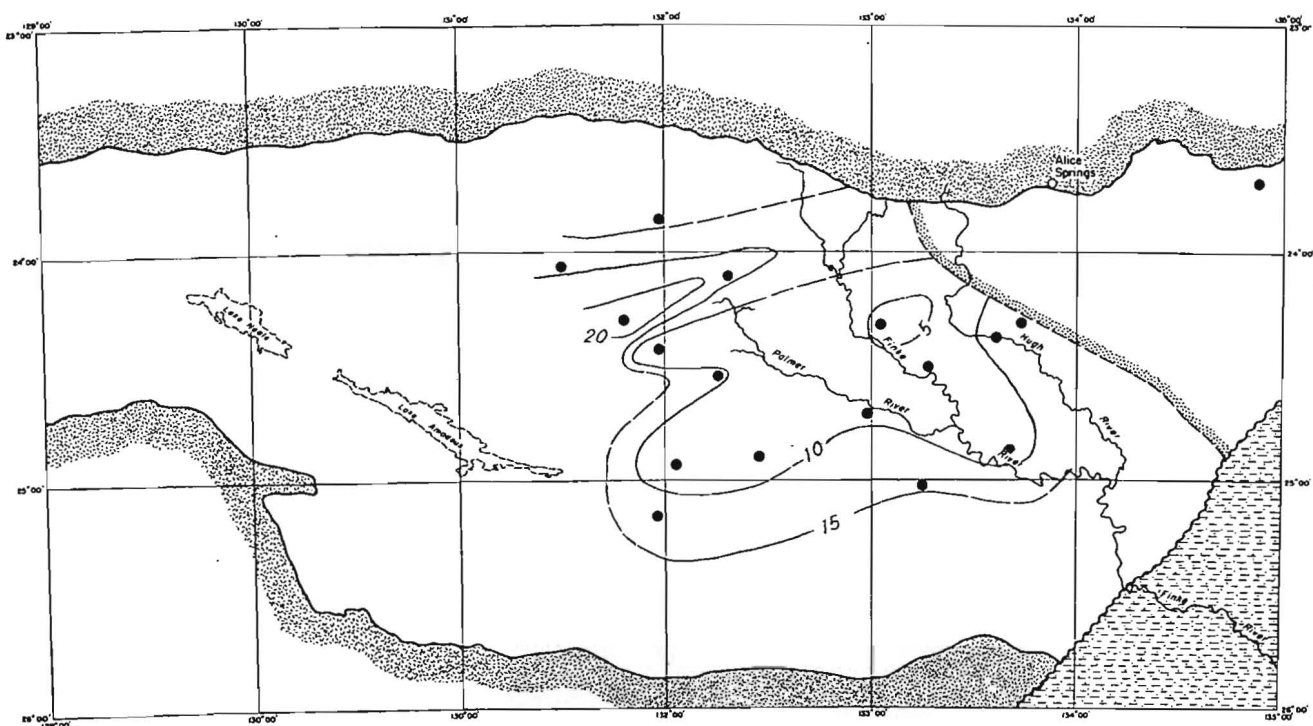
LOCALITY MAP

SCALE

16 8 0   16   32   48

MILES

Reference

Superficial mesozoic sediments

Western limit of removal of Stairway
Sandstone below the Mereenie unconformity

Igneous and metamorphic rocks
and metasediments

Iso set - thickness of
cross - bed set in inches

Locality with measured
thickness

To accompany Records 1966/1

AUS 1/111

cross-beds inclined at exactly the opposite direction to each
other (Logvinenko and Remizov, 1964). Alternatively, the variation
in the trend of the isosets may be a reflection of the fact that the
coarse sands are found predominantly in the lower Stairway which is
regressive whilst the fine sands occur mainly in the upper Stairway,
which is transgressive, though just how and why this would affect
the isoset pattern is unknown.

Summary

The isopachous maps clearly show that the present limits of
the Amadeus Basin are not the limits of Stairway Sandstone deposition.
The lower Stairway sea was probably fairly restricted and the middle
Stairway sea even more restricted with "sub-basins" developed. The
upper Stairway Sandstone sea was very extensive and spread far outside
the present limits of the Amadeus Basin.

The lithofacies map whilst treated with some reservation shows
the highest percentage of lutite in the middle of the basin and also
emphasizes the north-west south-east trend of the embayment. The
connection to the open sea lay to the north-west.

The palaeocurrent directions indicate flow predominantly from
the south-east to the north-west, which was independant of the
palaeoslope in most areas. There is however some modification of
this picture in the central part of the basin where the palaeocurrents
have a northerly component which suggests some flow down the
palaeoslope - possibly in response to a steepening of the slope.
The main currents appear to have had a direction parellel to the
axis of the embayment. The main source area for the sediments
probably lay to the east and south-east. The iso-angle map suggests

the presence of alternations of high energy current and low
energy current zones with a trend approximately at right angles
to the palaeocurrent direction. The range of values of the angle
of inclination is one normally met with in sub-aqueous cross-
bedding.

The isoset maps possibly show that the variation of thickness
of cross-bed sets may be influenced by whether the environment is
"high energy" or "low energy". Whether the sea was regressive
or transgressive may also have been an important factor, with
the sets thickening in the direction in which the sea is "moving"
(i.e. the direction of transgression or regression).

CHAPTER 6

PHYSICO-CHEMICAL CONDITIONS

General

There are no precise environmental indicators present in the Stairway Sandstone. Some of the fossils may have been subject to quite fine physical or chemical limits but this type of detailed palaeontological data is not available. Therefore the mineralogy, grain size etc. of theStairway Sandstone have to be used as keys to the physico-chemical conditions (Fig.21).

Physical Conditions

(a) Rate of Deposition

The Stairway Sandstone has a maximum thickness of approximately 1800 feet and embraces a time-span of 20 million years. This is equivalent to an average rate of deposition of about 0.3 mm. per annum in the northern part of the basin (western Macdonnell Ranges area). In the vicinity of AP1 the average rate of deposition would have been about 0.1 mm per annum. However, the grain size of many of the lower Stairway sands is in the order of 0.5 mm. diameter so that sedimentation was probably interrupted by a great deal of erosion in between periods of fairly rapid deposition. The presence of abundant cross-bedding in the coarse sands of the lower Stairway also suggests fairly rapid deposition at times.

The form and frequency of infauna is considered to be of value in the interpretation of rate of sedimentation (Middlemiss, 1962). The straighter the vermiform burrow the more rapid the sedimentation (e.g. as with Scolithus); the more contorted the burrow the slower

VERTICAL VARIATION OF PHYSICO-CHEMICAL CONDITIONS IN THE STAIRWAY SANDSTONE
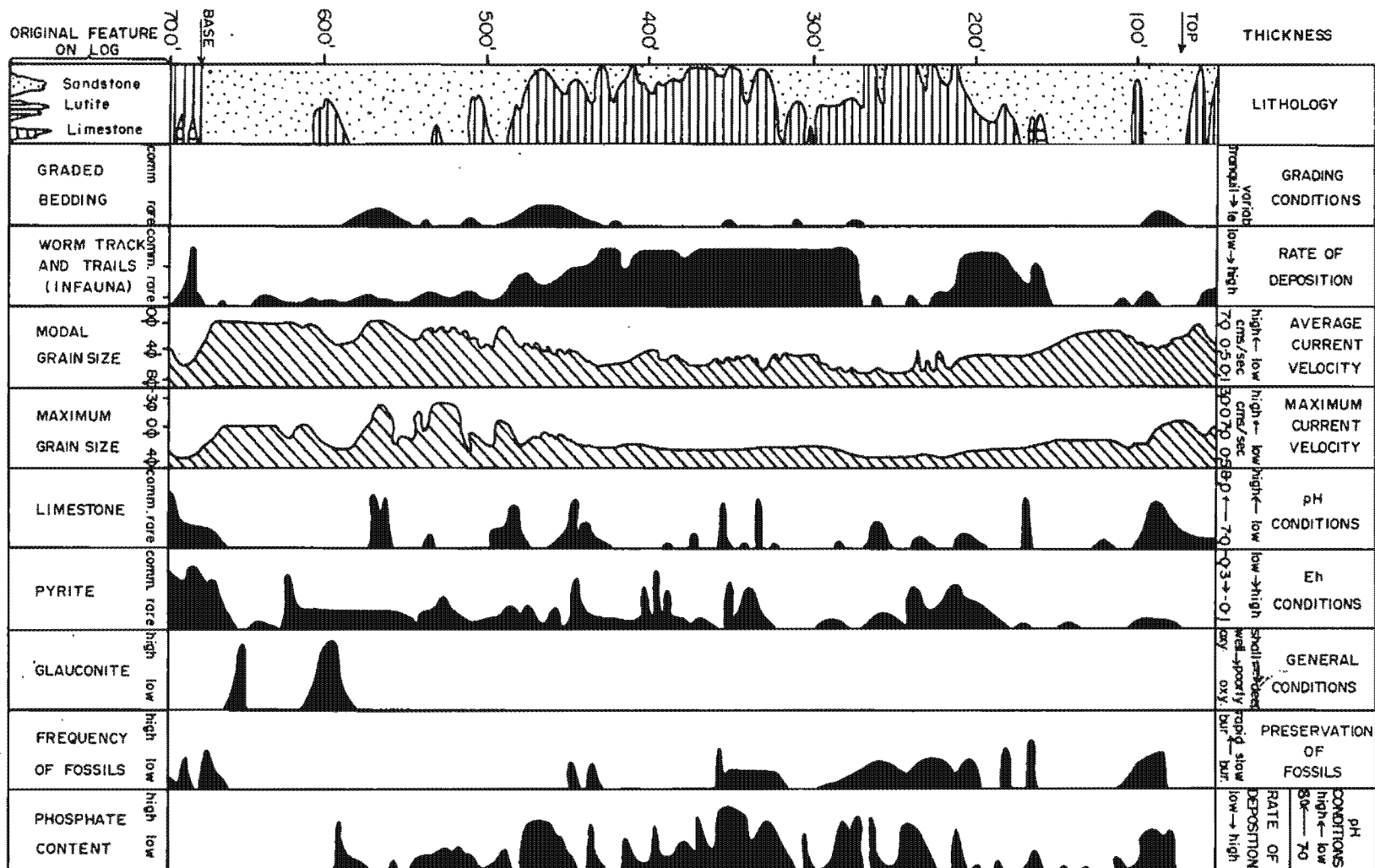
TO ACCOMPANY RECORD 1966/1

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Fig

the rate of sedimentation (thus giving the burrower greater
opportunity for reworking the sediments).   If sedimentation is
extremely rapid then it is possible for the infauna to be
completely destroyed as it is unable to keep pace with sedimentation.
On this basis, in the lower and upper Stairway the lack of burrowing
and the fact that what burrowing there is is mainly of the vertical
variety, suggests that the rate of sedimentation was fairly rapid.
The abundance of burrowing in the middle Stairway Sandstone
suggests that the sedimentation was extremely slow.   This view
is supported by the distribution of phosphate (rare in the lower
and upper Stairway and abundant in the middle Stairway),abundant
phosphate commonly being taken as evidence of a slow rate of
deposition.

In some circumstances the abundance of fossils may be taken
as an indication of rapid burial; it may however also be an
indication of rapid burial; it may however also be an indication
of optimum conditions for the development of a rich fauna, or of
lack of scavengers, or of mass mortalities.   The presence or
absence of fossils cannot therefore be used with any reliability
for the interpretation of physico-chemical conditions.

(b) The variability of conditions

The presence of graded bedding (of the non-turbidite type)
may be taken as evidence of predominantly tranquil conditions.
However the converse does not apply, i.e. the absence of graded
bedding (the case throughout most of the Stairway Sandstone)
cannot be taken as evidence of vigorous conditions.   The number

of sedimentation units per unit interval may give some indication of the variability of conditions and Fig.23 suggests that conditions were fairly variable throughout the formation and particularly in the middle part where there are numerous alternations of thin beds of arenite, lutite or phosphorite.

(c) Current velocities

Some idea of the current velocities operating during Stairway Sandstone times may be obtained from the grain size by using the curves computed by Hjulstrom (1939). The modal grain size (which may reflect the average current velocity) indicates the current velocity ranged from 7 cms/sec. in the lower and upper Stairway down to 0.4 cms/sec. in the middle Stairway. The current velocities obtained by use of the maximum grain size range from 30 cms/sec. in the lower Stairway to 10 cms/sec. in the Upper Stairway and to about 1 cm/sec. in the middle Stairway.

If phosphatic pellets are considered as detrital grains (as has been suggested by Crook, 1964), a very different pattern emerges with velocities of up to 150 cms/sec. being postulated to move the pellets. Velocities of this order are considered to be highly unlikely and the present author believes that the pellets are not detrital. This is discussed in more detail later (Chapter 8).

(d) Bathymetry

The Stairway Sandstone has many indications of extremely shallow water sedimentation such as ripple marks, and tracks and trails of the mud flat type. It is also possible to fit the sedimentary sequence into the barrier-bay, the inter-tidal

flat or the epeiric sea environments (see Chapter 7) all of which are shallow. Cloud (1955) has suggested that glauconite may form between depths of 5 fathoms and 1000 fathoms but that it is most likely to form between 10 and 200 fathoms so that the glauconitic parts of the lower Stairway were probably deposited at depths within this range.

Kazakov (1937) has suggested that phosphorites form between depths of 50 and 200 metres but McKelvey, et al. (1959) have suggested the depth range is 200-1000 metres. It is probable that much of the Stairway Sandstone was deposited in depths similar to those suggested by Kazakov (1937) rather than those of McKelvey, et al. (1959). The abundance of phosphorites in the middle Stairway may indicate a greater depth than is the case for the upper or lower Stairway where there are few phosphorites and abundant indications of very shallow water sedimentation. However, the discussions in Chapter 7 reveal that in the epeiric sea or intertidal flat model, the middle Stairway may be a shallower water environment than that of the lower or upper Stairway.

(e) Temperature

Cloud (1955) has shown that glauconite is of little value as an indicator of temperature except that its formation is likely to be inhibited in "markedly warm" waters. Phosphorites are most commonly found within the palaeo-climatic belt corresponding approximately to the present-day zone $30^{O}N$ to $30^{O}S$. Within this zone the water temperatures in shallow marine seas range from fairly warm to very warm (about $75^{O}F$). The presence of red-beds, dolomites and super-mature ortho-quartzites all suggest tropical

Fig 22

THE Eh AND pH LIMITS OF SEDIMENTARY CHEMICAL ASSOCIATIONS
AND THEIR ENVIRONMENTAL LIMITS. (After Krumbein and Garrels, 1952)
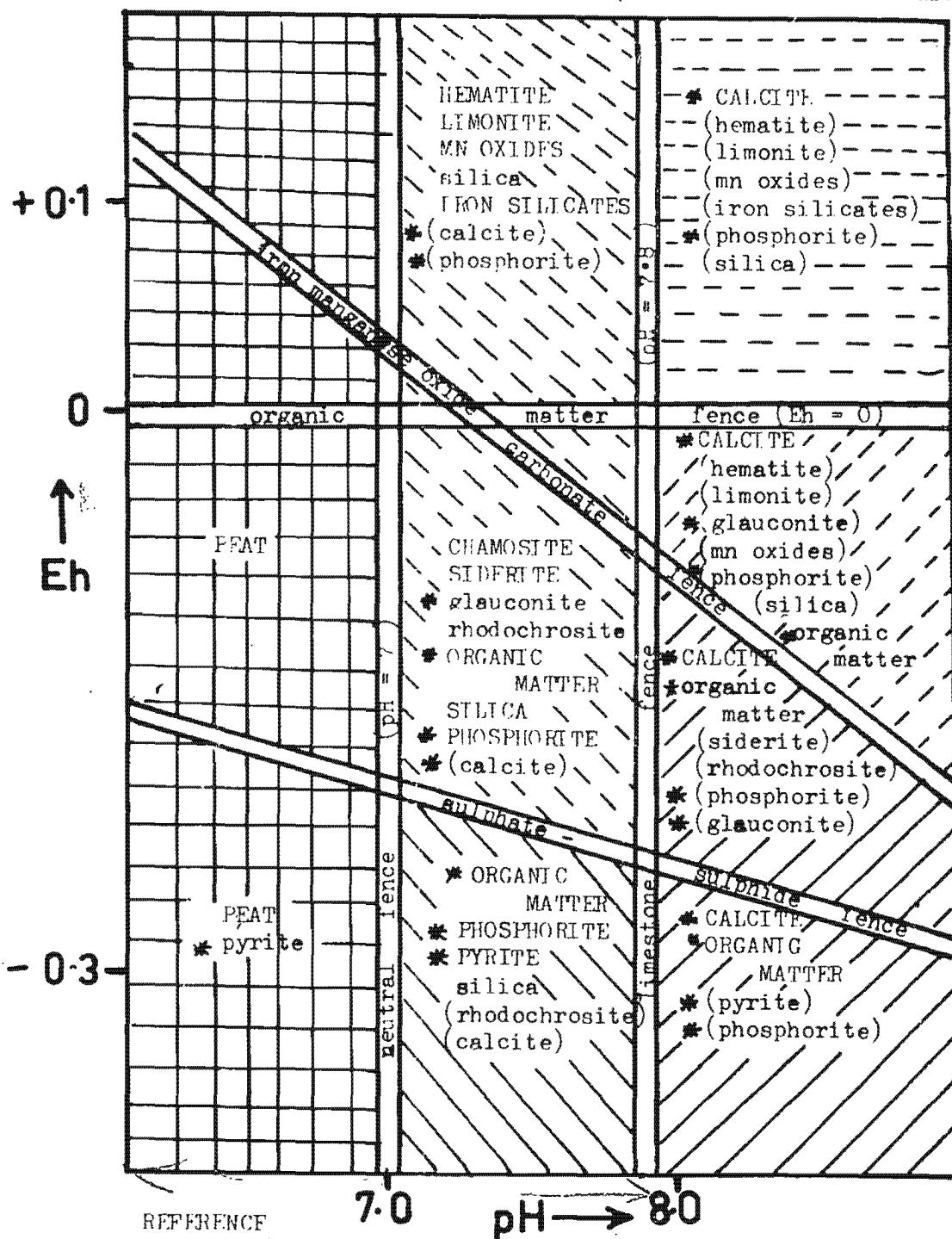
REFERENCE
CALCITE - present in large amounts.
pyrite -- present in appreciable amounts.
(phosphorite)- present as accessories only.

  ＊ Present in the Stairway Sandstone.
Acid environment (e.g. peat bog).   Normal marine open circ[n] cond[s].

Iron-rich environment   Euxinic, with partial stagnation.

Euxinic (Stairway Sandstone cond[s]).   Euxinic, with complete stag[n].

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or sub-tropical climates with associated warm to very warm

shallow marine seas.

Chemical Conditions

(a) Salinity

There are few indications of abnormally high salinities in

most of the Stairway Sandstone. There is some evidence of

evaporites east of Mount Charlotte on the south-east margin of

the basin, where a surface outcrop of the middle Stairway red-beds

is gypseous; this may indicate locally highly saline conditions

within the Mount Charlotte embayment. Some of the dolomites and

dololutites of the middle Stairway may be precipitates resulting

from abnormal salinities. There is also evidence of uncongenial

conditions for marine fauna at the time of carbonate deposition as

the only fossils are generally extremely small gastropods. There

is no evidence of abnormal salinities in the lower or upper Stairway.

(b) pH conditions

The work of Krumbein and Garrels (1952) has greatly assisted

the delineation of the chemical conditions at the time of deposition

of sediments; such chemical sediments as limestone and phosphorites

are of particular importance (Fig.22).

Chemical sediments are fairly rare in the lower Stairway with

only minor pyrite and phosphorite but with fairly common inter-

granular calcite and silica. The minor pyrite and phosphorite

suggest that conditions were in part at least moderately alkaline

with the pH ranging from 7.0 to 7.8. Some of the phosphatic

pellets might be derived from other parts of theStairway Sandstone

basin but this is thought to be of only minor importance (see

Chapter 8). Some of the pyrite ooliths in the sandstones may
be produced by reworking of the underlying Horn Valley Siltstone
which contains abundant pyrite ooliths, but the ooliths show no
signs of mechanical attrition to support the "reworking" hypothesis.
The sediments are therefore probably a faithful reflection of the
chemical conditions prevalent at the time of deposition. The
intergranular calcite possibly suggests that below the water/
sediment interface conditions may have been slightly more alkaline
with a pH greater than 7.8. Conditions throughout most of lower
Stairway times were probably mainly fairly open circulation
conditions with normal open sea pH values which according to
Krumbein and Garrels (1952) range from 7.8 to 8.4.

In the middle Stairway the abundance of phosphorites suggests
that conditions were generally within the pH range of 7.0 to 7.8
for most of the time although the development of fairly common
carbonates in the Seymour Range (Fig.16) suggests that conditions
may have become more alkaline to the south-east with pH values in
the order of 8.0 or greater.

The upper Stairway is very similar to the lower Stairway
though intergranular carbonate is less common and phosphorites
are more common. The pH value was probably within the range 7.0
to 7.8 for much of the time.

(c) Eh conditions

The presence of glauconite, and pyrite ooliths (and possibly
some marcasite ooliths) suggests reducing conditions in the lower
Stairway with Eh values ranging from about -0.1 to -0.3. The
abundant intergranular silica would also support the suggestion

of reducing conditions.

Much of the middle Stairway contains abundant pyrite and organic matter (in the black shales and within the phosphorite pellets) but glauconite is absent. This suggests that conditions were strongly reducing with an Eh range of -0.2 to -0.4. However the presence of the "red-beds" in the Mount Charlotte embayment although probably mainly due to lateritic weathering in the source area, may also in part be indicative of an oxidizing environment. Therefore the Eh probably increased to the south-east in middle Stairway times and attained positive values in the vicinity of Mount Charlotte.

Eh conditions in upper Stairway times were similar to those of lower Stairway times with fairly common pyrite (with some marcasite) and glauconite (e.g. in the MountCharlotte area). These, together with the presence of organic matter imply a reducing environment. The presence of siderite in places suggests the environment may have been less strongly reducing than that of the lower Stairway, with Eh values in the range 0 to -0.2.

<u>Summary</u>

The physico-chemical conditions in Stairway Sandstone times may be summarized as follows:-

<u>Lower Stairway Conditions</u>

(a) Rate of deposition - fairly rapid (greater than .1 mm per annum)

(b) Conditions - fairly constant

(c) Current velocities - 5 to 30 cms/sec.

(d) Depth - shallow - possibly 10 - 200 fathoms

    (e)   Temperature - probably very warm (75°F plus)

    (f)   Salinity - normal

    (g)   pH - normal open sea values - slightly alkaline with a range of 7.8 to 8.4

    (h)   Eh - generally reducing, with an Eh range of -0.1 to -0.3.

Middle Stairway conditions

    (a)   Rate of deposition - probably very slow (less than .1 mm per annum)

    (b)   Conditions moderately variable

    (c)   Current velocities - generally 0.5 to 1.0 cms/sec. but occasionally higher

    (d)   Depth - shallow with a range of 50 to 200 fathoms

    (e)   Temperature -probably warm (up to 75°F)

    (f)   Salinity - normal except to the south-east in the Mount Charlotte embayment where they may have been fairly high

    (g)   pH - slightly alkaline, generally 7.0 to 7.8 but increasing to the south-east to 8.0 or higher.

    (h)   Eh - generally strongly reducing with an Eh range of -0.2 to -0.4 but possibly becoming more oxidizing to the south-east where the Eh value may get as high as +0.1

Upper Stairway Conditions

    (a)   Rate of deposition - relatively rapid (in the order of .1 mm per annum)

    (b)   Conditions - fairly constant

    (c)   Current velocities - generally range from 5 to 10 cms/sec.

    (d)   Depth - very shallow - possibly as shallow as 10 - 200 fathoms

    (e)   Temperature - probably very warm (75°F plus)

(f) Salinity - normal

(g) pH - slightly alkaline range of 7.6 to 8.4

(h) Eh - slightly reducing with an Eh of 0 to -0.2

CHAPTER 7

THE DEPOSITIONAL ENVIRONMENT OF THE STAIRWAY SANDSTONE

General

Both sub-surface and field information are valuable in
the interpretation of sedimentary environments. The basic
tool is the detailed graphic log (see appendix IV), compiled
from AP1. Bouma (1962) has used the detailed log approach
for the delineation of turbidity current environments, but it
has not, to the author's knowledge, previously been used in the
interpretation of shallow marine sediments. The methodology,
the meaning of the various symbols and the graphic logs may
all be found in the appendix.

Any interpretation of a graphic log of a vertical sequence
such as AP1 hinges on Walthers Law of Facies (Walther, 1893 -
94) which in effect states that where there are no time breaks,
sediments which succeed each other vertically must also succeed
each other laterally, i.e. the vertical sequence is a reflection
of the lateral sequence. This premise may then be applied to the
comparison of sedimentary models obtained from data on recent
sediments.

It has already been possible to demonstrate from the
petrography, from the fossils, from the general lithological
picture and from the size analyses that the Stairway Sandstone
is for the most part a shallow marine sequence and therefore
the search for models may be limited to Recent shallow marine
sediments. The shallow marine environment includes such
environments as open shelf, marine deltaic, tidal flat,

lagoonal and estuarine. The littoral zone must also be considered in this context. It is possible to distinguish for instance between beach and lagoonal environments by criteria such as size analyses. However, in most cases it is impossible to distinguish between the various shallow water marine environments by any single method. In spite of the intensive study that these sediments have been subjected to in, for instance, the Gulf of Mexico (e.g. Van Andel and Curray, 1960), no characteristic patterns have emerged. Shepard (1960) has suggested that it is possible to distinguish between lagoonal and shallow shelf sediments by the following criteria:

(a) Lagoonal sediments do not contain glauconite whereas shelf sediments commonly do.

(b) Lagoonal sediments show good stratification (because the bottom fauna is largely killed off) whereas on the shallow shelf there is little or no stratification (because it is destroyed by chewing organisms).

(c) Evaporites form in semi-arid lagoons.

(d) Sandy clays low in silts are common in lagoons but rare in the shallow shelf environment.

It is however necessary to have most or all of these features before it can be confidently stated that the environment is lagoonal.

Visher (1965) gives a valuable series of sedimentological models for use in environmental reconstruction, again using the overall picture of sedimentation to delineate the environment.

It is therefore necessary to determine the overall

fig 23

Vertical variation in the number of sedimentation units

Point of Symmetry

Depth in feet

Number of sedimentation units per ten feet
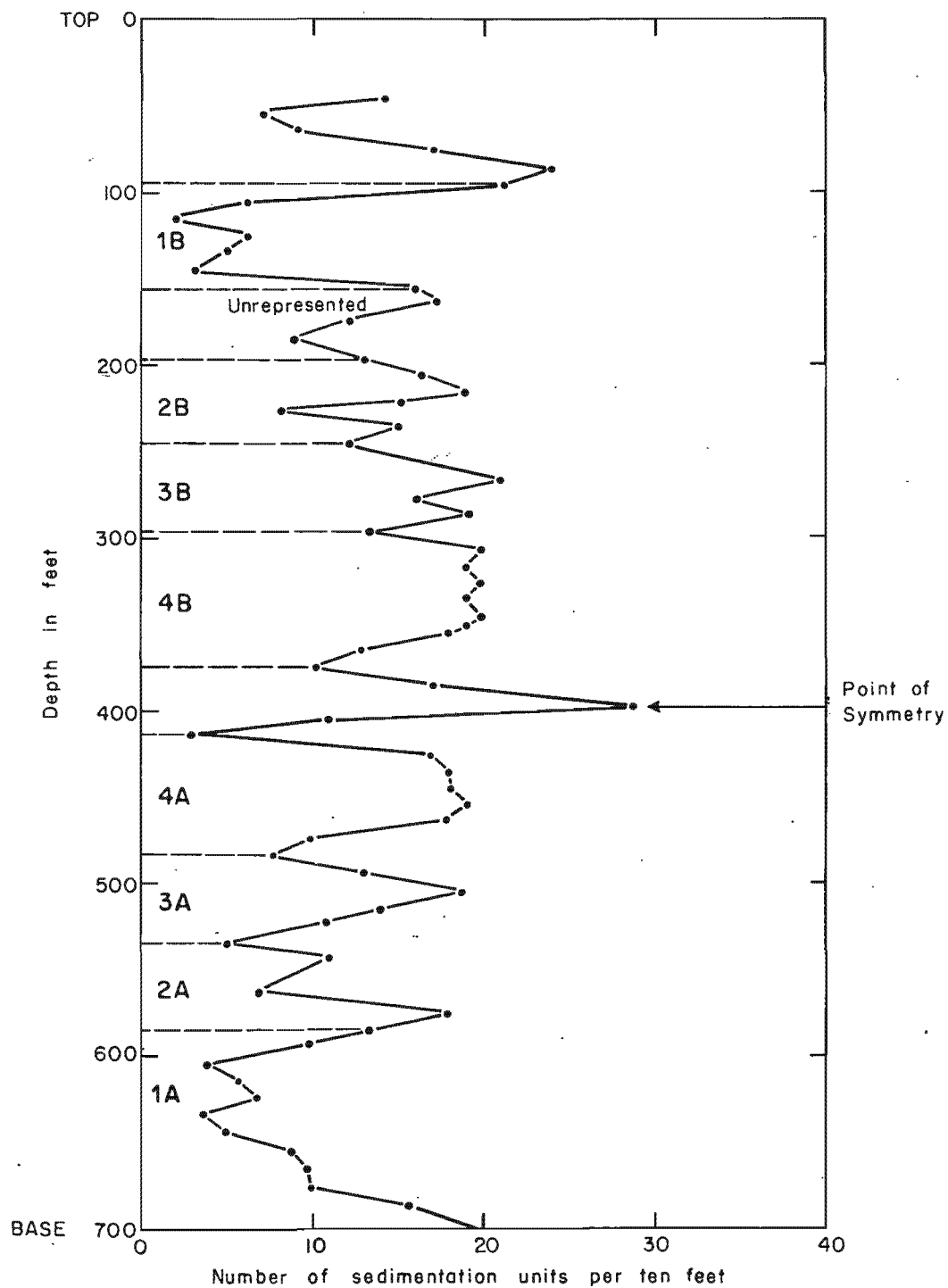
sedimentary picture in the Stairway Sandstone before reconstructing the specific environment.

Transgression or Regression?

Evidence of some kind of repeated sequence is immediately apparent in the Stairway Sandstone, with the upper body of sand bearing a strong resemblance to the lower sand.

The form of "repeating mechanism" is elucidated by Fig.23. The plot of the vertical variation of thickness of sedimentation units has been constructed from graphic log data and may give a qualitative guide to the stability or instability of conditions in a given interval - the greater the number of sedimentation units per 10 foot standard interval, the greater the instability. It is however merely a guide to conditions as the thickness of the sedimentation unit is governed to a considerable degree by the grain size and also there is no record of sedimentation units which were eroded away shortly after deposition. What the plot does show however is the way in which the upper part of the formation is the mirror image of the lower part of the formation, with a point of symmetry at about 400 feet, close to the middle of the formation. The striking similarity of the various parts of the lower half of the curve (A) to the equivalent parts of the upper half of the curve (B) is shown in Fig.24.

Such a mirror image in a shallow marine sequence can only be in response to a transgressive-regressive or regressive-transgressive cycle. If the lower half of the formation is considered, it is evident from Fig.21 that there is a vertical variation (and from Walthers Law a lateral variation also) in a

· FIG 24

Mirror symmetry of the sedimentation unit frequency plot

NUMBER OF SEDIMENTATION UNITS
PER TEN FEET
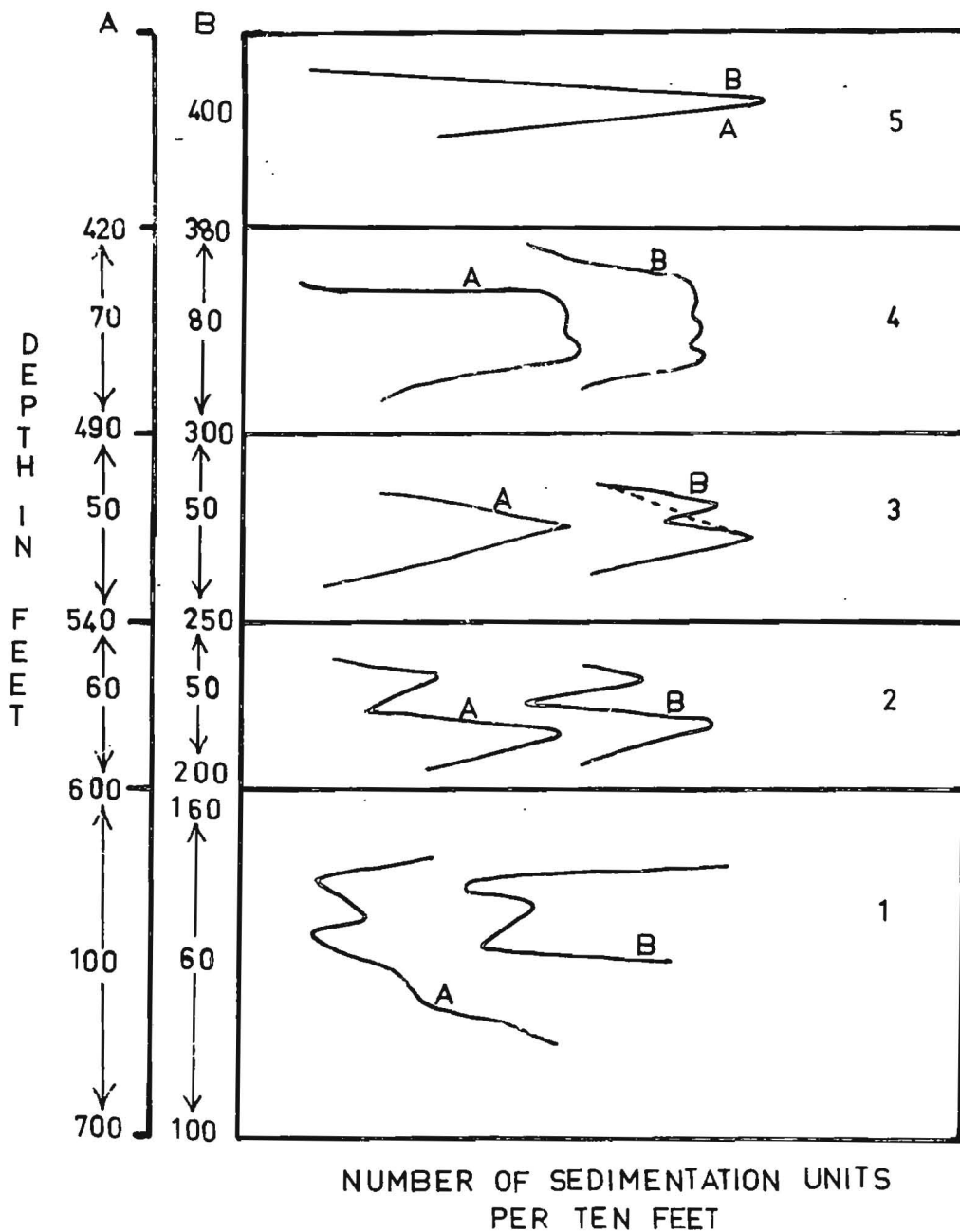
number of features.

The main vertical changes from lower to middle Stairway are as follows:-

(i) From predominantly arenite to predominantly lutite.

(ii) From coarse grained sands to fine silts and clays.

(iii) From "unchewed" sediments to strongly chewed sediments.

(iv) From non-phosphatic to phosphatic sediments.

(v) From glauconitic to non-glauconitic sediments.

Reference to the transgressive and regressive models of Visher (1965) strongly suggests that the lower part of the formation is a regressive sequence. This is further supported by the fact that the coarsest sediments are found near the top of the lower Stairway. If the sequence was transgressive then the coarsest sand would occur at the base of the sequence (Visher, 1965). Conclusive proof is available from the field data - Fig.13A shows that throughout most of the basin the southern limit of the Horn Valley Siltstone (pre-Stairway Sandstone) very closely coincides with the southern limit of the lower and middle Stairway Sandstone. This obviously would not be the case had a major transgression occurred at the base of the lower Stairway Sandstone. There is a very minor successive onlap of the lower and middle Stairway but this is probably a reflection of reworking of the underlying sediment on the margins of the lower and middle Stairway seas. Therefore it can be seen that the Stairway regression was not accompanied by a major offlap; in fact there was no change in the margin of deposition. Instead there was a shallowing of the seas and a seaward migration of near-shore environments. By contrast the

upper Stairway Sandstone shows very strong onlap and in fact
transgressed well outside the present southern limits of the
Amadeus Basin.

Therefore, the basic Stairway Sandstone sequence is
regressive-transgressive.

Curray (1964) considers that transgressions and regressions
are the result of one or more of the following factors; the rate
of sedimentation, the intensity of oceanographic processes which
will sort or disperse the sediments, the shape of the shelf and
the rate and direction of changes in sea level. A modern regressive
sand from the Gulf of California has been described by Curray and
Moore (1964); the regressive sand sheet forms by the rapid supply
of sediment to longshore bars which coalesce and a new bar is
formed seaward of the old bar so that a large sheet sand develops
seawards. The basal regressive sand of the lower Stairway may
have developed in such a way although the texture of the basal
sands suggests an extremely mature sediment and a much slower rate
of sedimentation than is the case in the Gulf of California. It
is impossible at this stage to establish the factors causing the
lower and middle Stairway regression.

With the generalized environmental condition (the mega-
environment) established, it is now possible to establish the
macro and micro-environments from the graphic log.

The Sedimentation Unit

Otto (1938) defines the sedimentation unit as "that
thickness of sediment which was deposited under essentially
constant conditions". The smallest sedimentary division of

the graphic logs is equivalent to the sedimentation unit and in all, over 800 have been recognized in the Stairway Sandstone (see Appendix IV). Very few of these 800 units are exactly the same and therefore it is extremely difficult to work out a simple environmental picture for a sedimentation unit or for a group of sedimentation units. Also, as each sedimentation unit has up to 30 parameters within it, such as graded bedding, modal grain size, maximum grain size etc., there are in the order of 25,000 sedimentary features to consider in the whole formation. The handling of such a mass of data proved extremely difficult.

Crook (1964) considered that "composite units" could be set up by making the base of the unit the point where a significant rise in maximum grain size occurs. In his method, phosphatic pellets were considered along with detrital quartz, on the grounds that the phosphate was detrital. This meant in most cases a phosphatic band at the base of the "composite unit". By this means Crook (1964) was able to set up 281 "composite units" which were further grouped into 30 intervals.

The present author considers that the phosphatic pellets are not detrital and that on these grounds the approach of Crook (1964) is not strictly valid. However, the incoming of phosphate (whatever the process) denotes an important environmental event and therefore because of this, the base of each sedimentation unit is marked by the incoming of a new phosphatic band irrespective of the size of the phosphatic pellet. This gives a total of 192 composite sedimentation units (many of which are in fact identical with those of Crook (1964) in spite of the difference in approach). By considering

VERTICAL DISTRIBUTION OF PARAMETERS

PERCENTAGE OF PHOSPHATIC MATERIAL

GRAIN SIZE OF PHOSPHATIC PELLETS (PHI)

DISTRIBUTION OF COMPOUND SEDIMENTATION UNITS

TOP OF THE STAIRWAY SANDSTONE

BASE OF THE STAIRWAY SANDSTONE
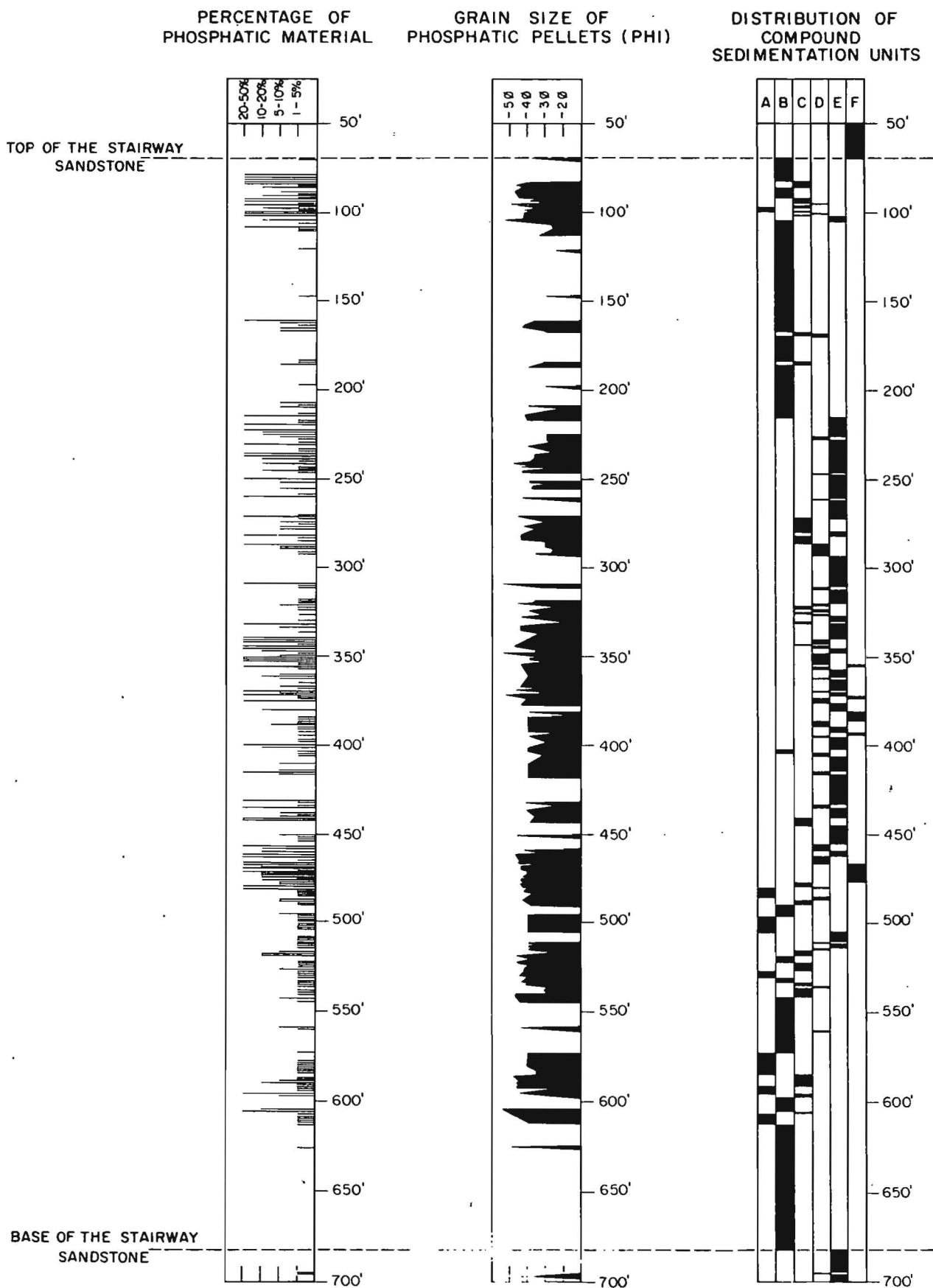
all the other sedimentological data it is possible to set up six

basic types of composite sedimentation units (A - F). The average

sedimentological characteristics of each of these six units are

summarized in Table 10 (Appendix) and in Fig.27. The order of the

sedimentation units is established mainly on the order of appearance.

To some extent the average values in Table 10 are misleading in that

the average modal grain size of Unit B in the lower Stairway is in

the order of $1\emptyset$ whereas the average modal grain size of unit B in

the upper Stairway is $3\emptyset$ to $4\emptyset$. This does not however invalidate

this type of approach for the sedimentary processes are still basically

the same, but are taking place at different energy levels (i.e. a

difference of degree rather than of kind).

The vertical distribution of the six composite sedimentation

units is shown in Fig.25. The distribution of phosphatic material

is also shown. It is apparent that the greatest concentration of

phosphate occurs in the middle part of the formation, which is also

the part of the formation composed predominantly of the lutaceous

composite sedimentation units D and E. There is no immediately

apparent relationship between stratigraphic position and the grain

size of phosphatic pellets. It can be seen in Fig.25 that in the

lower half of the formation, i.e. below about 400' there is a well

developed ascending sequence of A - B - C - D - E - F. In the upper

half of the formation the ascending sequence is F - E - D - C - B - A.

As it has already been established that the basal sequence is

regressive, then the A - F sequence must be regressive, whilst the

F - A sequence must be transgressive.

The vertical distribution of the composite sedimentation units

Fig 26

VERTICAL DISTRIBUTION OF COMPOSITE SEDIMENTATION UNITS
AND THE ENVIRONMENT OF DEPOSITION

TOP OF STAIRWAY SANDSTONE

BASE OF STAIRWAY SANDSTONE

D transgressive
S regressive
SO simple oscillatory
CO compound oscillatory
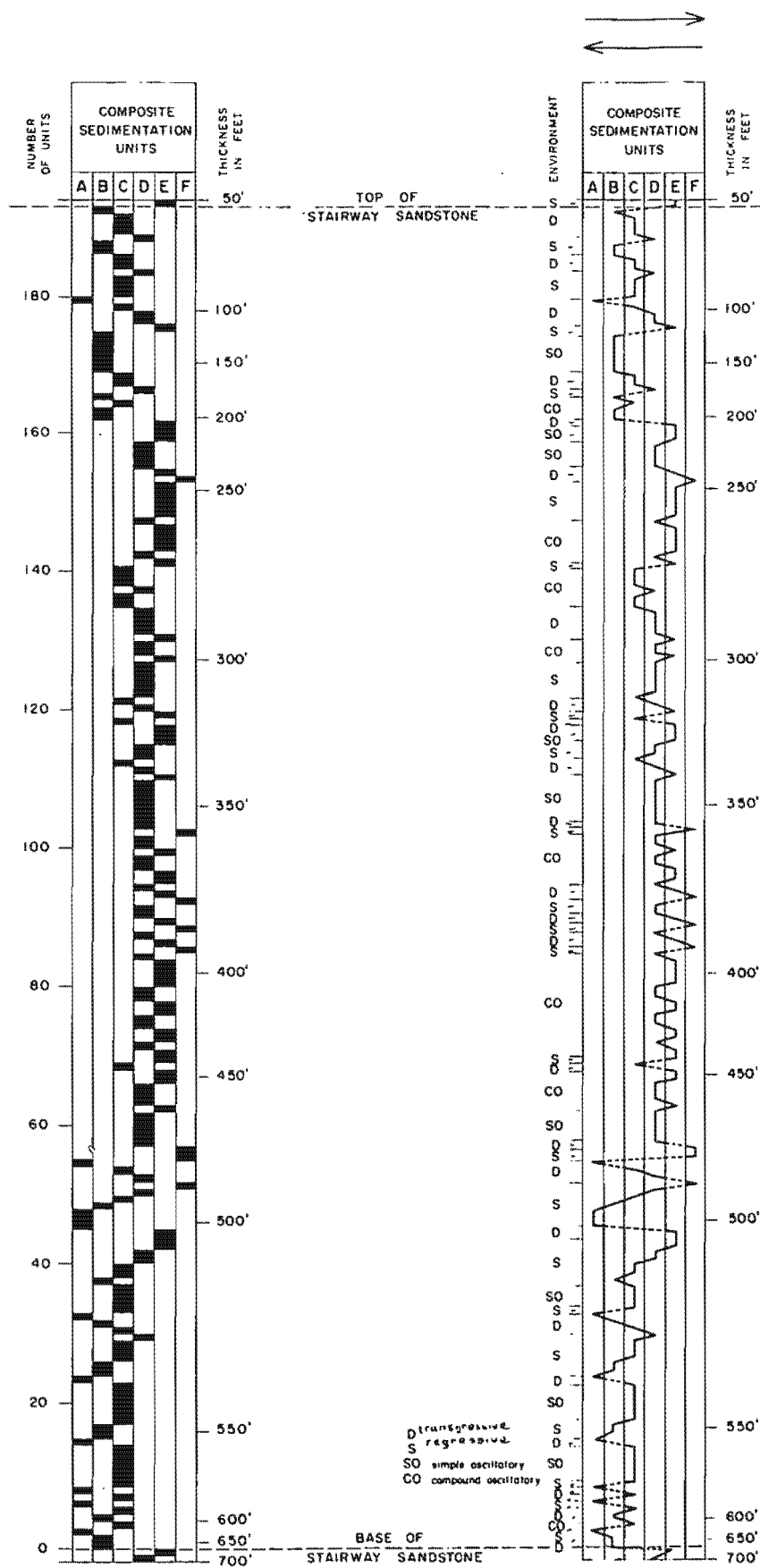
is shown in Fig.26. Each sedimentation unit is represented by unit thickness, i.e. the vertical scale is not a linear foot scale (although footages are shown), because the thickness of the composite sedimentation unit is inherent in the type of unit. The actual form of the cyclicity is now apparent and can be seen to be not just one major regression-transgression but a series of regressions and transgressions. The fact that the sequence A - F is regressive should not however necessarily be construed at this stage as indicating that for instance unit D formed in a shallower environment than unit A, for in fact the reverse may hold if A represents a sand bar environment and D a lagoonal environment.

The Compound Sedimentation Unit

The Compound sedimentation unit is a unit made up of all 6 of the composite sedimentation units A, B, C, D, E and F. It is the idealized complete sequence (Fig.27) but as can be seen in Fig.26, there is no complete, unbroken A - F sequence in the formation. Many of the sequences shown in Fig.26 cannot be designated as indicating regressive (S) or transgressive (D) for they are made up of the same unit repeated (C - C - C - C etc.) which is designated "simple oscillatory" (SO), or alternatively they consist of repeats of adjacent composite sedimentation units (C - D - C - D - C - D etc.); this is designated "compound oscillatory" (CO). Within the Stairway Sandstone there is evidence of 25 episodes of appreciable regression and transgression; 9 separate episodes of simple oscillatory sedimentation and 8 episodes of compound oscillatory sedimentation.

The basic environment in which all these fluctuations were taking place can be ascertained from the compound sedimentation unit.

THE BASIC SEQUENCE — COMPOUND SEDIMENTATION UNIT

Fig 27
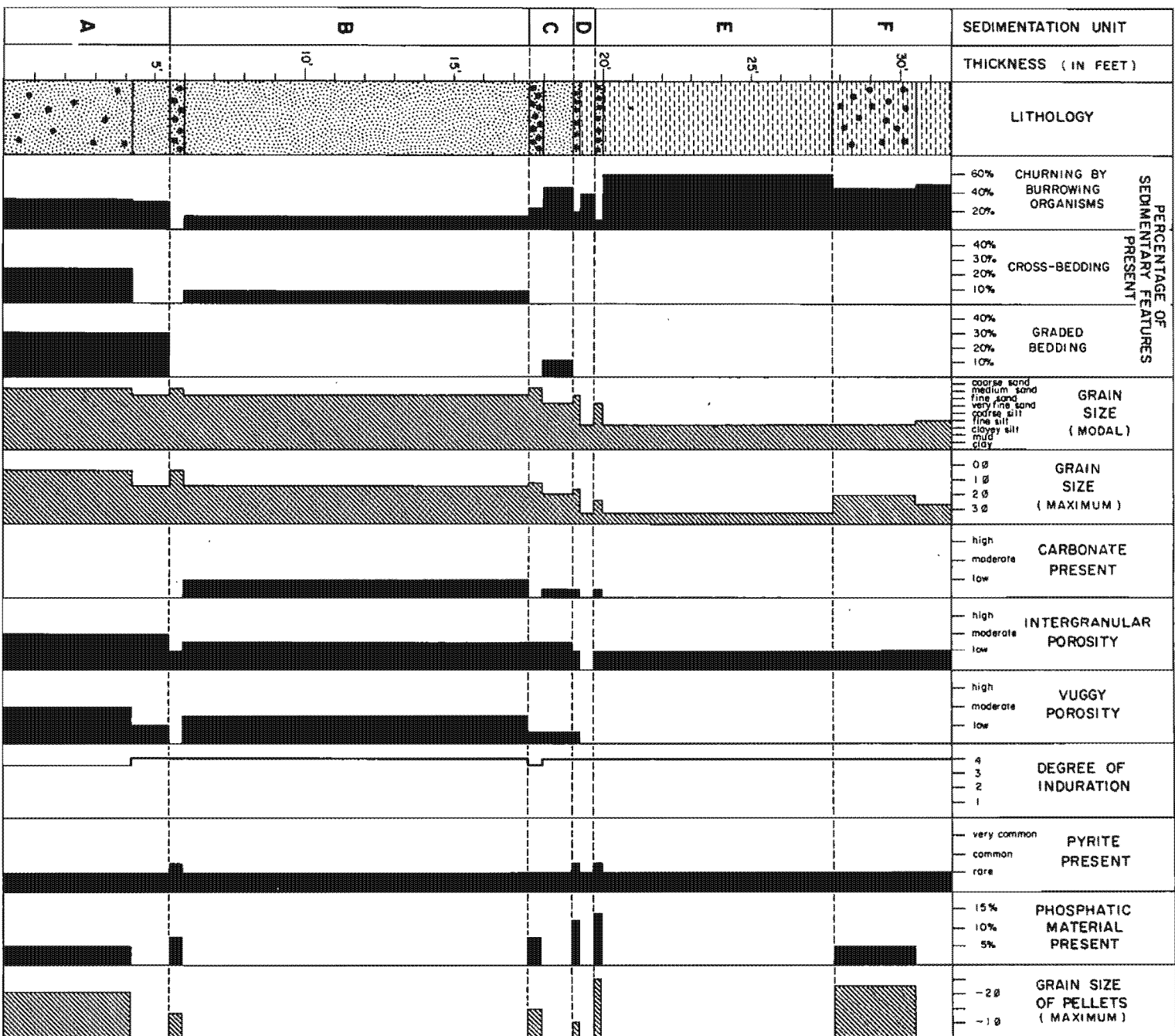
The Sedimentological Model

To find a present day sedimentological model in which to fit the available Stairway Sandstone data, we must look initially for a regressive phase in which the shoreward sediments are finer than the seaward sediments. There are two well documented modern environments in which this occurs - the barrier island-coastal lagoon environment and the intertidal flat environment.

The Barrier Island-Lagoon Environment:

Rusnak (1960) describes in detail the sub-environments of the barrier island-lagoon complex of the Laguna Madre of the Gulf of Mexico. His environments are shown in Fig.28 together with the Stairway Sandstone equivalents. The "correlation" between the Stairway compound sedimentation unit and Laguna Madre environments are:-

A = Barrier island (fairly coarse grained, cross-bedded sands)

B = Barrier flats (Bedded sands)

C = Shallow bay (mixed sediments)

D = Shallow bay

E = Central bay (mixed sediments)

F = Central bay or upper bay (silty clay).

The environmental implications of these correlations for each of the composite sedimentation units can now be considered. All the information on the modern environment is from Rusnak (1960).

A. As can be seen in Fig.27, unit A is the most prominently cross-bedded unit in the sequence - this is completely compatible with a barrier island sand. The presence of some

COMPARISON OF THE COMPOUND SEDIMENTATION UNIT WITH MODERN ENVIRONMENTS
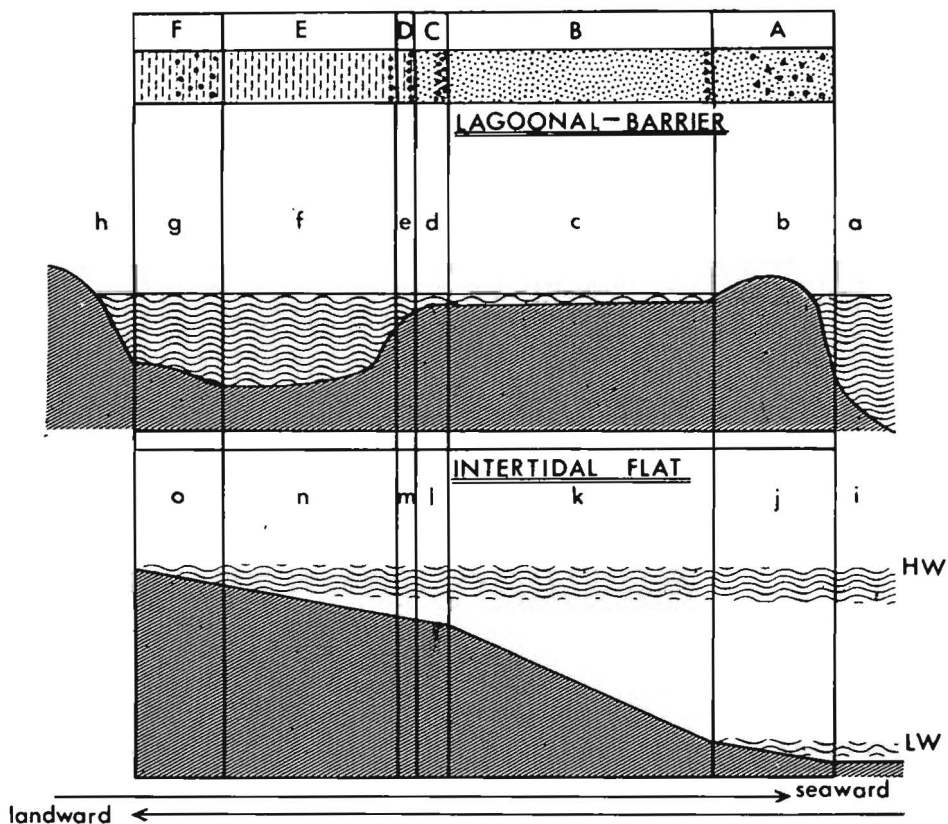
fig28

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Reference to Fig.28

A - F - composite sedimentation units (see Figs.25-27)

LAGOONAL-BARRIER

a inlet (open sea)

b barrier island

c barrier flat

d shallow bay (1)

e shallow bay (2)

f central bay

g central/upper bay

h upper bay-beach

INTERTIDAL FLAT

i open sea (below low-water)

j lower sand flat

k lower mud flat

l Arenicola sand flat

m inner sand flat

n higher mud flat

o higher mud flat or salt marsh

graded bedding suggests some inlet sands may have been included within this composite sedimentation unit.   It is suspected that some of the phosphate of unit A may have been derived, the pellets and nodules having been reworked from some other part of the basin and then due to wave action on the seaward side of the postulated barrier island, incorporated in the barrier beach sands. The presence of some chewing by burrowing organisms is not a feature normally associated with barrier islands.   This may again be due to some inlet sediments being included within unit A or alternatively the barrier island may have been submarine for a considerable part of its history.

B.   This unit is the thickest unit of the compound sedimentation unit; it may also have been the widest environmental zone. Most of the textural and other features could be associated with the barrier flat environment of Rusnak (1960) apart from the presence of burrowing organisms - this again may be attributable to the sediments of Unit B having been deposited at a greater depth below sea level than the equivalent zone in the Laguna Madre. Deposition during unit B sedimentation was probably too arenitic for rich phosphorites to form, but some concentrations occur at the base of the unit.   The concentration is probably the result of winnowing, occurring either as a result of onshore winds or due to waves or currents coming over the barrier island, or both.

C.   The shallow bay environment occurs on the barrier island side

of the shallow bay of the Laguna Madre. In unit C there is evidence of an appreciable rise in the infaunal activity, and a decrease in grain size. Phosphatic pellets were able to form in the unit C environment and moderate concentrations of phosphorites were produced when currents were available to winnow the sands. As the shallow bay environment is some distance away from the source of the detrital quartz (the barrier island) it is to be expected that by analogy unit C would be thinner than unit B. This is found to be the case (see Fig.27).

D. The bay side of the shallow bay subfacies of Rusnak (1960) which is beyond the zone of appreciable arenite sedimentation, is the likely zone for the formation of unit D. As in unit C, the environment of unit D is one of appreciable phosphate deposition, with a high phosphorite to lutite ratio, probably because the shallow bay environment is within the reach of winnowing action.

E. The most likely environment of deposition of unit E is the central bay in the zone of silt/clay sedimentation, where there is little terrigenous material. Unit E contains the greatest thickness of lutite of any of the composite sedimentation units, and phosphate pellets are rare. Winnowing took place only very rarely (perhaps when a major breach of the postulated barrier island occurred), so that the proportion of phosphorite band to lutite is very low in unit E.

F. A slight increase in grain size occurs in Unit F as compared

with E. This may indicate that unit F is equivalent in part
to the upper bay environment of the Laguna Madre. The
increase in grain size may not however be significant as there
is a corresponding decrease in amount of infaunal activity
in unit F, suggesting that it is probably equivalent to
nearer the middle of the central bay environment of the Laguna
Madre. The environment represented by unit F is probably
one of optimum conditions for the deposition of phosphate,
as phosphate occurs throughout much of the lutite sequence.
Enrichment does not however occur, as the environment
represented by unit F is either at too great a depth or
too far removed from the open sea for the effects of currents
or waves not to be felt.

Thus the compound sedimentation unit will fit satisfactorily
into the barrier-bay facies of Rusnak (1960). The application of
this model cannot be too strict as the type of lagoonal environ-
ment envisaged for units D, E and F during Stairway Sandstone times
is very much less restricted than that of the Laguna Madre.

There are however difficulties in this concept - the major
one being the magnitude of the lagoon. It can be seen in the
Stairway Sandstone of AP1 (Fig.25) that the interval 470' to 200'
is made up of simple oscillatory or compound oscillatory sequences
of D, E or F so that for the whole of the middle Stairway times
a central bay (with minor shallow bay and upper bay) environment
of the Laguna Madre type prevailed over an area of about 20,000
square miles. Therefore in spite of the way the environment of
the compound sedimentation unit fits the bay-barrier island

concept it cannot be considered as <u>normal</u> when it is necessary to spread this essentially restricted environment over many thousands of square miles.

The comparison is not therefore entirely satisfactory and it is necessary to look at the second model.

The Intertidal Flat Environment:

The intertidal flat environment and its subfacies has been well documented by Evans (1965) who studied the intertidal flat sediments of the Wash. Possible correlations between the subfacies of the intertidal zone of theWash and the composite sedimentation units of the Stairway Sandstone are shown in Fig.28. The correlations are as follows:

A = Lower sand flats. (Little or no organic reworking, minor wave action, strong tidal currents, slow sedimentation.

B = Lower mud flats. (Little reworking by waves or organisms; rapid sedimentation).

C = <u>Arenicola</u> sand flats. (Extensive reworking by waves and <u>Arenicola</u>; slow sedimentation).

D = Inner sand flats. (Limited reworking by waves; extensive reworking by <u>Corophium</u>; slow sedimentation)

E = Higher mud flats (very limited reworking by waves and organisms. Fairly rapid sedimentation).

F = Upper part of the higher mud flats or the lower part of the salt marsh (no reworking by waves or organisms; fairly slow sedimentation, filter effect of plants).

The terms "mud flat" and "sand flat" used by Evans (1965) are field terms based on general appearance and not on size composition.

The "lower mud flat" has for instance a median diameter of
3.57∅ which in fact would place it in the very fine grained sand
range.   All the information used below for the modern
environment is from Evans (1965).

A.   Megaripples are extremely common in the lower sand flat

part of the intertidal environment, due to very strong

currents.   Had such currents been operating during the

deposition of composite unit A they would have produced

cross-bedding indistinguishable in the core from any

other form of cross-bedding and could have brought in

phosphatic pellets from other parts of the basin.   Boring

organisms are fairly common both in the lower sand flat and

in composite unit A.

B.   The lower mud flat zone is the most steeply dipping part of

the intertidal zone;   it is generally poorly laminated with

alternations of sand and mud (unlike unit B which is virtually

all sand) and it is only rarely rippled.   Burrowing organisms

are rare in both unit B and the lower mud flat zone.   Little

reworking and winnowing of the lower mud flat zone occurs,

consequently little concentration of phosphatic pellets takes

place, in unit B and the ratio of phosphorite to arenite is

low.

C.   Unit C is thought to be the equivalent of the Arenicola sand

flat zone which is composed of well sorted sands, with poorly

developed laminae, and with abundant infauna - especially

Arenicola (a living form probably very similar to the

Ordovician Diplocraterion, a common fossil in the Stairway

Sandstone). The <u>Arenicola</u> sand flats are apparently subjected to fairly strong current action at times - by analogy, composite unit C would be subjected to current action, which would winnow away sand to produce enriched pelletal bands and give a high phosphorite-arenite ratio.

D. Composite sedimentation unit D may be a fine grained equivalent of the inner sand flat. There is an abundant infauna in the inner sand flat environment - particularly <u>Corophium</u> sp. which leaves a trail not unlike that of <u>Scolithus</u>, and likewise, unit D shows the effects of fairly intense burrowing activity. There is some reworking in the inner sand flat environment of the Wash, by wave action. Wave action (even if only minor) would produce the type of winnowing of phosphorites which is apparent in composite unit D from the high phosphorite:lutite ratio.

E. This unit is considered to be equivalent to part of (or possibly the whole of) the higher mud flat environment which is made up of well developed laminated muds. The average median diameter of the sediments is 4.51∅ - compared with unit E which is clayey silt (Table 10, appendix). The size ranges are therefore very similar. Mud cracks are common in the higher mud flat environment, but could not be observed in the AP1 core. The lack of organisms reported by Evans (1965) in the higher mud flat environment is somewhat different to the abundant infauna of unit E. The absence of wave activity is however entirely compatible with the situation in unit E where a very low value for the phosphorite to lutite ratio

suggests that little winnowing occurred during most of the

sedimentation. Such reworking as did occur in the unit E

environment would probably have been in response to some

exceptionally high tide or storms.

F. The affinities of unit F are a little uncertain. Its

position above unit E (the equivalent of the higher mud flat

environment) would suggest that it should be correlated with

the salt marsh environment. This is also supported by the

grain size; the median grain size is in the range 6ϕ to

7ϕ for unit F and 5.8ϕ to 7.6ϕ for the salt marsh environment.

In the salt marsh environment there is no reworking by waves.

This is entirely in accord with the distribution of the

phosphatic pellets within unit F - the pellets have formed

in situ and have undergone no winnowing or other reworking to

give any concentration. Evans also considers that infauna

is rare - this does not fit in with the abundant infauna in

unit F; nor does the abundance of such surface markings as

mud cracks or fossil tracks and trails. There is no evidence

of sub-aerial exposure in unit F. Also the salt marsh

environment is not one in which phosphorite pellets would form

in situ. Conditions of pH of 7.1 to 7.8 (the conditions

necessary for the formation of phosphorites - Krumbein and

Garrells, 1952) are not conditions attained in salt marshes.

Therefore F is either equivalent to the top of higher mud

flats or else represents a somewhat modified version of the

salt marsh environment.

However, in general, the sediments of the intertidal zone have many similarities with the composite sedimentation units of the Stairway Sandstone, but as with the lagoonal environment, there is a size problem. It is impossible to imagine an intertidal zone hundreds of miles wide. Once a shallow-water zone has this great width it loses its "normal" shallow water characteristics because a very different mechanical system is set up. It is therefore necessary to look at a third model which has no present-day counterpart but which may be considered as having affinities with the intertidal zone model.

The Epeiric Sea Environment:

The environmental implications of epeiric sea sedimentation have been clearly set out byShaw (1964) and Irwin (1965). Both authors consider that there are three basic environments, delineated by their hydraulic energies (named X, Y and Z by Irwin, 1965). The outer zone (X) is a wide low energy zone below open sea wave base. The second zone (Y) is fairly narrow and has high energy; it represents the zone where the oceanic waves impinge on the sea-floor, expending their kinetic energy. The inner zone (Z) is a very wide shallow zone of very low energy in which even the effects of tides are not felt. Therefore in this inner zone the sediments are all extremely fine grained and evaporites may form, for the lack of circulation is likely to produce high salinities. The high energy zone is the zone of the coarsest sediments. Irwin and Shaw both consider that this is the zone of biogenic sediments. However, under the right circumstances it can also be the zone of coarse

fig29

THE "EPEIRIC SEA CONCEPT" APPLIED TO STAIRWAY SANDSTONE SEDIMENTATION

TO ACCOMPANY RECORD 1966/1   AUS I/I20
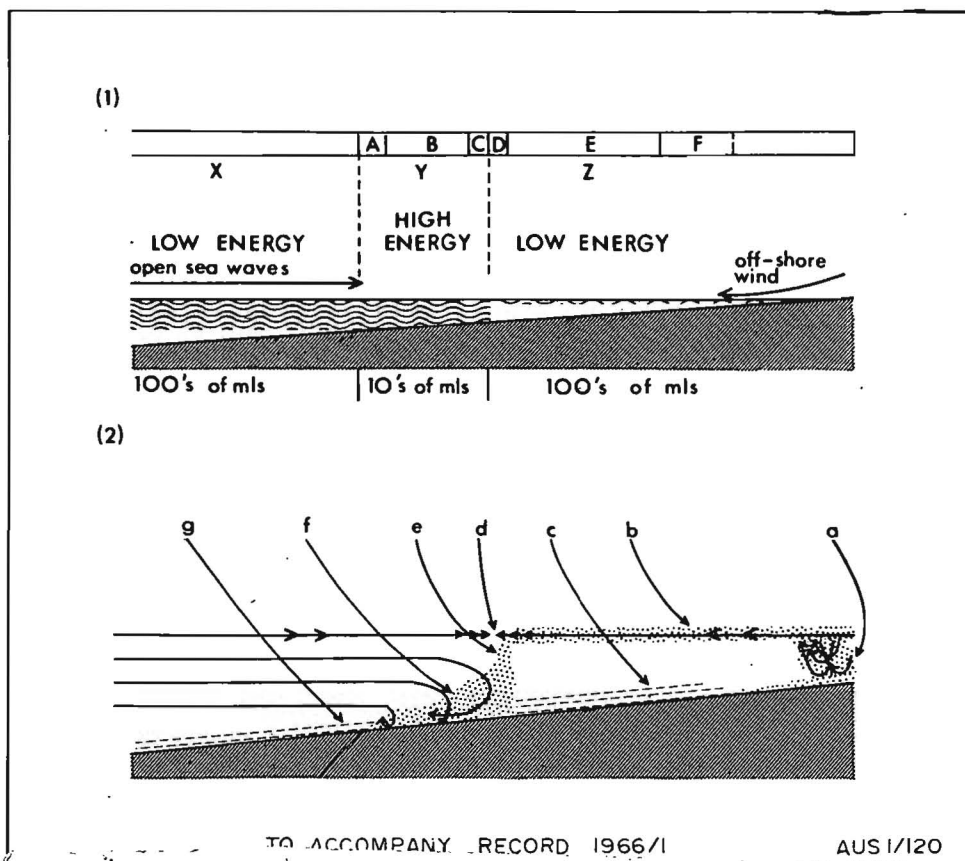
Reference to Fig. 29

A, B, C, D, E, F - composite sedimentation units (See Figs. 25-27)

X, Y, Z - the energy zones of Irwin (1965)

a - sediment picked up at strand line

b - sediment carried in shallow offshore wind-induced current

c - very fine grained sediments in low energy environment

d - the offshore wind induced current meets the open sea
     currents and waves

e - the velocity of the sediment-carrying current is reduced
     to zero here therefore the load of sediment is dropped

f - sediment being winnowed by oceanic currents so that only
     coarse sands remain

g - winnowed-out fines are carried into deeper water.

terrigenous sedimentation particularly if there is a fairly
strong offshore wind or occasional offshore storms. This
will result in offshore currents, and waves in the shallowest
zone, i.e. the strand line, which is also commonly a zone of
sands. These ?wind induced shore currents will carry strand-
line sediments until they meet the oceanic currents in the high
energy zone, the sediment carrying current is reduced to zero
so that the load of detritus is now dropped into the high energy
zone. Within the high energy zone a considerable amount of sorting
and winnowing will take place to produce coarse grained well sorted
well rounded sands. The finer material may be carried out into
the Zone X of Irwin (1965). Alternatively, the sands of Zone Y
may be carried into the zone by longshore currents, which would
not necessitate having to move terrigenous sediments across the
low energy zone of the epeiric sea.

Shaw (1964) is wrong in asserting that an epeiric sequence of
coarse sediments overlain by fine sediments implies transgression
for in fact it can equally well imply regression - it all depends
whether the overlying fine sediments are those of the deeper Zone X
or those of the shallower Zone Z.

In the compound sedimentation unit (Fig.27) of the Stairway
Sandstone the sequence is regressive coarse into fine, in which
the sediments of units A, B and C are deposited in the high energy
zone (Y), and D, E and F in the low energy zone (Z). The sediments
of zone X are not represented in the sequence - they may be
represented by the predominantly silt/clay sediments of the
underlying Horn Valley Siltstone. The presence of phosphate is

an added complication to the hydrodynamic picture for it may mean that cold upwelling currents (McKelvey et al., 1959) are also impinging on the epeiric sea. This is unlikely to alter the energy picture appreciably. The epeiric sea model and its Stairway Sandstone equivalents are now discussed in detail:-

A. Composite sedimentation unit A represents the seaward side of the high energy zone, where there is a great deal of reworking of sediments so that the sands are coarse grained. Irwin (1965) considers that this high energy zone is the zone of highest porosity (due to the winnowing action) and in the Stairway Sandstone it is in fact found that unit A has the highest porosity (Fig.27). Phosphorites are probably not precipitated in this zone but reworking of pellets occurs.

B. Unit B is still within the high energy zone but a considerable portion of the energy has already been expended in the zone of unit A sedimentation, therefore the effects of winnowing are less pronounced. It is also the zone of maximum arenite accumulation, and this coupled with the lessened winnowing action produces a thick sand sequence with only rare, thin, pelletal bands.

C. Unit C is on the edge of the high energy zone, consequently current action is only minor and little reworking of sediments occurs. There is however only minor arenite sedimentation, therefore the ratio of phosphorite to terrigenous sediment is fairly high. High energy currents do occasionally impinge on this unit so that winnowing (and subsequent enrichment) of phosphorites occurs. This is a zone of slow sedimentation,

therefore there is an appreciable rise of infaunal activity
between unit B and unit C.

D. Unit D is situated on the seaward side of the low energy
    zone Z and is outside the zone or arenitic sedimentation.
    Sedimentation is probably extremely slow so that the
    proportion of phosphorite to lutite would be moderately
    high.   This is however coupled with the fact that whilst
    the oceanic currents will only rarely impinge on this zone,
    it is nevertheless, compared with the other lutite units E
    and F, a zone subjected fairly frequently (again, comparatively),
    to high energy reworking. Consequently, the ratio of
    phosphorite to lutite is very high.

E. Unit E is well within the low energy zone (Z); sediments
    are predominantly lutites, sedimentation is slow, infaunal
    activity is considerable.   Because of its position within
    zone Z, unit E is hardly ever subjected to high energy
    winnowing action.   Therefore enrichments of phosphatic
    pellets occur only extremely rarely and the proportion of
    phosphorite to lutite is very low.

F. Unit F is the most shoreward development of the low energy
    epeiric sea environment represented in the compound sedimentation
    unit of the Stairway Sandstone.   It is evident that the
    environment is one of extremely restricted circulation and the
    fauna inhibited, for there is an appreciable decrease of
    infaunal activity in unit F as compared with unit E.   There
    is a slight increase in the grain size and this may be a
    reflection of the proximity of the strand line.   Sedimentation

is extremely slow in this environment so that phosphatic pellets

can "make their presence felt" because of the lack of

diluting terrigenous material.   There is evidently no

reworking in this zone (because it is very far removed

from high energy zone Y) so that there are no winnowed

phosphatic concentrations in Unit F.

It would therefore appear that the compound sedimentation

unit can be fitted most satisfactorily into an epeiric sea

model by modifying the model of Shaw (1965) to account for

terrigenous sedimentation. Concentrations of phosphatic

pellets are in most cases a reflection of the impinging of

the high energy zone.   The reasons for migration of the high

energy zone are a little obscure.   The most likely reasons are:-

(i)   local subsidence of the epeiric sea floor may take

place, so that the high energy waves now impinge on a

more landward zone.

(ii) a general rise in the levels of the oceans, involving

global climatic changes.   This is unlikely in view of

the frequency of winnowed phosphatic pellets.

(iii) Storms may produce higher energy waves than normal so

that they are able to penetrate further into the epeiric

sea.

(iv) the amplitude of waves may vary so that waves with a

smaller amplitude than the normal impinging waves would

also penetrate further into the epeiric sea.

It is likely that all of these mechanisms acted at some

time or other during the Stairway Sandstone sedimentation.

Summary

The Stairway Sandstone is a regressive-transgressive sequence. The large number of sedimentation units in the Stairway Sandstone may be grouped into six types of composite sedimentation units (A, B, C, D, E and F) which together form a regressive compound sedimentation unit (A to F) or a transgressive compound sedimentation unit (F to A).

The compound sedimentation unit can be equated with two modern nearshore environments, the barrier island-lagoon environment and the intertidal zone environment and a more hypothetical epeiric sea model.

STAIRWAY SANDSTONE	BARRIER-LAGOON	INTERTIDAL FLAT	EPEIRIC SEA
F Slightly phos fine silt	Central or upper bay	Higher mud flat or salt marsh	Inner low energy zone (Z)
E v sparsely phos clayey silt	Central bay	Higher mud flat	Middle low energy zone (Z)
D Richly phos clayey silt	Shallow bay	Inner sand flat	Outer low energy zone (Z)
C Richly phos v fine sand	Shallow bay	Arenicola sand flat	Inner high energy zone (Y)
B v sparsely phos fine sand	Barrier flats	Lower mud flat	Middle high energy zone (Y)
A Slightly phos medium sand	Barrier island	Lower sand flat	Outer high energy zone (Y)

Both the models of modern environments are inadequate because of their small areal extent compared with the enormous extent of the Stairway Sandstone environments. This difficulty could possibly be partly resolved by the intertidal or lagoonal environment migrating over the basin so that gradually a

coalescing body of lagoonal or intertidal sediments formed. The third model is more satisfactory and it is possible to account for most of the features of Stairway Sandstone sedimentation, with the sands being laid down in the high energy zone (Zone Y), the silts and clays being deposited in the low energy zone (Zone Z) and the pelletal phosphorite concentrations resulting from reworking of sediments brought about by migration of the high energy zone.

CHAPTER 8

THE STAIRWAY SANDSTONE PHOSPHORITES

General

Phosphatic sediments have been found in the Upper Proterozoic

and Lower Palaeozoic sediments of the Amadeus Basin, but it is only

in the Stairway Sandstone that they are abundant. The occurrence

of phosphorites in the Stairway Sandstone was first noted by

Wells, Forman and Ranford (1962). Subsequent work by Cook (1963)

and Barrie (1964) showed that the Stairway is slightly phosphatic

throughout but sediments regarded as phosphorites occur mainly

in the middle Stairway, as is clearly shown in Fig.21. The

phosphatic mineral is crypto-crystalline but X-ray studies by

Greaves (pers.comm., in Cook, 1963) have shown it to be apatite.

The phosphorites most commonly are pelletal or nodular and

they are generally grey or brown in colour, although purple

phosphorites are present in the Mount Charlotte area, and white

phosphorites are known from the vicinity of The Sisters, west of

the Mount Charlotte Range. The phosphatic beds range in thickness

from less than 1 inch to about 8 inches but their average thickness

would only be from 2 to 4 inches. Little is known about the

lateral extent of individual phosphorite beds as poor exposure makes

it impossible to follow such thin beds for more than a few feet.

However, the same stratigraphic interval appears to be phosphatic

over a wide area. Boundaries between phosphatic and non-phosphatic

sediments are extremely sharp, particularly the lower boundary.

Current induced sedimentary structures appear to be extremely rare

in the actual phosphorites, though they are common in associated

sediments (e.g. ripple marks, cross-bedding). Rare worm burrows have been seen in very slightly phosphatic sandstones.

The nodules are extremely varied in size and shape (Fig.54, appendix) and P_2O_5 content. Pellets and nodules may range in size from a $\frac{1}{2}$ inch or less, to 5 inches. The two main types of nodules are grey and brown. The grey pellets may have an extremely irregular form with surfaces commonly re-entrant. The surfaces are frequently finely pitted and have an appearance not unlike that seen in the surface of some fossil algae. The brown pellets are smoother than the grey pellets; they tend towards an eliptical shape, whilst the grey pellets are flatter and slightly more disc-shaped. In hand specimen, the brown pellets appear to be more sandy than the grey pellets. The few analyses that have been undertaken indicate that the grey pellets are more phosphatic than the brown pellets, e.g. in analyses from a locality near AP1, a grey pellet was found to have a P_2O_5 content of 19% and a brown pellet was found to have a P_2O_5 content of only 13% (probably a reflection on the higher sand content - see Fig.80, appendix).

Detailed study of many of the 219 phosphorite bands in the AP1 core confirmed the majority of the field observations. It was not however possible to distinguish different types of pellets in the core, all the pellets being black (chroma N3 - N4). In subsurface, boundaries between phosphatic and non-phosphatic sediment were also found to be extremely sharp. In addition, 16 bands showed good positive grading (i.e. coarse pellets at the base and fine pellets at the top) and negative graded bedding occured in 8 of the phosphorite bands. The

graphic logs (see Appendix IV) indicate that many of the phosphorite bands show a particular type of bimodality, with a fine mode within the pellets and a coarse mode in the surrounding sediment. This is discussed more fully later. Both the modal and maximum grain size of detrital grains increases with the incoming of phosphatic pellets. This will also be discussed more fully later.

Generally, the pellets appear to show a higher degree of rounding and sphericity than is shown by the pellets in outcrop, but as in most cases, the sub-surface pellets were only visible in two dimensions, this difference may be more apparent than real. The pellets are commonly (but not always) aligned with their long axes parallel.

Chemical Analyses

The results of P_2O_5 and trace element analyses on samples from the Stairway Sandstone are recorded by Ranford, Cook and Wells (1966), Wells, Stewart and Skwarko (1966) and Barrie, (1964).

A total of 90 outcrop samples and subsurface samples have so far been analysed for P_2O_5 (by colorimetric methods, using molybdo-vanadate). The highest value obtained is 27% P_2O_5 for a grey phosphatic nodule (specimen number LA701C) from the Inindia Bore area. The highest value obtained for a phosphatic bed (as opposed to an individual nodule) is 21.6% P_2O_5 for specimen LA 535(9) from the Johnny Creek area of the Lake Amadeus sheet. There appears to be a wide variation in the P_2O_5 content of pelletal or nodular bands but most values fall into the range 10 to 18% P_2O_5. Very few analyses of StairwaySandstone lithologies

have P_2O_5 contents below 0.5%, indicating that throughout the whole Stairway Sandstone, the P_2O_5 contents are at least two to three times above the average values for sediments. Barrie (1964) considers that there may be some secondary enrichment of the P_2O_5 content of beds at the surface as so far, the highest value obtained for a subsurface sample is about half that obtained for surface samples. However, this cannot be confirmed until many more analyses have been carried out.

The lack of an adequate number of analyses make it impossible to reach any conclusions regarding the lateral or vertical variations of P_2O_5 content of phosphorites within the Stairway Sandstone.

Fourteen samples of Stairway Sandstone sediments have been spectrochemically analysed for nickel, cobalt, copper, vanadium, and lead (Ranford, Cook and Wells, 1966). Many of the samples were found to have somewhat higher values for these trace elements than is normal for sediments. This is particularly true for the values obtained for lead and in a sample with a P_2O_5 content of 18% (ML37) the lead content was 400 parts per million; in the same sample, the copper content was 100 parts per million. The few results available show a crude correlation of increase in trace elements such as lead with an increase in the P_2O_5 content (Fig.30), but it is impossible to reach any definite conclusion at this stage, with so few analyses available. It is, however, anticipated that more work will show a good correlation between phosphatic concentration and trace element concentration as is found for instance in the Phosphoria Formation (McKelvey et al., 1959).

fig 30

Variation of trace element content with phosphate
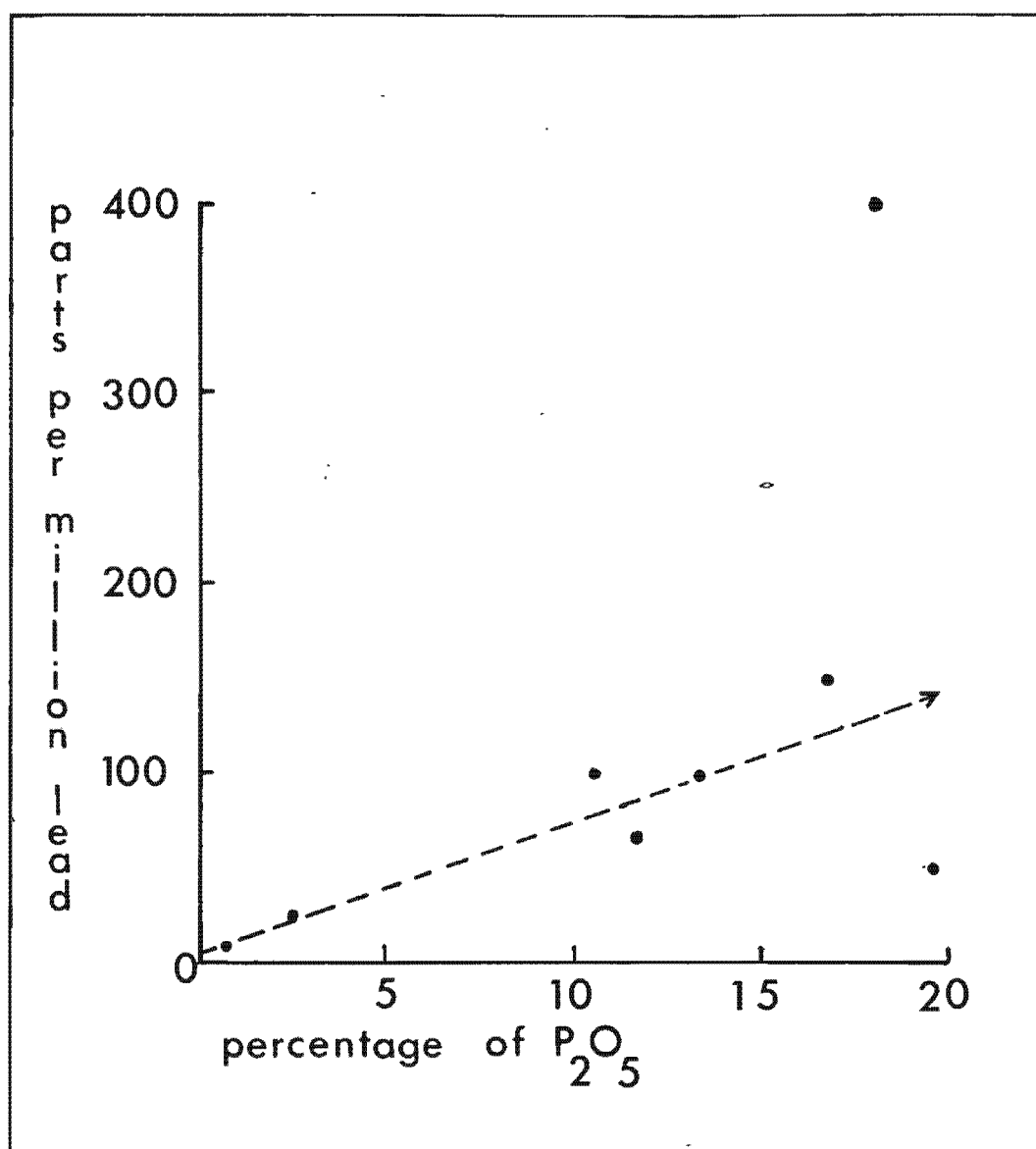
Petrography

Thin section examination of the phosphorites has shown that there are a large number of forms in which the phosphatic material (generally apatite) may occur. Its overall colour may range from almost colourless to almost black but the most normal colour is pale brown to dark brown. It shows all the normal properties of the minerals referred to under the collective term of collophane, such as high relief and isotrophy.

There appear to be ten main modes of occurrence of phosphatic material, most of which are pelletal or nodular in form. In the type of empirical classification used here, there is of course overlapping, with some pellets showing features of two or more classes but in such cases compound names may be used to describe the pellets. Most of the pelletal names pre-suppose that the outline of the pellet is rounded and sub-spherical but if necessary the class may be qualified by "irregular" etc. If it is desired to give the phosphatic types a size connotation, "pelletal" may be replaced by "nodular" for coarser grades (generally 2mm. and above). The ten classes of phosphatic types are now discussed individually.

1. Structureless pelletal phosphate (Figs.55-58, appendix).

This is one of the commonest pelletal forms and shows no internal structure whatsoever (Fig.55, appendix), although it may have a single thin dark rim (Fig.56, appendix) (suggested by Emigh (1958) as being caused by the outward migration of carbonaceous material in the phosphatic pellet). These pellets may range in size from silt size and below to coarse grained sand size and above. In some cases, the modal grain size of these pellets is the same as

the modal grain size of the detrital quartz in the enclosing sediment, suggesting that the phosphatic material may have been swept in with the detrital sand or that it may have been winnowed.

In some thin sections (e.g. AP3/44/0), there is a striking similarity of shape and size between structureless pellets and glauconite pellets, and grains, suggesting that the structureless pellets may be in part the result of early diagenetic replacement of glauconite (Fig.57, appendix). Alternatively it may just indicate that phosphate precipitates are formed in a similar way to glauconite precipitates.

2. Concentric Pelletal phosphate (Fig.59, appendix)

This type of pellet is distinguished by the dark and light bands within the pellets, which are concentric to the exterior of the pellet, even when the exterior of the pellet is extremely irregular (e.g. in LA 131 and in AP1/73/2 (Fig.59, appendix). Emigh (1958) has suggested that the banding must be a diagenetic feature otherwise it would not be parallel to the irregular exterior of the pellets. He attributes the banding to the outward migration of organic carbon. Some of the banding in the concentric pellets may possibly be attributable to this migration but little evidence for or against Emigh's theory could be found.

There are however two special cases of concentric banding in which the banding is almost certainly a primary feature. In thin section LA 535 (A), very fine mica flakes within a pellet are arranged with their long axes concentric to the outside of the pellet. It is thought that this type of banding developed by the rolling around of the relatively soft phosphatic pellet on

the sea floor and as it rolled the fine flakes of mica were
picked up and subsequently incorporated into the pellets.
Similarly, in AP1/596/0, very fine ooliths of ?pyrite are
arrnaged in two bands concentric to the exterior of a pellet
of about .075 diameter.   As with the mica, the ooliths may
have been picked up by the pellet and subsequently incorporated
in it as it rolled over them, or alternatively, they may have
formed within the pellets during diagenetic pyritization.

3.   Composite pelletal phosphate (Fig.60, appendix)

As is suggested by the name, this pelletal form is made up
of other smaller pellets (generally structureless).   The composite
pellet is fairly common; a good example may be seen in AP1/97/3
(Fig.60, appendix).   This type of pellet probably forms by the
cementing together of earlier formed pellets or more rarely
(generally restricted to the very fine grained pellets) by the
"growing together" of pellets.   These processes either form
primary composite pellets or else beds which are subsequently
broken up to form pellets, or nodules.

4.   Structured pelletal phosphate (Fig.61, appendix)

This pelletal type shows an internal structure but is
distinguished from the concentric and composite pellets by
the fact that the internal structure is neither concentric nor
pelletal, but irregular.   An example of this type of pellet
may be seen in LA139 (Fig.61, appendix), in which the internal
structure of the pellet is strongly convoluted. Few examples
of this type of pellet have been seen. The convoluted form
of the internal structure suggests that this type of pellet

may possibly be formed by the phosphatization of fecal pellets although R.P.Sheldon (pers. comm.) reports that similar internal structures thought to be the result of algal activity are present in phosphorites of the Phosphoria Formation.

5. Encasing pelletal phosphate (Figs.62-63, appendix)

The phosphatic material in this type occurs as a thin skin around detrital grains (in most cases quartz). The "skin" is generally extremely thin relative to the diameter of the grain or fragment it is encasing; it is also commonly oolitic, as may be seen in AP1/398/0 (Figs.62-63, appendix). The encased grains are generally well rounded and normally fine grained. The encasing pellets probably form in the manner as calcareous ooliths, i.e. by the detrital grains acting as nuclei on which the crypto-crystalline apatite may precipitate and that as the grains are gently rolled around, further layers of crypto-crystalline apatite are added. This type of pellet may remain discrete or quite commonly, the layers appear to have continued growing until they are sufficiently thick to come into contact with their neighbours, so that movement of grains became impossible and precipitation of phosphate either ceased or continued as a cement.

6. Sandy pelletal phosphate (Figs.64-65, appendix)

This type of pellet is one of the commonest (and possibly the most common) pelletal form and is readily distinguished by the high percentage of sand-sized detrital grains within it. The detrital grains are generally quartz, or rarely feldspar, or heavy mineral grains such as tourmaline or zircon. The crypto-crystalline apatite is present as a cement or matrix, forming up to 50% of the

total pellet (Fig.64, appendix). In most cases, there is a considerable difference in the grain size of the detrital quartz inside the pellets and that outside, suggesting that the pellets have been either reworked or winnowed. It is uncertain whether the primary formation of the pellets resulted from the initial precipitation in a pelletal form of the crypto-crystalline apatite around detrital grains, or from the cementation of bedded detrital quartz to give bedded phosphorites which were later broken up and the material rounded to form pellets. In some of the pellets (Fig.65, appendix), there is a distinct banding of the detrital quartz within the pellets. In some cases, the sandy pellets appear to have formed by the aggregation of encasing pellets.

7. Cementing phosphate (Fig.66, appendix)

This type, in many cases, differs from the sandy pelletal phosphate only by its lack of a pelletal outline. Instead it has indistinct boundaries which may grade into calcite, dolomite, glauconite or clay cements (Fig.66, appendix), although they were not examined with a universal stage microscope to confirm this. This type of gradational boundary suggests that the phosphatic cement may have formed by the early diagenetic phosphatization of the original cement. The cementing phosphate commonly has inclusions of mica (both muscovite and biotite) which lends weight to the idea that the matrix was originally clayey. However, much of the matrix is probably a primary phosphatic cement.

8. Laminate phosphate (Figs.67-69, appendix)

This is a common form of crypto-crystalline apatite and

and is composed of thin elongate laths and laminae which are possibly also platey. They are very variable in size ranging up to 2 mms. in length. Their average width ranges from 0.05 mm. to 0.1 mm. The laminae frequently are aligned with their long axes parallel (Fig.67, appendix). Many of the laminae show a tripartite division into thin upper and lower layers, in places showing extremely fine "micro laminations" at right angles to the axis of the macro-lamina (Fig.69, appendix) and a middle layer which is structureless and very much thicker than the two outer layers. The outer layers of many of the laminae shows signs of corrosion - the corrosion possibly resulting from either the action of micro-organisms or from chemical corrosion (Fig.68, appendix).

The laminate phosphate has either been formed by the break-up of what was once thinly bedded phosphorite or alternatively is phosphatic shell material. The second possibility is the more likely because of the tripartite form of the laminae. The original shell material may have been phosphatic (e.g. an inarticulate brachiopod) or it may have been a calcareous shell which was subsequently phosphatized.

9. Phosphatized Fossils (Fig.70, appendix)

In addition to the laminate phosphate whose fossil affinities are somewhat uncertain, fragments of phosphatized shells of ?lamellibranchs, ?brachiopods and other indeterminate fossils are fairly common in the phosphorites of the Stairway Sandstone (Fig.70, appendix). However, the number of cases of phosphatized fossil fragments forming the centres of pellets or even occurring

anywhere at all in pellets is remarkably small, especially when
compared with modern phosphorites such as those of Southern
California, where a great many of the pellets or nodules contain
fossils.

10. Secondary phosphates (Figs.71-74, appendix)

There are probably a large number of secondary phosphate
minerals in the Stairway Sandstone, resulting from the alteration
and/or replacement of the original crypto-crystalline apatite.
However, because of the lack of diagnostic optical properties,
the extremely complex chemical form of many of the phosphates
and because a thorough search has not so far been made, only
one secondary mineral has so far been positively identified -
corkite.

The presence of corkite - a lead arseno phosphate complex
(Dana 1947) was first confirmed by Goadby (pers.comm., in Wells,
Stewart, and Skwarko, 1964), by X-ray diffraction analysis on
samples from the southern margin of the Henbury sheet area,
collected by Wells and Stewart. In thin section, the corkite
appears to be mainly interstitial, forming from 5 to 15% of the
total rock. Rarely, it has the form of structureless pellets
or ooliths (Figs.71-72, appendix). It is commonly isotropic
but is distinguished from cryptocrystalline apatite by its
characteristic bright green colour.

A colourless phosphate mineral commonly with a spherulitic
habit (Fig.73, appendix), occurs in vugs and in matrix and pellets,
replacing crypto-crystalline apatite (Fig.74, appendix). In
specimen HY 762 there is evidence of the mineral being both

replaced by and replacing corkite. It also occurs subsurface
in AP3 (specimen AP3/710/0) at a depth of several hundred feet
so that it is possible that it is also an early stage alteration
produce of crypto-crystalline apatite, or a phosphate mineral,
as well as possibly being a recent weathering product. The
mineral has not been identified any more positively than
?apatite. Its optical properties suggest that it may be
dahllite.

Previous ideas on the origin of phosphorites

One of the earliest attempts to explain the origin of
phosphorites was made by Murray and Renard (1891), who as a
result of oceanographic observations made during the"Challenger"
voyage suggested that mass mortalities of fish and other marine
creatures are a major factor in the formation of phosphorites.
They suggested that ammoniacal solutions derived from the decay
of organisms would precipitate the phosphate. Blackwelder (1916)
also considered the decay of marine organisms to be a major factor
in the precipitation of phosphate, particularly in stagnant basins.
He postulated that in this reducing environment, the phosphate
may have replaced carbonate in places. Mansfield (1918), also
supported the idea that phosphorites result from the replacement
of calcium carbonate by phosphate-rich solutions obtained from
the decay of marine organisms. He later suggested (Mansfield,
1927), that phosphorites may also be precipitated directly from
a colloidal suspension of phosphate. A third hypothesis which
Mansfield (1940) put forward was that fluorine appears to
play a vital role in the precipitation of phosphorites and

therefore times of vulcanism, when considerable quantities of fluorine are available, would also be times of maximum phosphate precipitation. Pardee (1917) invoked climate as being of primary importance in the formation of phosphorites and suggested that phosphorites such as those of the Phosphoria Formation were laid down under cold glacial conditions, when the seas would be unsaturated in calcium carbonate; hence deposited calcium phosphate would not be "diluted" by an accompanying precipitation of calcium carbonate. Breger (1911), suggested that bacteria is of importance in the concentration of phosphate. This has been supported by Baas Becking (1957) who showed that bacteria in sea water is able to concentrate phosphate by a factor of 200.

Phosphatic nodules and pellets have commonly been ascribed to the phosphatisation of fecal pellets (Hayes and Ulrich, 1903; Cayeux, 1939), but Emigh (1958) suggests that most phosphatic pellets were formed by the phosphatization of calcium carbonate pellets. Sauchelli (1962), also strongly supports the idea of replacement of calcium carbonate. Frondel (1943), points out that the phosphatization of coral limestones occurs on "guano islands".

Poncet (1964) has good evidence to suggest that phosphatic pellets and nodules in the Ordovician of France are the product of the phosphatization of clay pellets. Jitts (1959) has shown that bottom muds may absorb considerable quantities of phosphate.

Bushinski (1964) also considers that the phosphatization of silts and clays is an important process but believes that the phosphatization occurs in situ and that the silts are later

winnowed to remove all sediments except the phosphatized silts and clays which have aggregated to a pelletal or nodular form.

Because of textural and other differences between phosphatic pellets and their surrounding sediments, many workers have postulated that the pellets have been reworked from older formations. Hayes and Ulrich (1903) consider that the Devonian phosphates of Tennessee have been formed by the mechanical reworking of Ordovician phosphorites. Adams, Groot and Hiller (1961) also suggest that the phosphatic pellets of the Brightsea Formation of Maryland may have been derived.

Kazakov (1937) postulated that phosphate may precipitate out directly from sea-water given the right physico-chemical conditions. He considered that precipitation occurs as cold water ascends onto the shelf from the deep parts of the ocean on the western sides of the continents. Calcium carbonate would be first precipitated out as the temperature and pH of the water increases and the partial pressure of CO_2 decreases. The calcium phosphate would be precipitated out at depths of between 50 and 200 metres. The detailed work of the United States Geological Survey on the Phosphoria Formation of the Western United States has broadly supported the conclusions of Kazakov. McKelvey, Swanson and Sheldon (1953), McKelvey et.al.(1959), Sheldon (1963) and Cressman and Swanson (1964), all consider that upwelling ocean currents are the primary source of the phosphates and also that much of the phosphate is probably precipitated out directly. They considered however that phosphate is precipitated out before calcium carbonate and also that the precipitation took place

at depths of between 200 and 600 metres. Upwelling currents are now generally accepted as being a major (and possibly the major) source of phosphate, although Bushinski (1964) has suggested that in fact rivers flowing into barred basins are capable of bringing in sufficient dissolved phosphate to form many of the major phosphorite deposits.

Work by Dietz, Emery and Shepard (1942) on Recent phosphorites on the sea-floor off southern California has shown that topography may bea major factor in the formation of phosphatic nodules for almost all the nodules are found on topographic highs and in a strongly oxidising environment. They considered that the phosphate precipitated directly out from a colloidal suspension and formed in situ. Both topographic and tectonic control have been found by Bentor (1953) and Altschuler (1958) to have influenced the deposition of the phosphorites of the Middle East. Unlike the southern California phosphorites, they found that the phosphorites occur in the synclines which also formed the topographic lows during deposition. The depositional environment was apparently strongly reducing. Youssef (1965) also points out that the phosphorites of Egypt formed in depressions in a strongly reducing environment. He considers that the precipitation of phosphate is mainly a biochemical process and also questions the validity of the upwelling current concept. McConnell (1965) also considers that the precipitation of phosphates is brought about by biochemical influences and suggests that certain enzymes may be of considerable importance in these biochemical processes.

Few hypotheses have so far been advanced to account for the origin of the Stairway Sandstone phosphorites. Cook (1963) suggested that the pellets formed in situ, in localized basins or depressions when the bottom waters which were saturated with phosphate, were subjected to an influx of more oxygenated water also carrying detrital quartz and the phosphate precipitated. Barrie (1964) considered the environment of deposition of the phosphorites was oxidizing and that the phosphorites were mainly formed on topographic highs. He also suggested that the Horn Valley Siltstones underlying the Stairway Sandstone acted as a "reservoir" of phosphate which was "tapped" in Stairway Sandstone times. Crook (1964) considered on petrographic evidence that the phosphatic pellets were detrital allochemical, i.e. that they were formed in one part of the basin and then later transported to another part by current action.

This brief summary is sufficient to show the diversity of previous hypotheses and indicate the difficulty in finding a single theory to explain all features of the Stairway Sandstone phosphorites.

The Origin of the Stairway Sandstone Phosphorites

From the previous pages of this chapter it is apparent that there are several things to be considered in the Stairway Sandstone phosphorites:

i) Are the phosphatic pellets the result of reworking of an older formation; have they been reworked and transported from some other part of the Stairway Sandstone basin of deposition or have they formed in situ?

ii) Were the phosphate pellets precipitated authigenically
by inorganic or organic means or did they form by the
diagenetic phosphatization of pre-existing pelletal
material.

iii) What was the environment.

iv) Did topography and/or tectonics influence the formation
of phosphorites in any way.

v) What was the primary source of the phosphate.

i) <u>Transported or in situ?</u>

Phosphatic pellets are found in several pre-Stairway
Sandstone formations of the Amadeus Basin; the Areyonga
Formation, the Tempe Formation, the Pacoota Sandstone, and the
Horn Valley Siltstone. However, little reworking of these
formations is thought to have occurred during StairwaySandstone
times and in addition, the quantities of phosphate pellets in
these four formations are extremely small. Reworking even of
vast areas of these formations would still not give the quantities
of pelletal phosphate present in the Stairway Sandstone. Reworking
of an older phosphatic formation can therefore be discounted as
the source of the Stairway Sandstone phosphorites.

The question of whether the pellets have been reworked
within the confines of the Stairway Sandstone basin of deposition
or whether they have formed in situ is a difficult question to
settle. Examination of thin sections of the pellets immediately
suggests that the pellets have been transported into their
final resting place. Crook (1964) considers that the

allochthonous origin of the phosphate is indicated by the
following features -

    "(a)   slight to major differences in modal size of quartz
          between pellet and enclosing sediment"

    "(b)   different appositional fabric between pellet and
          sediment"

    "(c)   generally elliptical to ovate, sharp outline of
          pellets"

    "(d)   truncation of rounded quartz grains within pellets
          to conform with pellet margins"

    "(e)   darkening of peripheral zone of pellets in some cases".

Barrie (1964) also states that the phosphatic pellets are
transported, but gives no supporting evidence.

Additional evidence which suggests that the phosphatic
pellets are transported is the almost ubiquitous relationship
between phosphate and the incoming of detrital quartz of very
fine to coarse grained sand size. A rise of both the modal and
maximum grain size of detrital quartz occurs with the incoming of
phosphate in the majority of cases.

Change of modal grain size with incoming phosphate

Rise	85%
Fall	6%
Remains the same	9%

Change of maximum grain size with incoming phosphate

Rise	70%
Fall	13%
Remains the same	17%

Therefore it appears that there is strong evidence to suggest that the pellets are derived or detrital.

If the evidence is examined more carefully however it becomes clear that other explanations are equally valid.

The darkening of the peripheral zone of pellets adds no weight whatsoever to the allochthonous hypothesis for it is probably formed not by sub-aerial exposure, as has been suggested by Crook (pers.comm.) but by the migration of organic material (Emigh, 1958), or by the partial diagenetic pyritization of the phosphatic pellet or by the deposition of more organic matter during the last accretion of the apatite. In addition, dark concentric zones which are clearly not formed by sub-aerial exposure occur well within the pellets (Fig.59,appendix), and are identical with the dark peripheral zone.

The present author has seen few cases of truncation of rounded quartz grains in the Stairway Sandstone phosphatic pellets. By comparison, however, quartz grains quite commonly project out of the margins of phosphatic pellets; such a texture could not be attributed to transport as the quartz grain would very soon be torn from the pellet. Similarly, pellets commonly have highly irregular shapes with knobs and re-entrant faces; it is most unlikely that such irregular features would survive any appreciable transportation.

The difference in appositional fabric and grain size of detrital quartz between the pellet and the enclosing sediment can be explained by moving the pellets into the environment represented by the surrounding sediment as is suggested by

Crook (1964). However the same effect may be achieved by the
pellets remaining in situ and new sediments (i.e. that now
surrounding the pellets) being swept into the environment in which
the pellets are forming and the pre-existing sediment being swept
out. Alternatively the sediment may have been brought in,
phosphorites were precipitated and the sediment was winnowed so
that only the coarse detrital grains and the phosphatic pellets
remained.

It is relevant to return to the previous chapter briefly -
and especially to Fig.27. If the pellets were transported then
the coarsest pellets would be found in the most coarsely grained
sedimentation unit. In fact, precisely the opposite occurs, for
the coarsest pellets are found in composite sedimentation unit F
- the most fine grained of the units. It is exceedingly difficult
to explain this size distribution by a "transportation theory".

In the author's opinion the hypothesis of the pellets being
transported is immediately suspect because of the considerable
difference in grain size between the phosphatic pellets and
nodules, which have diameters of up to 5 inches (approximately
$-7\emptyset$), and the accompanying coarse grained sand with a diameter of
only $0\emptyset$ to $1\emptyset$. Thus, the two types of particles are out of
normal hydrodynamical equilibrium. Nor can the argument be
invoked that the pellets and nodules had much lower specific
gravities than the associated quartz, as specific gravity
determinations on nodules (Table II, appendix) have shown the
average specific gravity of grey pellets to be 2.67 and 2.61 for
brown pellets; both values are close to the specific gravity

of quartz (2.65). It is possible to explain away the grain
size discrepancy by the suggestion that the reason for the
absence of sand coarser than approximately $0\emptyset$ is that coarser
material was not available in the source area, or did not reach
the depositional area. However, this argument is virtually
invalidated by the fact that when conglomeratic or pebbly beds
occur within the Stairway Sandstone they are with few exceptions
completely non-phosphatic which is completely contrary to what
would be expected if the phosphatic material was transported.
The only exception known to the author occurs on the southern
margin of the Amadeus Basin (the Mount Sunday Range and the Erldunda
Range) where large phosphatic pellets occur in the conglomerate at
the base of the Stairway Sandstone.

There are also considerable hydrodynamic difficulties in
moving nodules. The current velocity necessary to transport a
nodule of 5 inches diameter would be in the order of 200 cms.
per second (Hjulstrom, 1939). This is faster than the Gulf Stream
at its fastest point and in the Stairway Sandstone times any such
current must have swept over the entire basin in order to give the
widespread pelletal and nodular phosphorites intervals. This
would have produced tremendous scouring effects within the Stairway
Sandstone, yet these are not preserved. It is also physically
impossible for currents of this magnitude to sweep over 40,000
square miles of shallow seas, for the resistance with the bottom
would be too great and also phenomenal quantities of water would
be moved so that many areas of the basin would have literally been
swept "dry" by the current. Also, if times of maximum deposition

of phosphate do indeed represent times of extremely high current velocities, then it is remarkable that the phosphorites should occur in a predominantly silty-clayey sequence which has all the features of quiet, slow deposition.

Thus, it is apparent that there are many difficulties in the suggestion of a transported origin for the phosphatic material.

In order to establish whether the phosphatic sediments have been modified by transporting or by winnowing, the textural features of the phosphatic pellets and their associated sediments must be examined in detail.

Fig.9 shows a number of cumulative frequency plots for specimens from the Stairway Sandstone of AP1.   As has already been mentioned in Chapter 4, the curves at the left hand side (the coarse grained end) of the plot, e.g. AP1/601/0 (c) represent plots of phosphatic pellets and those at the fine grained end of the plot represent the size distribution of very fine grained sands and also the sands within phosphate pellets.   Plots in the middle of the field, e.g. AP1/792/66 are commonly coarse basal sands.   The plot of AP1/51/2 is of a phosphatic sandstone in which both the detrital quartz grains within the phosphatic pellets and those in the surrounding sediment are included in the grain size count.   The sinuous form of the curve is clearly the result of the combination of a "normal" fine grained cumulative frequency curve with a "normal" coarse grained cumulative frequency curve.

Fig.31A shows four cumulative frequency curves from the one sample (AP1/601/0) - a sandy pelletal phosphorite.   Curve AP1/601/0 (A) represents a textural analysis of the fine quartz within the pellet

CUMULATIVE FREQUENCY CURVES

Fig 31A
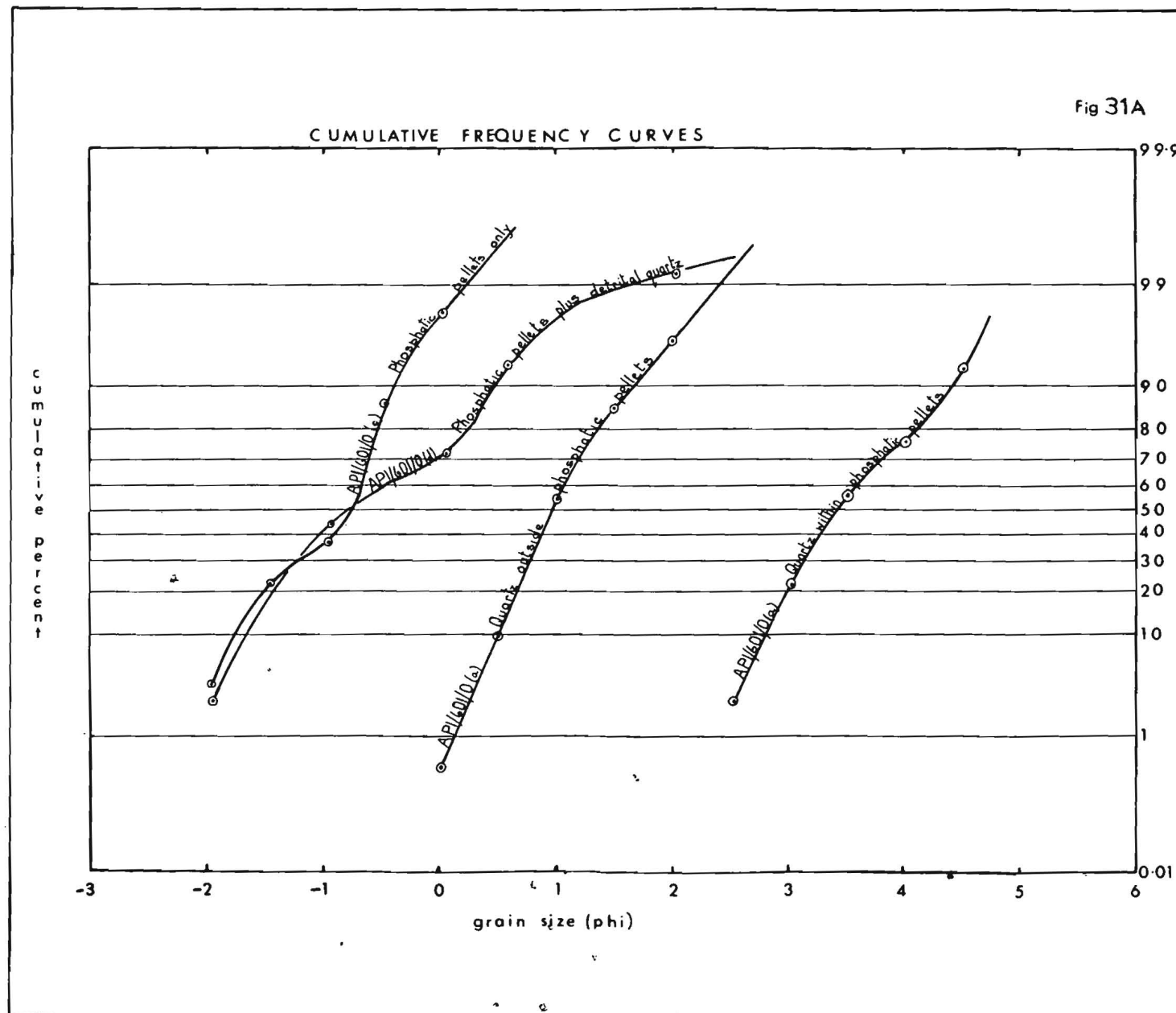
and is therefore an analysis of the sediment in which the pellets
formed originally.   Curve AP1/601/0 (b) is a textural analysis of
the coarse quartz associated with, but outside, the phosphatic
pellets (see Fig.75) - this plot therefore in effect assumes that
the coarse quartz has not moved with the pellets.   AP1/601/0 (c)
is a size analysis of the coarse quartz plus the phosphatic
pellets - and therefore in this plot the assumption is made that
the pellets have moved with coarse quartz.   AP1/601/0 (d) is
an analysis of the phosphatic pellets only, and therefore the
assumption is made in this case that either the pellets were swept
in, in an entirely separate episode from that which brought in the
coarse quartz, or alternately that the pellets have grown in situ
and therefore their size bears no relation to that of the coarse
quartz.   The differences of median grain sizes between the four
curves can be clearly seen, with for instance a median grain size
of about $3.3\emptyset$ for the detrital quartz within the phosphatic pellet
and about $1\emptyset$ for the detrital quartz in the surrounding sediment.
This difference of about $2.3\emptyset$ in the median diameter is typical of
many of the phosphorites.

The significance of the plots of skewness etc. have already
been discussed (Chapter 4 pages 32 - 34); it is however of value
to discuss here their significance in terms of phosphate
deposition.

A plot of kurtosis against standard deviation (Fig.11B) shows
three fields - I, III, and V.   Field I represents the zone of
the textural parameters of the phosphatic pellets; field III is
the zone of the detrital quartz which occurs within phosphatic

intervals, but outside the actual phosphatic pellets; field V

is the field into which the majority of samples fall - it is the

field into which the non-phosphatic sands and also the sands

from _within_ the phosphorite pellets fall. It appears that many

of the pellets are formed in the environment represented by field V,

which apparently was the commonest environment of deposition during

Stairway Sandstone times. Therefore it is field III which

represents the atypical Stairway Sandstone environment.

The plot of mean diameter against standard deviation (Fig.11A)

shows fields similar to those of the kurtosis-standard deviation

plot - fields I and III are identical and are the fields of

phosphatic pellets and coarse detrital quartz outside phosphatic

pellets respectively. Field II is the field of coarse sands from

the non-phosphatic basal sands of the Stairway Sandstone. Field IV

is the field of the majority of the fine sands of the middle and

upper part of the sequence together with the fine detrital quartz

from within phosphatic pellets. Thus again, the evidence suggests

that the precipitation of phosphate occurs in the "normal" Stairway

Sandstone environment, particularly the environment of the very

fine sands and that this environment is strongly dissimilar to

that of fields II or III. Therefore it is most unlikely that

a current bringing with it sediments from field III (or field II)

would also carry with it phosphatic material, for the phosphatic

material has clearly formed in an environment divorced completely

from that in which the coarse grained sediments were laid down.

It is also significant that field I (the field of the phosphatic

pellets) is separated from field III (the field of the coarse

grained detrital quartz associated with pellets) by field II.

If the phosphatic pellets were detrital then fields I and III

should at least be adjacent and should in fact overlap, instead

of being widely separated by the non-phosphatic field II.

The Folk and Ward (1957) parameters of standard deviation,

skewness and kurtosis (see tables 3-4, Appendix), of the detrital

quartz within the phosphatic pellets and that outside the

phosphatic pellets, gives further clues to the depositional history

of the sediments.   The standard deviation indicates that the

degree of sorting of the detrital quartz is both more constant and

better outside the pellets than inside.   Skewness values show

the detrital grains within the pellets are near symmetrical whilst

those outside the grains are fine-skewed which suggests that it

is not strictly unimodal.   The kurtosis values indicate that the

quartz grains within the pellets are mesokurtic, but the quartz

sand outside the pellets is leptokurtic, implying that it is not

unimodal and that it received its textural characteristics in an

environment other than that in which it is now found.   A summation

of the textural parameters suggests that the coarse sands were

originally laid down in a high energy environment and were later

transported to a low energy environment.

If the equations of Sahu (1964) are applied to AP1/601/0

(see Chapter 4, pages 34-36, and Table 5, appendix) in order to

find the environment of deposition, the value of the discriminant

function indicates a beach environment for the coarse sand outside

the phosphate pellets, and a shallow water marine environment for

the fine grained sand within the phosphatic pellets.   If the

discriminant function is calculated out for the phosphatic pellets
on the assumption that the phosphatic pellets are detrital, then
a fluviatile environment is suggested. As it is known from
other sedimentological and palaeontological evidence that the
phosphatic pellets were not laid down in a fluviatile environment,
then either Sahu's equations are incorrect or the initial
assumption of the pellets being detrital is incorrect. The author
contends that it is probably the initial assumption of detrital
origin which is incorrect. It may be that the Sahu equations
are unable to differentiate between fluviatile and tidal channel
deposits, but as there are no sedimentary structures interpretable
as tidal channels within the Stairway Sandstone, even this "escape-
clause" is unacceptable.

As mentioned earlier, an increase of 85% modal and 70%
maximum grain sizes occurs with the incoming of phosphate. This
may be taken as evidence of either transport or winnowing, but
when the amount of increase of modal and maximum grain sizes is
considered, the evidence is in favour of winnowing.

Fig.31B shows in histogram form the amount of increase in phi
units for both the modal and maximum grain size. If the phosphatic
material was derived and the sandy sediment surrounding the pellets
swept in with the pellets, then there would be no difference in the
degree of the increase of the modal and maximum grain sizes with
the incoming of phosphate as both would reflect the current velocity.
This is clearly not the case, for there is a very much greater
increase in modal grain size than there is in maximum grain size,
with the majority of units showing increases of modal grain size

fig.31
B

Increase of grain size with the incoming of phosphate
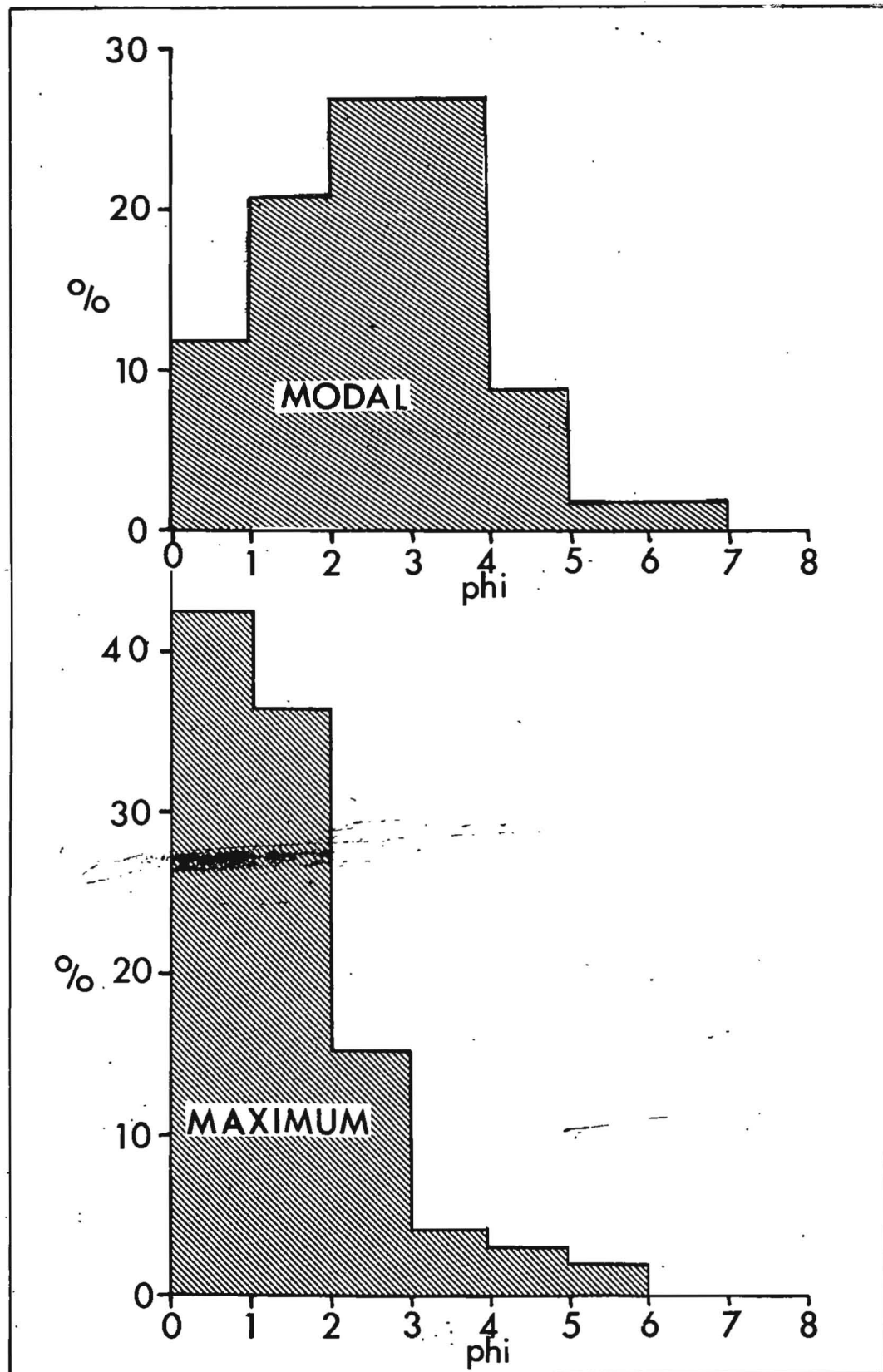
of from 2 to 4 phi units (mean of 2.85 phi units) but increases of maximum grain size of only from 0 to 2 phi units (mean of 1.12 phi units). These results may be adequately explained by winnowing which would remove the finer material producing a very marked increase in the modal grain size, whilst little or no increase occurs in the maximum grain size unless the winnowing current also carries appreciable quantities of coarse sand. It may be that the grain size which was previously the maximum grain size, on winnowing will become the modal grain size. Therefore it appears that the magnitude of the increase of modal and maximum grain size which occurs with the incoming of phosphate favours the winnowing concept.

If the modal and maximum grain sizes of detrital quartz in the sediment surrounding the phosphatic pellets are examined (Fig.32) it is apparent that there is no correlation whatsoever between modal or maximum grain size and increase in the percentage of phosphatic material. The phosphate should be accompanied by such a correlation if it was of detrital origin, with the curves shown in Fig.32 migrating to the coarse side (i.e. to the left) as the percentage of phosphatic material increases. However, no such migration occurs. The curves show a marked bimodality but the position of the peaks remains constant with increase in phosphate. The median diameter of the maximum grain size is remarkably uniform in the four classes of phosphate. The values are as follows:-

Percentage of phosphatic material	Median diameter
1-5%	1.25∅

fig 32

SIZE DISTRIBUTION OF DETRITAL GRAINS IN PHOSPHATIC SEDIMENTS
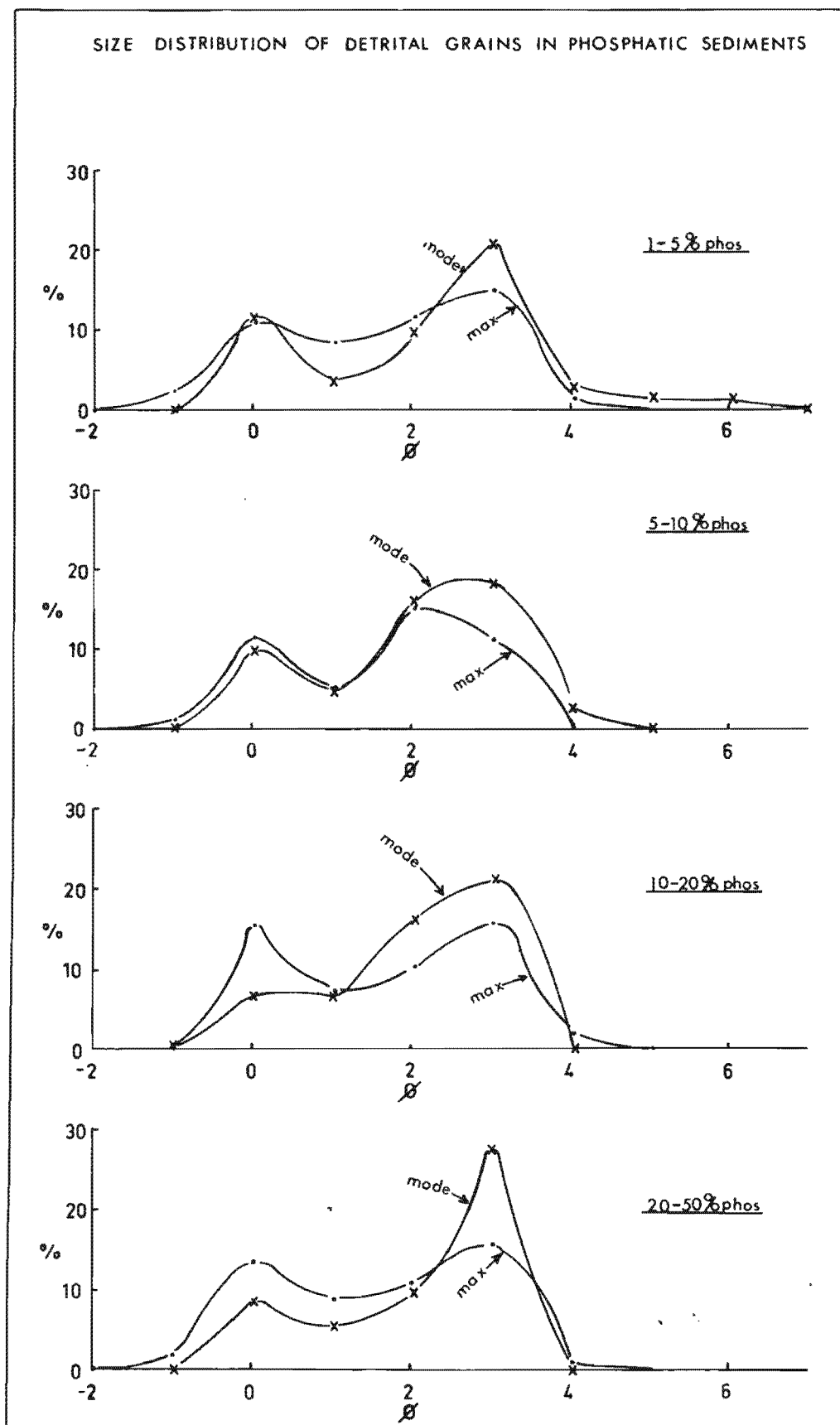
Percentage of phosphatic material	Median diameter
5-10%	1.10∅
10-20%	1.20∅
20-50%	1.10∅

The consistency of these values is inconsistent with a detrital origin.

Even more significant in Fig.32 than the absence of any change in the median values of the curves with increasing phosphate, is the presence of a prominent fine tail in the modal grain size curves, which gradually disappears with increasing phosphate, suggesting a winnowing mechanism. This tail is particularly well brought out by replotting the four modal grain size curves on probability paper (Fig.33). This shows that with low phosphate the fine tail is extremely well developed; as winnowing proceeds, the fine material is gradually carried off with the consequent upgrading of the phosphatic material and the gradual loss of the fine tail. This winnowing action would mainly make its presence felt in the finer material and this is borne out by the lower (coarser) halves of the curves which are all almost identical and by the median diameters which remain constant with increase in phosphate content. The values of the median of the curves are as follows:-

Percentage of phosphatic material	Median Diameter
1-5%	2.0∅
5-10%	1.7∅
10-20%	1.8∅
20-50%	2.0∅

fig 33

DETRITAL   GRAINS IN PHOSPHATIC SEDIMENTS

CUMULATIVE FREQUENCY CURVES

cumulative percent

modal grain size (phi)
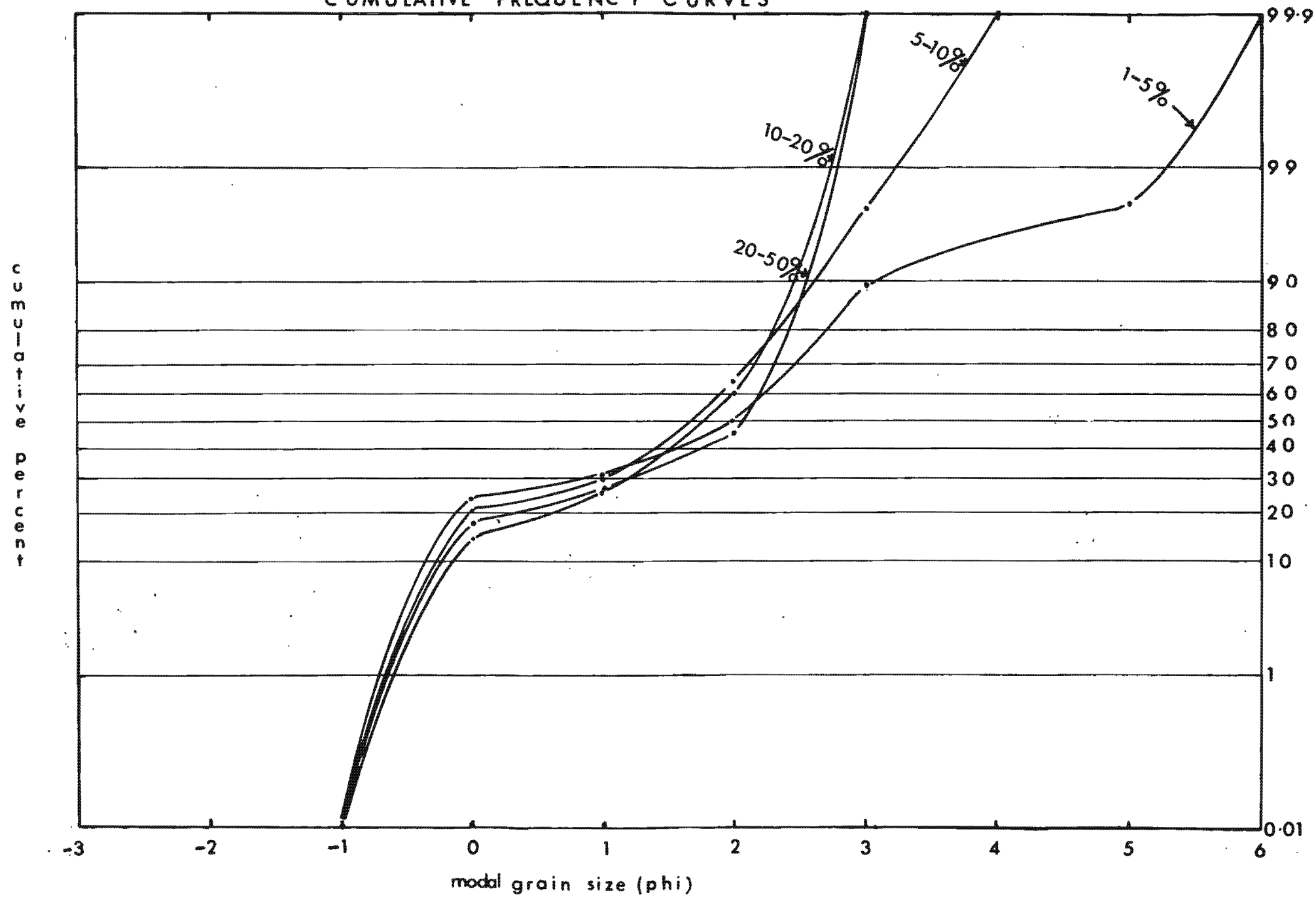
However, skewness, which is a measure of the tails of a curve, should show a consistent variation, with increase in phosphate if winnowing is of importance in the upgrading of phosphorites. The results obtained are as follows:-

% of phosphatic material	Skewness
1-5%	-0.25
5-10%	-0.37
10-20%	-0.50
20-50%	-0.83

These skewness results confirm that indeed winnowing is of major importance in the formation and enrichment of phosphate pellet concentrations.

(ii) Primary v Secondary origin

The question of whether the phosphorites are inorganic or organic primary precipitates or whether they are formed by diagenetic replacement, has already been mentioned briefly. There are few remains of macro-fossils associated with the phosphorites to suggest that biochemical control was of importance. However, many of the pellets contain black ?organic material and the lutites in which the phosphorites occur are black and carbonaceous so that a paucity of preserved macrofossils does not necessarily indicate a shortage of organic material. It is therefore impossible to say whether primary precipitation was organically or inorganically controlled.

It is likely that at least some and perhaps even all of the structureless pelletal phosphates are primary precipitates. The phosphatic material in these pellets has the appearance of having

crystallized out as crypto-crystalline apatite from a colloidal suspension. The structureless pellets have extremely sharp well defined outlines even when the surrounding sediment is limestone. Had the pellet been formed by diagenetic replacement of the limestone, then the boundary would probably have been diffuse. The encasing pelletal phosphate may also be a primary precipitate, precipitating out in much the same way as aragonite does, with detrital grains forming the neucleii. Patchy developments of phosphatic cement occur in some sandstones which lack any other cement. This suggests that there would have been nothing for the phosphate to replace and that therefore the phosphate cement must be a primary precipitate. Finally, there appears to be a very common association between phosphate and detrital material in the range $3\emptyset$ to $4\emptyset$ suggesting that the precipitation of phosphate may in some way be helped by the presence of detrital material in this size range. Such an association is not however shown by calcite, clay or glauconite, so that if the phosphatic material was mainly formed by the replacement of one or other of these minerals, it would not show this association with $3\emptyset$ to $4\emptyset$ material. Therefore, as this association is in fact found, then it follows that the phosphate is in part a primary precipitate.

The phosphate is clearly diagenetic in part, e.g. in the structured pellet where it may be replacing fecal pellets or in the phosphatized fossils (Fig.70, appendix) - but both these types of phosphate are fairly rare. There is, however, evidence to suggest that phosphatization of calcite and/or dolomite, glauconite and clay occurs in a number of cases. Some thin sections

(e.g. AP1/244/0 - Fig.66, appendix) show a gradational boundary between phosphate (in the form of crypto-crystalline apatite) and adjacent carbonate, glauconite and clay, thus supporting replacement.

Replacement of glauconite is also supported by both the shape and size of the structureless pellets being identical with glauconite pellets in some thin sections. This however may merely show that phosphate precipitates are formed im a similar way to glauconite precipitates. The suggestion of the phosphatization of glauconite is also countered to some extent by the fact that numerous grains of glauconite with sharp fresh margins have also been observed within phosphate pellets. Similarly, a few phosphatic pellets have rims of glauconite which also show no signs of chemical corrosion or alteration at the interface, (Fig.s76-77, appendix).

The phosphatization of calcite is known to occur fairly readily. It certainly takes place in some of the Stairway Sandstone fossils which originally had calcareous shells. The similarity of some of the phosphatic forms (such as the encasing pellets) to calcite ooliths and other forms of calcite suggests that they may have formed by replacement. Emigh (1958) strongly advocates this line of argument. However, as with glauconite, it may well be that the similarity of form is merely due to a similarity in the mode of precipitation.

The replacement of clays by phosphate presents considerable chemical problems for it is difficult to replace a clay by a mineral such as apatite. In spite of the chemical obstacles

however, it appears that such a replacement may take place.
The gradational boundary has already been mentioned as evidence
of replacement.   In addition, mica which is common in a clayey
(but not a glauconitic or calcitic) matrix, is also extremely
common in the phosphatic pellets.   It has also been found that
of the sandy pellets, the one with the most poorly sorted included
detrital quartz and therefore the ones likely to have originally
had the maximum amount of clayey matrix (because of the lack of
sorting) are found to be the pellet with the highest percentage
of P_2O_5, i.e. the higher the original quantity of clayey matrix
present, the richer the ultimate phosphate.

Therefore, it appears that within the Stairway Sandstone, both
primary and secondary (replacing glauconite, carbonates and clays),
phosphates occur and that there is no single phosphatization
process as has been suggested for many other phosphorites.

Fig.35 indicates in diagrammatic form the processes involved
in the formation of the phosphatic sediments in the Stairway Sandstone.
Whilst the terms "primary" and "early diagenesis" are used, in fact
the two processes were probably going on almost simultaneously.
Winnowing may take place before or after diagenetic phosphatization.
The diagram indicates that without diagenesis or winnowing or both,
only slightly phosphatic arenites result.   The richest phosphorites
are probably formed when both diagenesis and winnowing take place.

(iii) The Environment of Deposition

Cook (1963) and Barrie (1964) suggested that at the time of
precipitation of phosphate, conditions were in part oxidizing.
Reference to Fig.21 shows that the main phosphatic portion of

Possible processes for the phosphatic enrichment of

Stairway Sandstone sediments.

winnowing ← primary seds → early diagenesis

Detrital
minerals
(mainly quartz)

Glauconite

Carbonates

Clays(?)

Fecal pellets

Fossils

PHOSPHORITE ← winn^g phos^n → PHOSPHORITE

Primary phosph
-ate minerals

winnowing

pyritization

Arenaceous &
argillaceous seds
with little or no
phosphate.

Slightly phos
arenite.

Pyritic seds
with varying
amounts of
phosphate.

the Stairway Sandstone is also the zone of greatest pyrite.
This together with the black colour of the interval (chroma
N2 to N4) indicating that organic matter is probably very
common, suggests that the overall environment was reducing
(Eh of about -0.2 - see Fig.22). However the question of the
Eh is not particularly relevant as the precipitation of apatite
is only pH controlled. The work of Krumbein and Garrels (1952)
shows that the pH lay within the range 7.0 to 7.8 during the
deposition of the phosphorites. Whether these pH - Eh conditions
were representative of the macro-environment, i.e. that of the
bottom water, or as is suggested by Bushinskii (1964), of the
bottom muds, is a little uncertain. The greatest concentration
of phosphate occurs in the interval 200' to 500', the zone of the
composite sedimentation units D, E and F (Fig.25) which are thought
(by reference to the epeiric sea model) to have been laid down
in fairly shallow water conditions. Therefore it may be that the
pH conditions of the environment is a reflection of shallower water
epeiric sea conditions.

(iv) Topography and Tectonics

Barrie, (1964) considered that the deposition of the Stairway
Sandstone phosphorites occurred on topographic highs. He took as
his evidence a ridge of Upper Proterozoic sediments north of AP4.
He considered that the ridge was also a submarine high during
Stairway Sandstone times, and that the phosphorites found in AP4
were initially formed on this high. There is however no geological
evidence that the ridge was an Ordovician high. The palaeocurrents
measured in the Stairway Sandstone just north of AP4 flow due north,

straight across the postulated high with no deflection whatsoever.
Therefore as the Upper Proterozoic ridge on which the "topographic
influence" hypothesis of Barrie (1964) is based has been shown to
have exerted no influence on sedimentation, then the entire theory
must be discarded until more reliable evidence is available.

Wells (pers. comm.) reports that in the Kernot Range
south east of AP4 there is geological evidence of a topographic high
(probably an island) in the Stairway Sandstone seas.   However, no
information on the Stairway Sandstone phorphorites or current
directions is available from this area to show whether or not this
more definite "high" influenced sedimentation.   Had there been any
submarine highs in the Stairway Sandstone seas then it is extremely
likely they would have influenced the deposition of phosphorites.
Phosphorites on a topographic high would have been more susceptible
to winnowing (and therefore of a higher grade) than those deposited
on the sea floor.   However such a process cannot be invoked until
sub-marine topographic highs in the Stairway Sandstone can be proved.

The isopachous map of the middle Stairway Sandstone (Fig.14A)
shows a marked thinning along a line through the Seymour Range,
the Chandler Range, and the James Range (the shaded area in
Fig.14A), dividing the basin into two with the western half
possibly representing more open marine conditions in which the
phosphorites appear to be common and the eastern half, in which
conditions were more paralic.   This line of thinning may merely
be a line along which deposition was minimal but it may also
represent a topographic high which influenced sedimentation.
It would certainly appear to have affected the overall picture

of sedimentation in the basin, but whether it also locally affected
the deposition and/or enrichment of phosphorites is uncertain.
The present rather sparse evidence suggests that the phosphorites
were not in fact affected.

Tectonics are thought to have played little part in
influencing sedimentation, for the Ordovician was a time of little
or no activity in the Amadeus Basin. There may be numerous minor
disconformities within the Stairway Sandstone all of which may
have influenced the deposition of phosphorites, but there are
certainly no unconformities or evidence of earth movement of any major
kind within the formation, (except see page 125).

Therefore, at the present time there is no evidence to suggest
that the deposition of the Stairway Sandstone phosphorites has been
influenced by topography or tectonics.

(v) The Primary Source of the Phosphate

Any attempt to establish the primary source of the phosphate
in the Stairway Sandstone is fraught with difficulties, the main
one being that the lack of an adequate number of P_2O_5 analyses
makes it impossible to estimate the quantity of phosphate in the
Stairway Sandstone with any degree of accuracy. However, as it
is necessary to have some idea of the quantity of phosphate
involved, an estimation is attempted below:

(a) The basic assumption is made that the total quantity of
P_2O_5 in section AP1 is approximately equal to that present
in any other section of Stairway Sandstone in the basin.
The philosophy behind this assumption is that as winnowing
has been shown to be an important mechanism then in the

thinner sections it is likely that winnowing has been

extremely active so that a thinner section results,

with abundant pellet concentrations, but the total

quantity of phosphate remains the same.

(b) Density of the phosphatic material - 2.7 x 62 lb/cu.ft.

(c) The quantity of apatite in AP1 may be calculated from

the average values obtained for the composite units given

in Table 10 (appendix):

Unit A

  phosphate = 11 x 4.25 x 2.8 = 131 percent/ft

Unit B

  phosphate = 22 x 0.42 x 7.1 = 66 percent/ft

Unit C

  phosphate = 48 x 0.54 x 7.2 = 186 percent/ft

Unit D

  phosphate = 61 x 0.17 x 11.8 = 122 percent/ft

Unit E

  phosphate = 43 x 0.23 x 13.8 = 136 percent/ft

Unit F

  phosphate = 8.x2.75 x 4.5 = 99 percent/ft

       Total phosphate = $\underline{732 \text{ percent/ft of apatite}}$

                       = $\underline{315 \text{ percent/ft of } P_2O_5}$

In addition if the average values quoted by Rankama and

Sahama (1950) are taken for the non-pelletal arenites and lutites

then there is a further quantity of

  (250 x 0.08 + 200 x 0.16) percent/ft of P_2O_5

  = 52 percent/ft of P_2O_5

Therefore the total quantity of P_2O_5 in AP1 = <u>367 percent/ft</u>

(d) The total weight of P_2O_5 present in a 1 sq.ft. column

right through the Stairway Sandstone near AP1

$$= \frac{367}{100} \times 2.7 \times 62$$

$$= 600 \text{ lb. of } P_2O_5 \text{ (per cylinder of 1 sq.ft.}$$
$$\text{cross-section)}$$

(e) The Stairway Sandstone crops out over an area of 40,000

square miles but it is estimated that 10,000 square

miles of this is occupied by poorly phosphatic red-beds

and carbonates.

The area of phosphatic sediments:

$$= 30,000 \times (5280)^2 \text{ square feet}$$

$$= 84 \times 10^{11} \text{sq.feet}$$

(f) Taking assumptions (a) as valid, the total quantity

originally present in the Stairway Sandstone:

$$= \frac{6.0 \times 10^2 \times 8.4 \times 10^{11}}{2240} \text{ tons}$$

$$= \underline{2.3 \times 10^{11} \text{ tons of } P_2O_5}$$

$$= \underline{5.4 \times 10^{11} \text{ tons of apatite}}$$

$$= \underline{1.7 \times 10^{11} \text{ tons of P.}}$$

(vii) Stairway Sandstone times are thought to have lasted for

approximately 20 million years.   Therefore the average quantity

of phosphorus deposited per annum was:

$$\frac{1.7 \times 10^{11} \text{ tons}}{2 \times 10^7}$$

$$= \underline{8.5 \times 10^3 \text{ tons of P. per annum}}$$

Buskinskii (1964) suggests that rivers are capable of

supplying abundant inorganic phosphorus. He states that the amount of dissolved inorganic phosphorus brought down the River Volga each year is 6,000 tons. 8,500 tons are estimated to have been deposited each year during Stairway Sandstone times. Therefore it is not outside the scope of one large river to bring down a sufficient quantity of phosphorus to form the Stairway Sandstone phosphorites. However the presence of a large river appears to be incompatible with the slow rate of sedimentation which occurred in Stairway Sandstone times, unless the river carried an exceptionally small amount of detrital material in the bed-load.

The estimate of 2.3×10^{11} tons of P_2O_5 for the original quantity of P_2O_5 deposited represents a considerable concentration, particularly when it is considered that the present oceans are estimated to have 3.2×10^{11} tons of P_2O_5 (McKelvey et al., 1959). It is interesting to note that McKelvey estimates the total quantity of P_2O_5 in the Phosphoria as 1.7×10^{12} tons (therefore seven Stairway Sandstones equals one Phosphoria!), and considers that such vast quantities of phosphate could only have come from the oceans. Sheldon (1963) has good evidence to show that upwelling oceanic currents were the source of the phosphorus. The richest phosphorites are for instance found in the seaward direction. Such a distribution is unlikely to occur if rivers were the source of the phosphorus. The distribution of the red-beds, carbonates and phosphatic siltstones and shales of the middle part of the Stairway Sandstone (Fig.16), bears a close similarity to the distribution of the same three lithologies in the Phosphoria of

Western Wyoming (Sheldon, 1963). As in the Phosphoria, the phosphorites of the Stairway Sandstone occur on the seaward side of the basin. Therefore, by comparison with the much better known Phosphoris it is likely that the phosphate of the Stairway Sandstone also originated from the oceans and probably from upwelling currents. Comparison of Fig.16 with Sheldon (1964, Fig.86) will show that such an analogy between the two formations is valid.

Summary

The phosphorites of the Stairway Sandstone are widespread but are found particularly in the middle part of the formation. The phosphorites cannot be regarded as being of high grade but beds do contain up to 22% P_2O_5. There are ten modes of occurrence of phosphatic material, many of which superficially look as if they are of detrital origin. However, textural work has showed that the majority of phosphorites have been winnowed in situ. Whilst some of the phosphate was probably a primary precipitate, several of the phosphatic forms also have apparently formed by alteration of glauconite, carbonates and clays. There is no evidence to prove that the phosphorites have formed on topographic highs.

Considerable quantities of phosphate are present within the Stairway Sandstone and by analogy with the Phosphoria Formation it is thought that upwelling oceanic currents were the major primary source of the phosphate. However it can be demonstrated that it is possible for one large river to bring the amount of phosphate deposited per annum in the Stairway Sandstone times.

CHAPTER 9

THE PALAEOGEOGRAPHY AND DEPOSITIONAL HISTORY OF THE STAIRWAY SANDSTONE

General

In the preceding chapters various facets of the history of the Stairway Sandstone have been elucidated. All these are now brought together to build up an integrated picture of the palaeoclimate, provenance, palaeogeography, and environmental conditions prevalent during Stairway Sandstone times.

Palaeoclimate

The small amount of palaeomagnetic data which is available for the Ordovician of Australia suggests Australia was probably within the Torrid Zone of the northern hemisphere (Bains, 1963; Irving, 1964, Briden, 1964). A suggested palaeolatitude picture which is not inconsistent with the palaeomagnetic data is given in Figs.36-38. This picture suggests that the postulated opening of the Amadeus Basin to the present day north-west during Stairway Sandstone times would have been towards the west. A westerly aspect would have been in the path of cold phosphate-bearing currents welling up on the west side of the continent if Ordovician ocean currents were similar to present day ones. A palaeolatitude in the order of $15^{\circ}N$ would probably place the Amadeus Basin within the trade wind belt, suggesting a desert climate.

The middle Stairway may contain evaporites, supporting an arid climate. The feldspar grains of the middle and upper Stairway are also fresh and well rounded, again implying a desert climate. However, the maturity of the lower Stairway orthoquartzites may mean the climate was humid tropical so that chemical action was

severe.   Alternatively this super-maturity can be achieved by
fairly normal weathering of a predominantly sedimentary provenance.
However, the lack of feldspar in the lower Stairway fairly certainly
suggests that the weathering in the source area was more severe
than during middle and upper Stairway times.

Provenance

The petrology of the Stairway Sandstone is perhaps best
explained by a desert hinterland from which little or no material
is derived but through this area flow a few rivers, bringing down
detritus from the more tropical areas to the Ordovician south.

Within this source area fairly severe weathering makes it
difficult to be sure whether the provenance was plutonic or
sedimentary.

In the lower Stairway there is little obvious evidence of
reworked sediments however, as mentioned in Chapter 2 the abundance
of common quartz in fact suggests that most of the quartz grains
have been recycled.   In many areas at the top of the lower Stairway
there is a prominent pebble band;   the pebbles are mainly of meta-
quartzite and silicified sandstone.   These pebbles may represent a
local sedimentary source (a pebbly silicified sandstone - such as
uplifted Winnall Beds of the upper Proterozoic).   Therefore the
major source area in lower Stairway times was probably sedimentary
mainly quartz arenites) and probably lay some distance to the south,
although right at the top of the unit the source area was in part at
least, of nearby sedimentary rocks.

In middle Stairway times, the abundance of common quartz again
suggests a predominantly sedimentary provenance. Some of the fresh

fig36

Palaeogeography of the Stairway Sandstone (lower)

30°N

LAND

SEA

?

15°N

0°

SEA

LAND
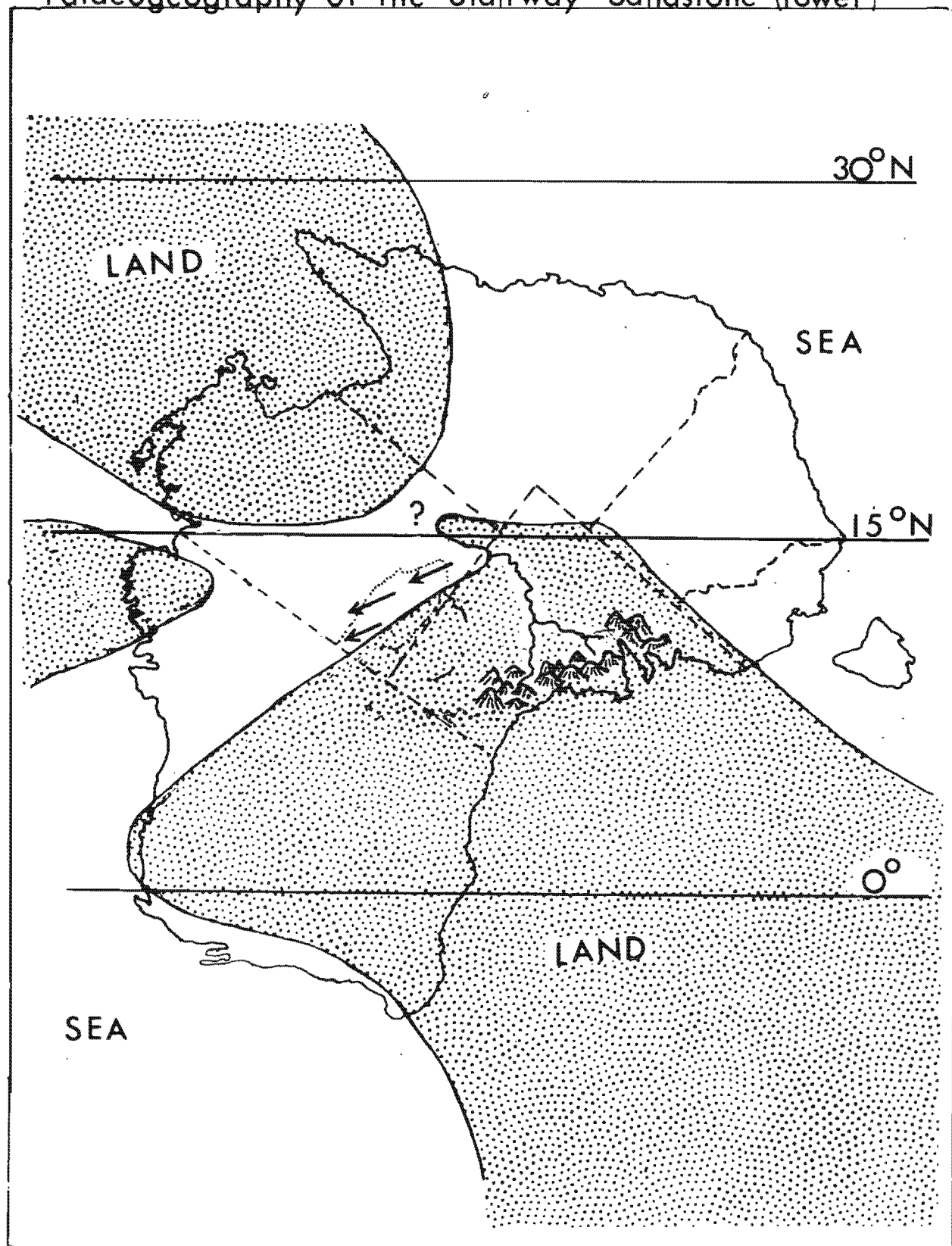
well rounded feldspar grains are probably derived from the nearby desert areas. The heavy minerals strongly suggest the provenance is plutonic (granitic) in part, for in one specimen (See Fig.7) euhedral grains of zircon occur in conjunction with extremely well-rounded grains. This suggests that the well rounded zircon is second cycle material obtained by reworking of sediments (mainly quartz arenites) whilst the euhedral zircon is first cycle material derived from a plutonic (?granitic) source.

The presence of red-beds in the middle Stairway of the Mount Charlotte embayment is thought to indicate lateritic weathering in the source area of some of the sediments.

In upper Stairway times abundant common quartz again suggests a predominantly quartz arenite source area. The presence of chert suggests that the provenance may have been calcareous in part. The absence of euhedral grains of heavy minerals support a wholly sedimentary source.

Palaeogeography (See Figs.36-38 - adapted from J.G.Tomlinson, pers.comm.)

As mentioned earlier, it is postulated that the present-day Amadeus Basin was for much of Stairway Sandstone times the major part of an embayment situated at a palaeolatitude of about $15^{o}N$. The dominant palaeocurrent direction was from the present-day south-east, therefore it is probable that a land mass lay to the south-east and south for much of Stairway Sandstone times.

At the close of Horn Valley Siltstone times sedimentation was restricted to a fairly deep, small basin or embayment. Lower Stairway times opened with the development of a subsidiary embayment in the south-east either due to the breaching of some

Palaeogeography of the Stairway Sandstone (middle)

30°N

LAND

SEA

15°N

upwelling

upwelling

0°

LAND

SEA

0°
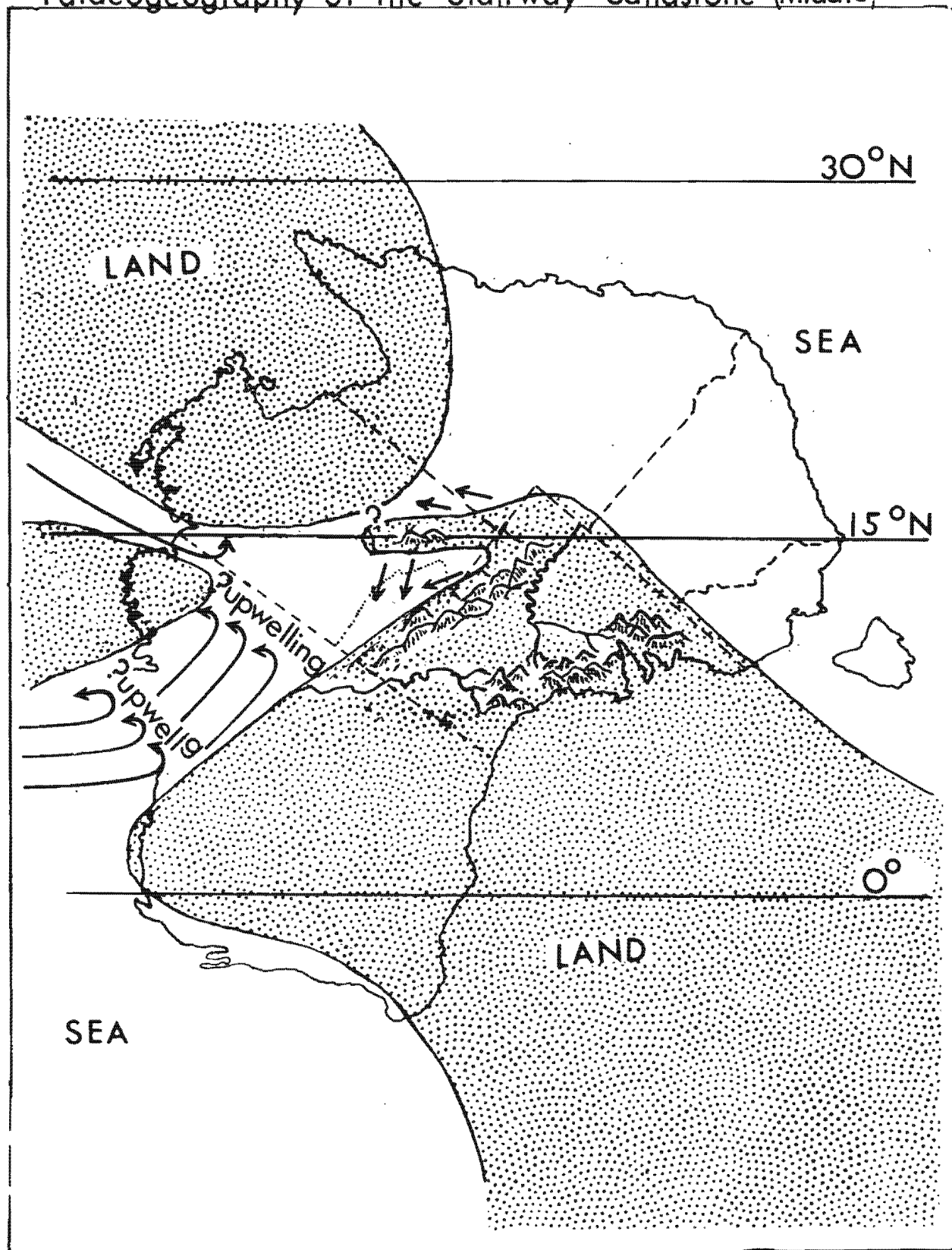
barrier or more likely, due to a local downwarping in the
south-east. It would seem that during lower Stairway times
the southern margins of the basin were formed by fairly high
cliffs of Cambrian and Upper Proterozoic sediments (there is
evidence of cliffs up to 100 feet high in the Mount Sunday range
area), but that once inlahd, the country was probably flat desert
with little relief andno local drainage. Further south and
south east was a large mass of sedimentary rocks (and minor
plutonic rocks), possibly with fairly high relief. This area
may have corresponded to the areas of Upper Proterozoic sediments
in the northern parts of South Australia or in the Flinders Ranges
area of South Australia. These areas lay within a zone of higher
rainfall. A river or rivers flowed from this area, finally
entering the sea somewhere in the vicinity of the present day
Amadeus Basin. To the present day east and south east lay a
ridge or peninsular (possibly a fairly broad one with moderate
relief) which severely restricted the connection between the
Amadeus Basin and the Tasman Geosyncline. To the north-west
a broad open shelf connected the basin with open ocean which was
situated in the position of the present-day Indian Ocean - Timor
Sea.

The same palaeogeographic picture persisted throughout middle
Stairway Sandstone times except that sediment from the rivers
postulated for lower Stairway times probably no longer reached the
Amadeus Basin due to the formation of a barrier or alternatively
the rivers now carried very much less detritus in response to a
lessening of the rainfall - perhaps due to an expansion of the

fig 38

Palaeogeography of the Stairway Sandstone (upper)

30°N

LAND

SEA

15°N

0°

LAND

SEA
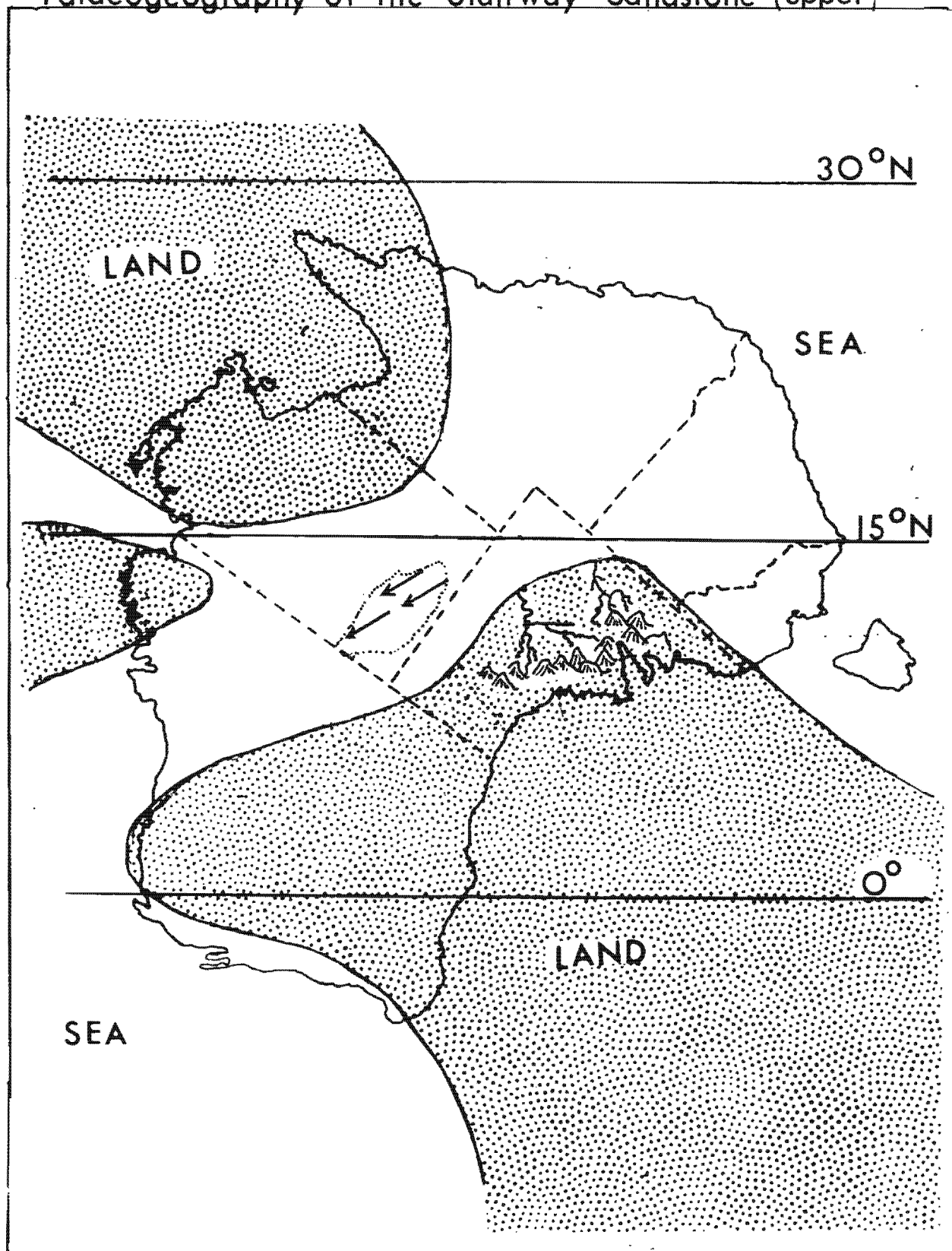
desert belt. The hinterland was probably a wide peneplained
desert area. The east ridge was probably now more prominent and
                              almost
the Amadeus Basin /·· completely cut off from the seas to the
east.

With the incoming of the Upper Stairway, the palaeogeographic
picture changed fairly radically and seas transgressed over the
peneplained land area. The deepest areas of the basin still lay
to the north but the south-east embayment had ceased to exist and
the seas were very much more extensive. The term "basin" was
probably not applicable; instead there was a very broad shelf
Connections to the open-sea lay to the north-west but also the
eastern ridge was breached and the upper Stairway "Amadeus Basin"
was connected (possibly across a broad shelf) to the Tasman
Geosyncline. Sediment from the rivers again reached the Amadeus
Basin area from the tropical areas to the south. Nothing is known
about the nature of the upper Stairway margin of sedimentation
except that it was far outside the limits of the present-day Amadeus
Basin.

Depositional History

At the end of Horn Valley Siltstone sedimentation a fairly
major change in sedimentation took place which resulted in a large
body of coarse regressive sands being deposited over the deeper
water sediments of the Horn Valley Siltstone. The area of deposition
of this regressive body of sediments was much the same as that of
the Horn Valley Siltstone except for the formation of the Mount
Charlotte embayment. This embayment did not however affect
sedimentation and conditions throughout the lower Stairway times

were extremely uniform.   The regressive sand body probably

formed by the gradual sea-ward migration of the high energy

zone of an epeiric sea (see Chapter 7, Fig.29).   The reason

for the regression is somewhat obscure.   It may either be due

to a relative fall in the level of the sea or to an increase in

the quantity of sediments being transported into the area.

At the top of the lower Stairway is a pebble band.   This pebble

band though only thin, occurs over thousands of square miles and

probably represents a relatively important event, as it corresponds

to the close of the fairly rapid sedimentation of the lower Stairway.

It may be a reflection of some fairly minor earth movements in

the area, which did little to alter the shape of the basin, but

was sufficient to influence the topography and possibly divert

the previous source of sediments away from the Amadeus Basin so

that sedimentation continued at a very much slower rate.

The middle Stairway sediments are the product of this slower

rate of sedimentation, and the depositional environment.   Once

the main body of sand had regressed during lower Stairway times, a

predominantly tranquil environment was established with the whole

basin probably covered by the low energy zone of the epeiric sea

(see Chapter 7, Fig.29).   It is apparent that there was a well

established connection with the open sea to the north-west so

that phosphate-bearing currents were able to enter the basin and

form the middle Stairway phosphorites.   However to the south-east

conditions became more saline - particularly at the south-eastern

end of the Mount Charlotte embayment.   Throughout this time

sedimentation was extremely slow, so that the chemical sediments

were not "diluted" by terrigenous material. During middle

Stairway times it is possible that some form of barrier was

set up in the Chandler Range - Seymour Range area which further

restricted circulation to the east and south-east. The ?barrier

may however merely be the limit of major terrigenous sedimentation.

The red-beds of the Mount Charlotte embayment are thought to be

both a reflection on the oxidizing environment of deposition and

also of lateritic weathering in the source area.

The advent of upper Stairway sedimentation represents a major

transgression together with a major faunal change. The transgression

was either in response to a downwarp of the land or a major rise in

sea level. It is thought that the second possibility is the more

likely as right up to the close of middle Stairway sedimentation

there is evidence of fairly major relief along the coast (e.g.

in the Mount Sunday Range area there is evidence of Ordovician

cliffs in the order of 100 feet high). This transgression

produced reworking of the local sedimentary Upper Proterozoic and

Cambrian rocks. It also profoundly influenced the palaeo-

geography and resulted in terrigenous epeiric sea sedimentation

(see Chapter 7, Fig.29), which ultimately produced a very broad

shallow sea and ushered in the overlying Stokes Formation

sedimentation.

Summary

During Stairway Sandstone times the Amadeus Basin was situated

at a palaeolatitude in the order of about $15°N$. The major features

of the three main periods of sedimentation can be summarized as

follows:

(1) Lower Stairway times

> Palaeoclimate: either hot humid tropical or hot dry
> desert
>
> Provenance: mainly a distant quartz arenite source area
> located to the south, in the zone of tropical
> weathering.
>
> Palaeogeography: connection to the open ocean to the
> north-west, with an embayment to the south-east.
> Probably a small land barrier or peninsula to the
> east but the major area of land is to the south-east
> and south.
>
> Depositional History: mainly a regressive sequence in
> response to relative lowering of the sea-level or
> an increase in the inflow of terrigenous sediments
> (the second possibility is favoured). The sand
> body is probably due to the seaward migration of the
> high energy zone of an epeiric sea.

(2). Middle Stairway times

> Palaeoclimate: hot dry desert locally, with more humid
> climate in the source area.
>
> Provenance: small amount of sediments derived locally,
> but some also derived from a distant source undergoing
> lateritic weathering. Provenance mainly sedimentary
> (quartz arenite), but with some igneous plutonic rocks
> in the source area.
>
> Palaeogeography: as in the lower Stairway but possibly
> even less relief now in the hinterland apart from

the development of a ridge or range which prevented

the major river (or rivers) reaching the Amadeus Basin.

The barrier between the Amadeus Basin and the open sea

to the east is now well developed so that there was little

or no connection between the two seas.

Depositional History: a shallow sequence with only very

minor terrigenous sedimentation but important chemical

sedimentation. The Mount Charlotte embayment exerts

a fairly strong influence on the type of sedimentation.

The overall environment corresponds to the low energy

zone of an epeiric sea.

(3) Upper Stairway Times

Palaeoclimate: probably hot dry desert locally with a

more humid climate in the source area.

Provenance: predominantly sedimentary (both carbonates and

quartz arenites)

Palaeogeography: a very much more extensive sea than in

lower and middle Stairway times, with limits well

outside those of the present day Amadeus Basin. The

eastern barrier was breached so that there were connections

to the open sea to both the north-west and the east.

Depositional History: fairly major terrigenous sedimentation

with a predominantly transgressive sequence. The sand

bodies represent landward migration of the high energy

zone of the epeiric sea.

CHAPTER 10

ECONOMIC IMPLICATIONS OF THE SEDIMENTOLOGY OF THE
STAIRWAY SANDSTONE

General

There are direct economic implications of this sedimentological study of the Stairway Sandstone which should be considered. The most fundamental application of the study is to the stratigraphy of the Stairway Sandstone but conclusions possibly of some importance can also be reached regarding the accumulation of hydrocarbons and the phosphate potential of the area.

Stratigraphy

As more wells are drilled for oil and gas, it will become increasingly important to subdivide the Stairway Sandstone and to know exactly the position of a horizon within the formation. The present work has shown that the informal sub-division of the Stairway Sandstone into lower, middle and upper is valid; the three units can be recognized over a considerable area of basin and could be accorded formation status. Generalized indications of this three-fold division are:-

(i) Coarse grained sands are generally restricted to the lower Stairway.

(ii) Rounding is very much better in the lower Stairway than in the middle or upper.

(iii) A predominance of lutites with phosphorites or carbonates or "red-beds" is characteristic of the middle Stairway.

(iv) The fossils of the lower and middle Stairway are of early Larapintan age whilst those of the upper Stairway are of

late Larapintan age.

In order to establish even finer stratigraphic control within the Stairway Sandstone, marker horizons must be recognized. Fossil marker horizons would be the most satisfactory type but present palaeontological data suggests that fossils will be unable (for some considerable time at least) to provide marker horizons. Therefore it is going to be necessary to use physical stratigraphic criteria.

The petrology of the arenites could be of major importance in this regard. It is suggested the following are likely to be of value:

(a) Composite quartz and metaquartzite are most abundant in a thin band at the top of the lower Stairway (Spec AP1/648/6, Table 1, appendix). This band is also characterized by pebbles.

(b) Chert grains are most abundant in the interval 130-160 feet in AP1 with a particularly rich band at 135' (Spec AP1/118/36 - Table 1, appendix).

(c) The sub-arkose class of arenite is probably of restricted range within the upper Stairway (the interval 130' - 150' in AP1).

(d) A glauconite-rich band (Spec.AP1/754/6 - Table 1, appendix) is thought to occur only near the middle of the lower Stairway.

(e) Coarse ooliths of pyrite within a coarse grained sandstone are restricted to a single horizon near the base of the lower Stairway.

(f) Phosphorites may be of value as marker horizons. As can

be seen from Fig.25, there are four main concentrations of phosphatic material in AP1 - 480' - 460'; 360' - 340'; 220' - 250'; 100' - 80'. It is not known whether these same concentrations also occur in other Stairway Sandstone sections, but it is suggested that some of them would. These horizons may be of especial value in subsurface work if gamma-ray logs are run, as there are likely to be major peaks at the maximum phosphate concentrations.

(g) Heavy minerals have been extensively used in many other formations for correlation purposes. The present study has shown that normal heavy mineral counts (particularly tourmaline:zircon ratios) are of limited value for correlation purposes within the Stairway Sandstone, although it may be possible to decide whether for instance the lower Stairway is missing by looking at the shape of the curve as a whole. Also it is suggested that by considering only the tourmaline types or only the zircon types, detailed correlations would be possible. This would require a careful study of colour, shape and inclusions, as advocated by Krynine (1946). The tourmaline group would perhaps be the best to use as it has a great number of forms in the Stairway Sandstone. However, zircon may also be of value; there is for instance one horizon in the middle of the formation (see Fig.7) which has a characteristic combination of extremely well rounded zircon grains with well developed euhedral zirzon grains - this may well be a useful marker horizon.

Hydrocarbon Prospects in the Stairway Sandstone

The Stairway Sandstone has already produced significant quantities of natural gas in the Mereenie wells (Exoil et.al.) and in the Palm Valley No.1 well (Magellan et.al.). In addition, nine feet of oil saturated sands were penetrated in the lower Stairway of AP1 and fluorescence was fairly common throughout the lower Stairway. One of the major obstacles to oil and gas accumulations is the very low permeabilities in the sandstones due to silicification. Unfortunately, this study is unable to contribute very much to this question although the author favours a pressure solution due to overburden or tectonism for the origin for the silica cement. If this is so then the Stairway Sandstone is likely to have low permeabilities throughout the basin although they may increase to the south where the effects of the Alice Springs Orogeny were less marked and the overburden of Pertnjara Formation and Mereenie Sandstone very much less. Hydrocarbon accumulations might be found in areas adjacent to faults, or other structurally disturbed areas although the work of Heald (1956) would not support this. Discussion of this type of trap is outside the scope of this study.

If, as has been suggested earlier, the isoset and iso-angle maps delineate high and low energy areas (see Fig.18) then an attempt should be made to define the high energy zones more accurately for in such zones, winnowing is likely to produce the highest intergranular porosities and the best potential reservoir rocks. Also if high phosphorite concentrations are found these are also probably the zones of maximum winnowing

and greatest intergranular porosities.

Overall, the Stairway Sandstone offers good petroleum prospects (providing the permeability is sufficient) for the underlying Horn Valley Siltstone would appear to be an excellent source rock whilst phosphatic shales (of the middle Stairway) rank as an exceptionally good source rock (Cheyney and Sheldon, 1959). Both the lower and upper Stairway contain known reservoir rocks and both have an excellent capping - the lower Stairway has the impermeable lutites of the middle Stairway capping it and the upper Stairway has the impermeable lutites of the Stokes Formation as a cap rock.

In considering the possibility of stratigraphic traps the most outstanding example brought out by this study is the pinch-out of the lower Stairway in the vicinity of the Seymour Range. In this same area in the middle Stairway, there is also inter-fingering of carbonate lenses with the "red-bed" facies of the Mount Charlotte embayment so that any eastward migration of oil from the phosphatic shales stands an excellent chance of being trapped within the carbonate facies.

A belt of stratigraphic thinning is postulated to run from the Seymour Range to the Chandler Range and then through the James Range area (Fig.14A). The belt is a zone where stratigraphic pinch-outs are extremely likely. Therefore the west side of this zone is an area where hydrocarbons migrating from the phosphatic shales of the middle Stairway are likely to have accumulated. The east side of this zone is unlikely to have very much potential as it is on the "red-bed" side. Similarly, the whole of the

Mount Charlotte embayment should be considered as a low priority area in the oil search.

The lithofacies map highlights the area of minimum sand: shale ratio. Such an area would have the largest amount of potential source rock and the smallest amount of potential reservoir rock, so that the maximum hydrocarbon concentrations should accumulate here. In addition, on its eastern side, the sand:shale ratio minimum abuts against the postulated zone of thinning so that here should be the best possible area for oil and gas accumulation in stratigraphic traps.

Phosphate Deposits

It is estimated that there are about 2.7×10^{11} tons of apatite (equivalent to 1.2×10^{11} tons of P_2O_5) in the preserved Stairway Sandstone, i.e. about 8 million tons of P_2O_5 to the square mile. The phosphatic sediments underlie an area of about 15,000 square miles but most of this is covered by considerable thicknesses of sediments. There is probably about 500 square miles of phosphatic sediment cropping out (Fig.2) and approximately the same area with an overburden of less than 100 feet. Therefore only 1,000 square miles (maximum) may be regarded as being underlain by Stairway Sandstone at potentially workable depths. This means that there are somewhere in the order of 8 billion (8×10^9) tons of P_2O_5 either outcropping or close to the surface.

Such a large figure should not however give rise to undue optimism for in fact much of this P_2O_5 is widely disseminated throughout the Stairway Sandstone and is of no economic potential whatsoever. The only hope of finding economic phos phate deposits

lies in being able to locate concentrations. Recent work by
the Geophysical Branch of the Bureau of Mineral Resources has
shown that there is a good correlation between areas of known
phosphorite occurrences (such as Johnny Creek) and radiometric
anomalies, so that any radiometric anomalies within the basin
should be clearly examined. However, radiometric surveys are
of limited application only, because they have only a shallow
depth of penetration and even a few feet of sand cover can be
sufficient to mask quite large bed-rock radiometric anomalies.
Therefore the only reliable method at present available for
finding sub-surface phosphorites is by drilling.

It has already been shown that winnowing has apparently
been of major importance in the enrichment of phosphorites,
therefore any drilling activities should be concentrated in
areas where winnowing is most likely to have occurred. As
mentioned earlier, such a thinning apparently takes place
along a line through the Seymour, Chandler and James Ranges
(Fig.14A). However, the present evidence suggests that this
zone served only to limit the eastern extension of the phosphate-
bearing seas and was not a zone of phosphate concentration. If
it can be proved (by for instance geophysical work) that there
were sub-marine topographic highs in Stairway Sandstone times,
then such areas would warrant close examination for winnowing
would produce phosphatic enrichment on the tops of such highs.
Thinning of the Stairway Sandstone occurs towards the southern
margin of the basin but here the question of whether the area
has phosphatic potential is hampered by lack of good

palaeontological control. The only division of the Stairway Sandstone at present possible is into Early and Late Larapintan (J.G.Tomlinson, pers.comm.) Even this one boundary is imperfectly known in the south and poor outcrops limit rock unit mapping. The present sparse palaeontological data suggests that only the late Larapintan (equivalent to the Upper Stairway Sandstone rock unit) is present in the southern parts of the basin which would mean that this area has little phosphate potential. However, if this southern sequence represents a condensed sequence of Early and Late Larapintan or if the lower, middle and upper Stairway rock units are diachronous, then the southern margin could be of considerable economic importance. The results of drilling at AP4 suggest that the second picture may be correct, for Barrie (1964) reports that the phosphatic enrichment in AP4 was better than in any of the other three diamond drill holes. The high energy zones postulated from the isoset and iso-angle maps may also give an indication of where winnowing is likely to have occurred.

In addition to phosphorites which may have been enriched by winnowing, the possibility of finding rich primary phosphorites which have not been "diluted" by terrigenous material must be considered. Fig.16 shows that the eastern half of the basin has poor phosphate prospects as the sediments are of the red-bed or carbonate facies. The palaeocurrent directions flow from south-east to north-west across the basin, therefore the area of least terrigenous sedimentation would be to the north-west. The best phosphatic areas to the north-west may have been situated in the region which suffered strong deformation during the Alice Springs

orogeny and subsequent erosion so that there is now no trace
of the high grade phosphorites.   Alternatively, theoptimum
area may have been situated even further to the north-west, in
the Canning or Fitzroy Basins.   A closer look at the Stairway
Sandstone equivalents of the Ordovician of these basins could
well bring good grade phosphorites to light.   The Upper Cambrian
and Lower Ordovician of these basins should not be neglected in
the search as the phosphate-bearing seas may have been strongly
diachronous - this is supported by the occurrence of pelletal
phosphorites identical in form to those of the Stairway Sandstone
in the Lower Ordovician of an area several hundred miles north of
the Amadeus Basin (R.A.H.Nichols, pers.comm.)

The scope of this study did not touch on the question of
secondary enrichment of phosphorites apart from noting the
presence of secondary phosphatic minerals in some of the thin-
sections.   Also in the Johnny Creek area the author has observed
quaternary gravels composed almost entirely of phosphatic pellets
and nodules.   Therefore secondary concentrations may constitute
important potential sources of phosphate but little is known
about them at the present time.

Summary

This sedimentological study is of stratigraphic importance in
showing the validity of the three-fold division of the Stairway
Sandstone and in suggesting that seven different mineralogical
criteria may have considerable potential as marker horizons.
These include quartz types, a sub-arkose horizon, a glauconite
band, a band of pyrite ooliths, phosphorite concentrations (and
also gamma-logs) and tourmaline and zircon types (though not the

conventional heavy mineral c ount).

In spite of the problem of fairly low permeabilities, the
Stairway Sandstone is believed to be an excellent hydrocarbon
prospect with source rocks, reservoir rocks and caprocks, all in
juxta-position.   In addition, it is possible to single out the
Seymour Range area, the west side of the Seymour Range - Chandler
Range - James Range zone of thinning and the east side of the
sand:shale ratio minimum as areas warranting particular attention.
High energy zones as delineated by the isoset and iso-angle maps
and areas of phosphate concentration are likely to be regions of
winnowing where intergranular porosity is likely to be a maximum.

It is estimated that there are 8×10^9 tons of P_2O_5 within
potentially workable distances from the surface - however much of
this is probably widely disseminated throughout the formation and
therefore of little economic potential.   It is postulated that
within the Amadeus Basin the greatest phosphate concentrations
are likely to occur in areas of maximum winnowing, which in many
cases will correspond to areas of thinning - possibly the Seymour-
Chandler line or the southern margin of the basin or the high
energy areas postulated from the isoset maps.   In addition, rich
primary phosphorites may lie to the north-west away from the
sediment-bearing currents - this area may be outside the present-
day limits of the Amadeus Basin.

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GEOLOGY AND GEOPHYSICS

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1966/1

(APPENDIX)

APPENDIX TO

Symp

THE STAIRWAY SANDSTONE
A
SEDIMENTOLOGICAL STUDY
BY
P J COOK

East

APPENDIX TO

THE STAIRWAY SANDSTONE -

A SEDIMENTOLOGICAL STUDY

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THIN SECTION STUDIES

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No.

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II	Rock type
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VI	Calcium carbonate content
VII	Porosity
VIII	Induration
IX	Supplementary data

Graphic Log
Sheet No.

1	50' — 150'
2	150' — 250'
3	250' — 350'
4	350' — 450'
5	450' — 550'
6	550' — 650'
7	650' — 700'

APPENDIX I

PHOTOGRAPHS
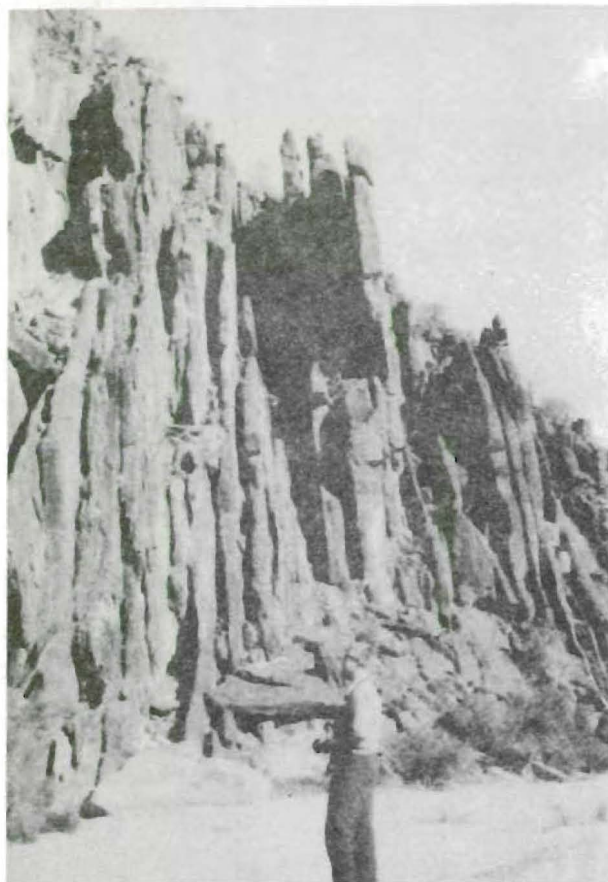
Fig.39 Vertically dipping lower Stairway, Glen Helen Gorge

Fig.40 "Ropey texture" (Cruziana) in Stairway Sandstone
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Fig.41   Ripple marks and worm tube markings in the
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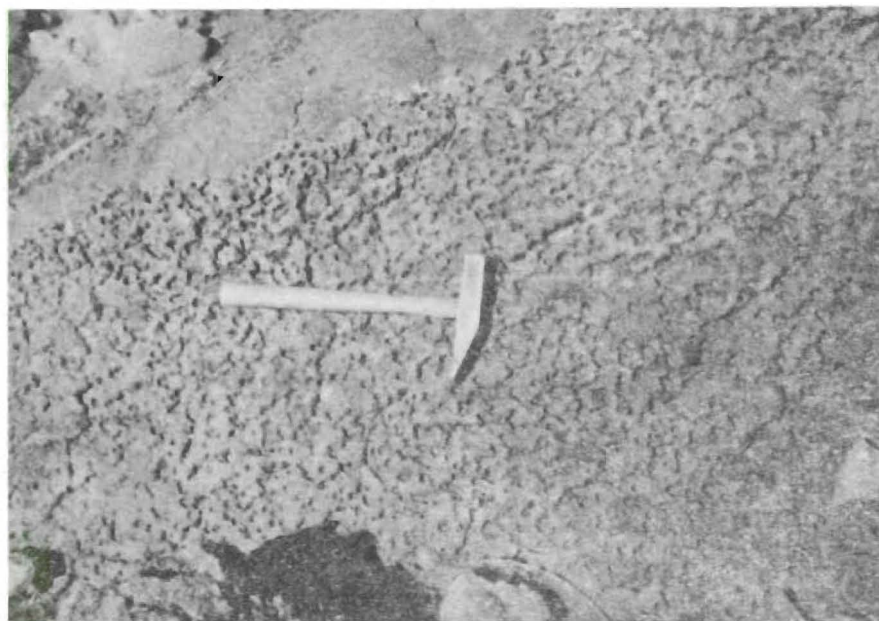
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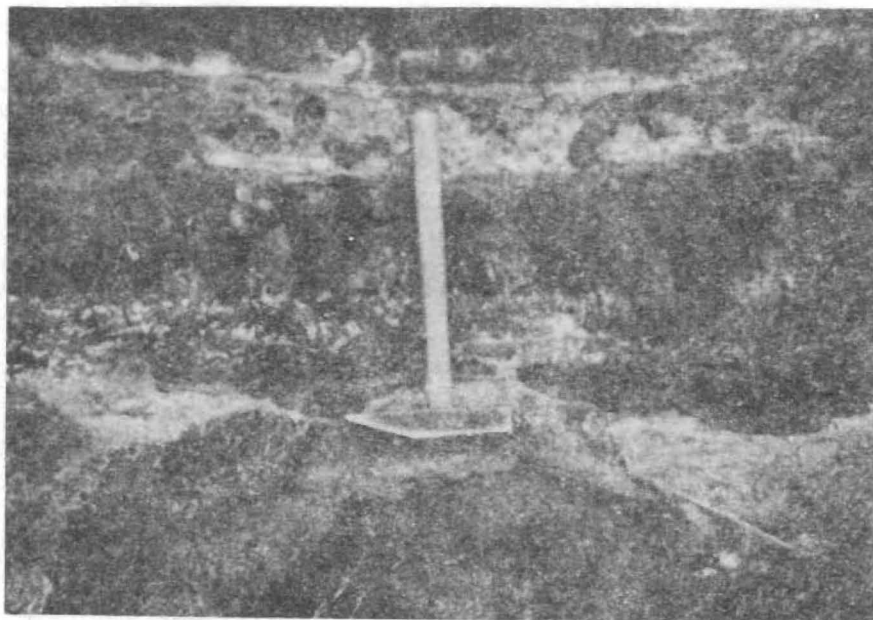
Fig.43   Horizon of weathered out <u>Diplocraterion</u> in the
middle Stairway, Mount Charlotte area
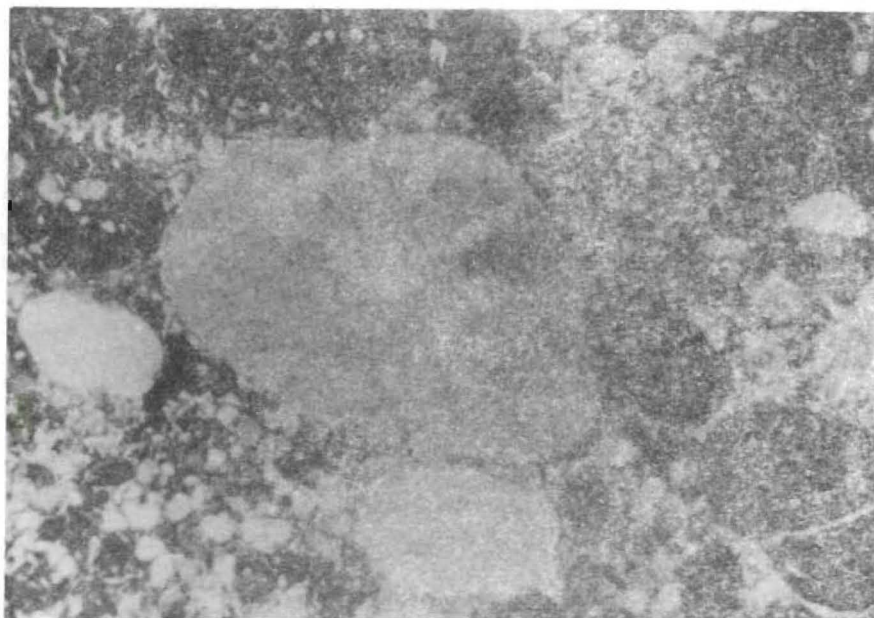
Fig.44   Spec.LA 133   linear mag x 80

Poorly sorted, well rounded orthoquartzite with a coarse,
well rounded grain of metaquartzite in the centre of the
field of view (crossed nicols).
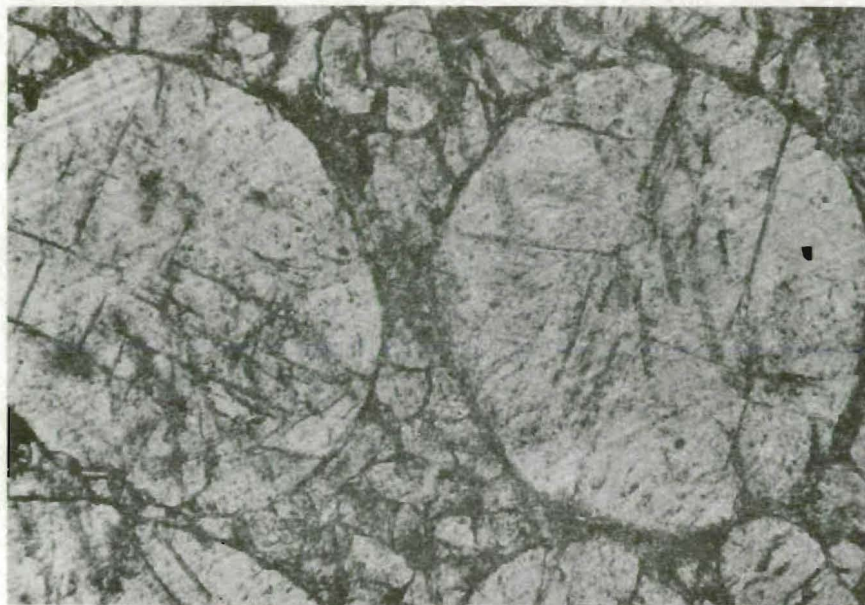
Fig.45   Spec.Hl   linear mag x 80

Extremely good example of a bimodal orthoquartzite (coarse
grains show strain lamellae due to structural deformation).

Fig.46   Spec.Rd 148   linear mag x 80

Typical "red-bed" lithology with poorly rounded quartz
grains, and ?limonitic clayey cement.   Transmitted light.

Fig.47   Spec.Rd 148   linear mag x 80

As in Fig.46, but reflected light. Shows the clayey
cement preventing contact between grains.
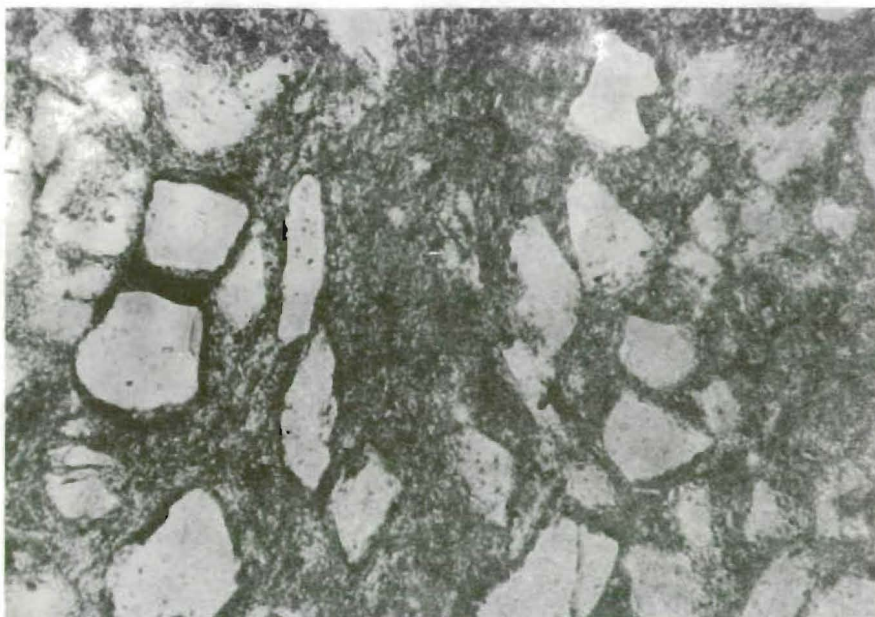
Fig.48   Spec.AP1/214/0   linear mag x 150

Typical clayey siltstone of the middle Stairway.
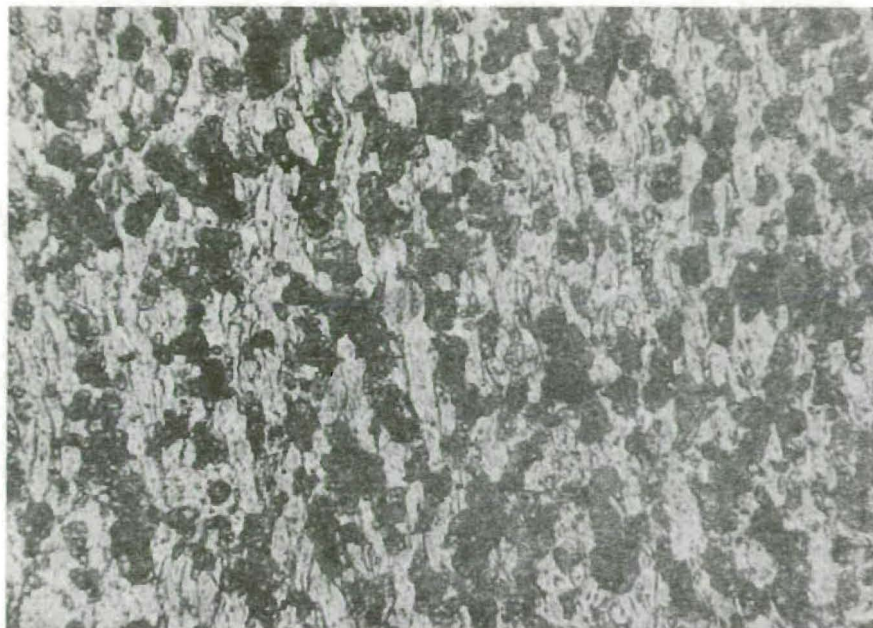
Fig.49   Spec.AP1/110/0   linear mag x 80

Sideritic claystone - clayey matrix light, siderite
dark crystalline form.
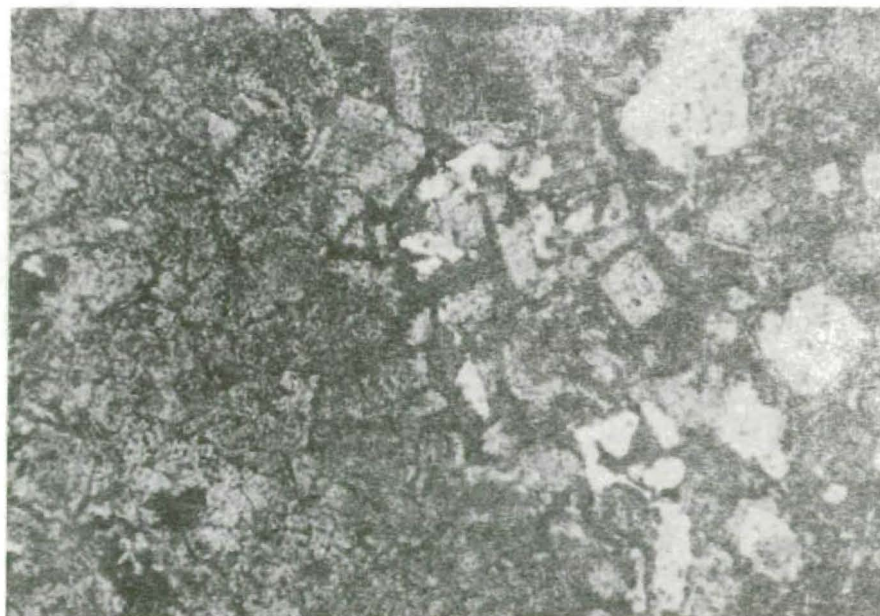
Fig.50   Spec.LA 188   linear mag x 80

Partly recrystallized dolomite showing well developed
rhombic form.
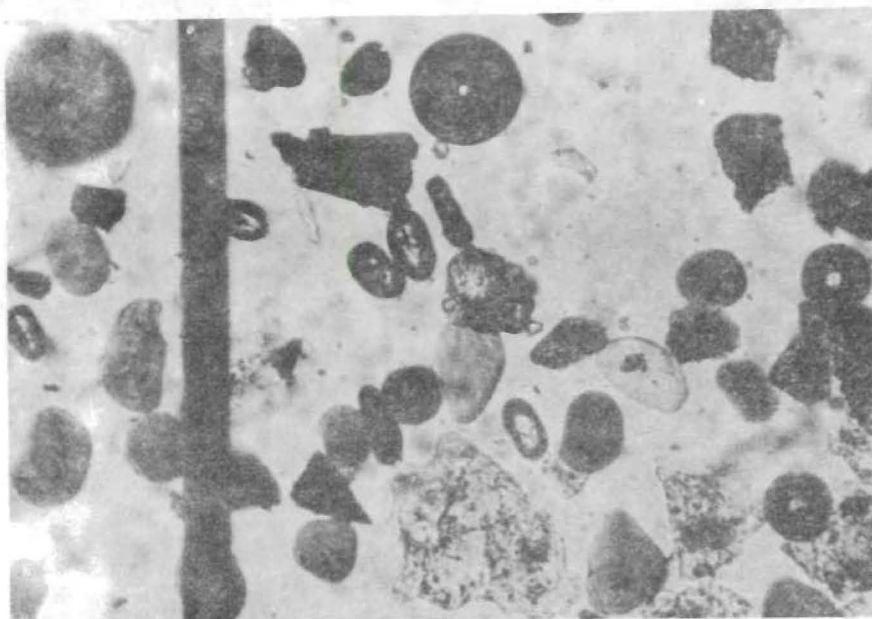
Fig.51   Spec.AP1/628/6   linear mag x 80

Typical heavy mineral assemblage showing tourmaline (well
rounded low relief) and zircon (well rounded, high relief),
also some pyrite (dark, angular). and quartz (light, angular).

Fig.52   Spec.AP1/628/6   linear mag x 400

Typical super-mature tourmaline - extremely well rounded.
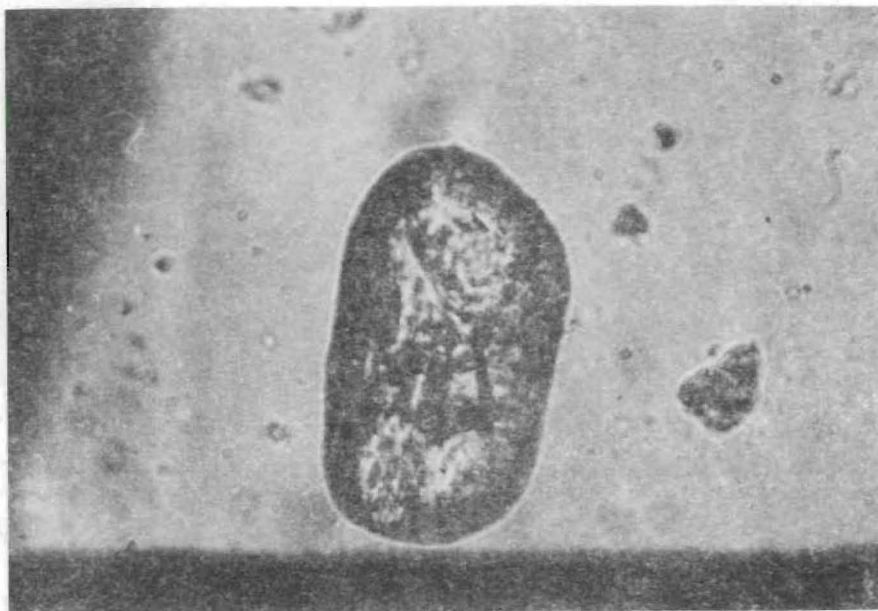
Fig.53   Spec.AP1/623/6   linear mag x 400

Typical super-mature zircon - extremely well rounded.

Fig.54 Typical phosphatic nodules collected from a
     quaternary gravel, in the Johnny Creek area.
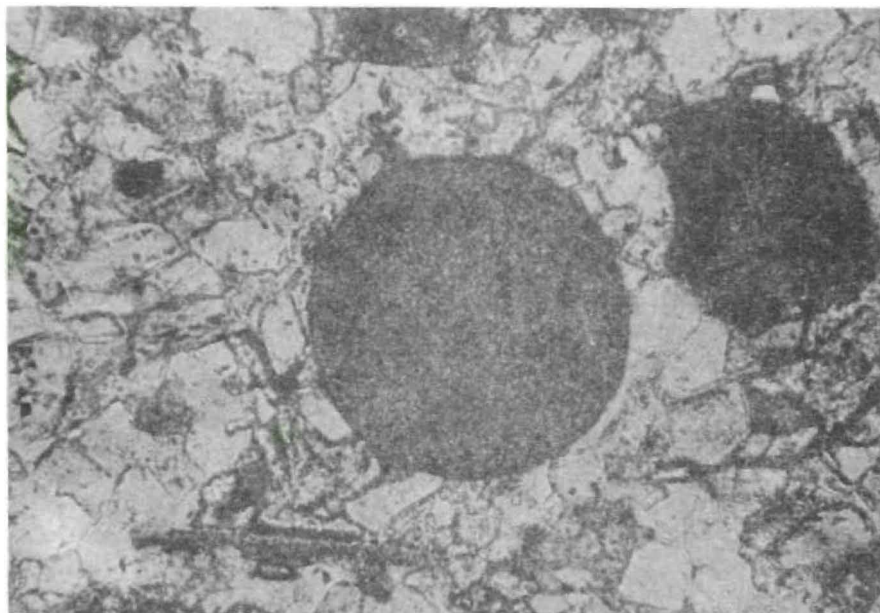
Fig.55   Spec.AP1/244/0   linear mag x 150

Well rounded structureless phosphatic pellet surrounded by
poorly rounded quartz grains.

Fig.56   Spec.AP1/97/1   linear mag x 150

Structureless phosphatic pellet with a prominent dark
rim - calcareous cement
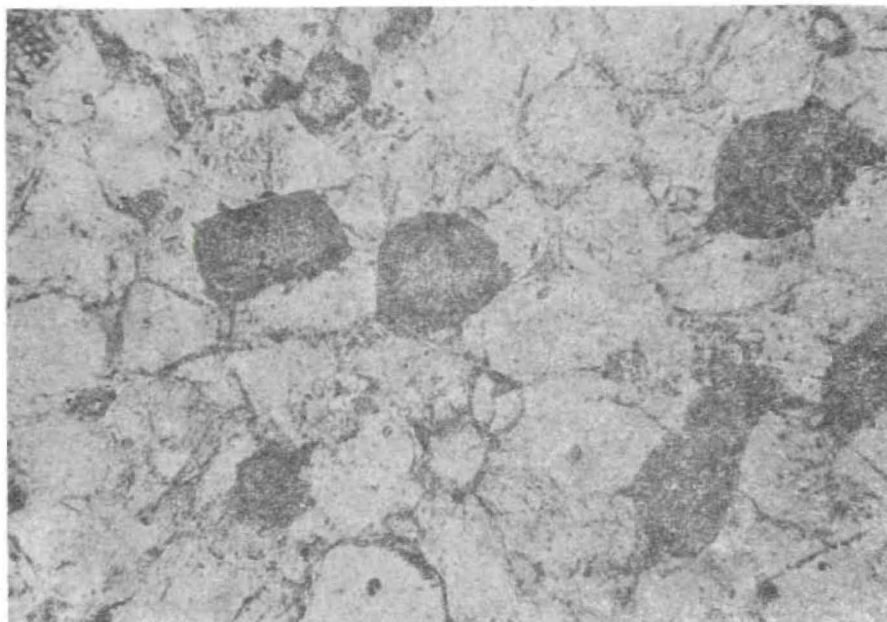
Fig.57   Spec.AP3/44/0   linear mag x 80

Structureless phosphatic pellets (dark), similar in form
to glauconite grains.   Grain size approximately equal
to that of the surrounding quartz (light).
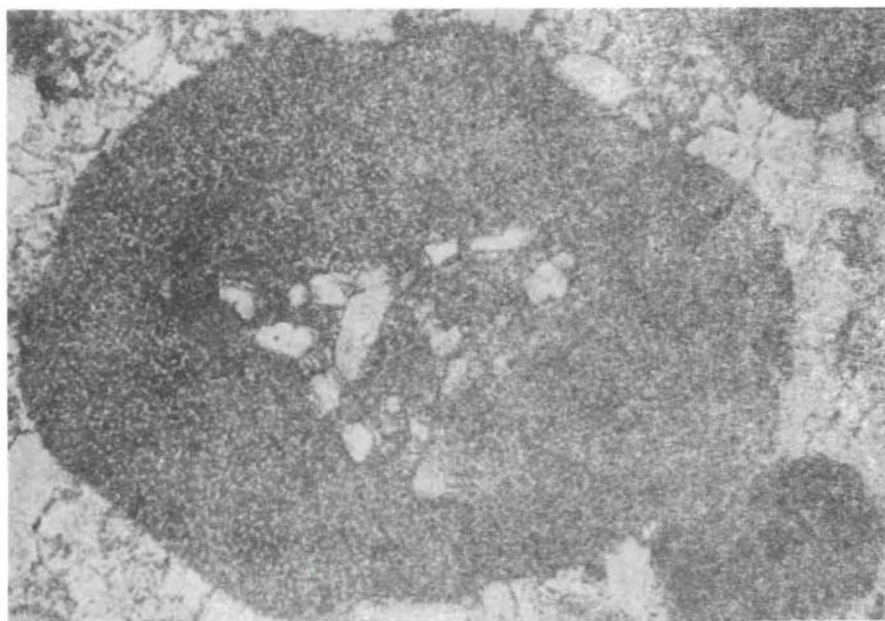
Fig.58   Spec.AP1/244/0   linear mag x 150

A structureless pellet with a small sandy core.
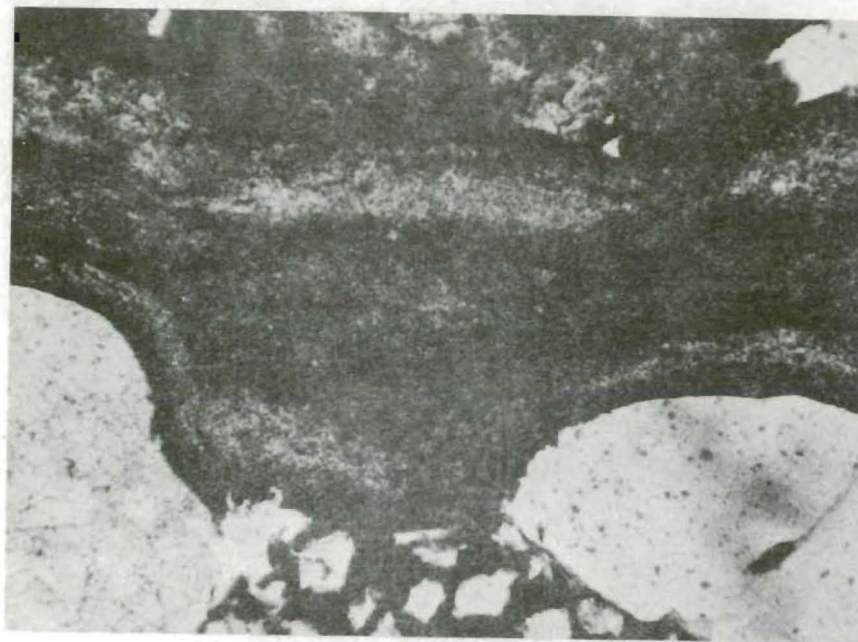
Fig.59　　　　　　Spec.AP1/73/2　　　　　　linear mag x 80

Concentric pelletal phosphate.　Internal banding
concentric to the irregular outline of the pellet.
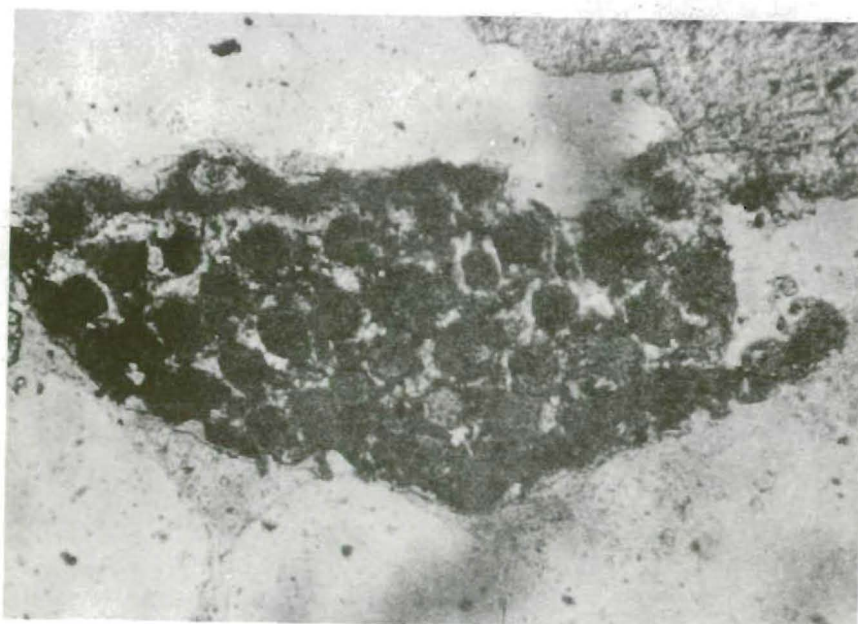
Fig.60　　　　　　Spec.AP1/97/3　　　　　　linear mag x 80

Compound pelletal phosphate - composed of small
structureless pellets.
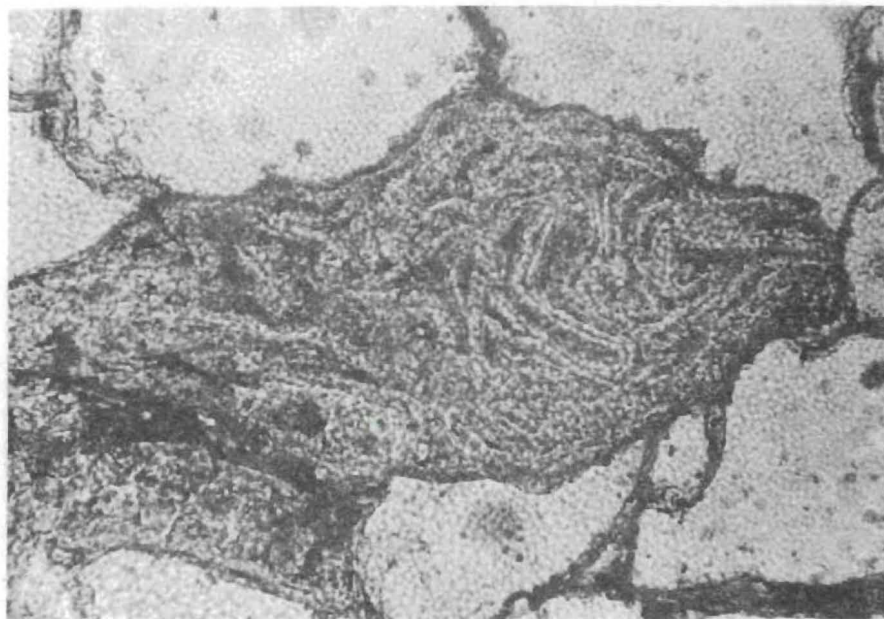
Fig.61   Spec.LA 139   linear mag x 150

Structured pelletal phosphate with a well developed intern
convoluted form.
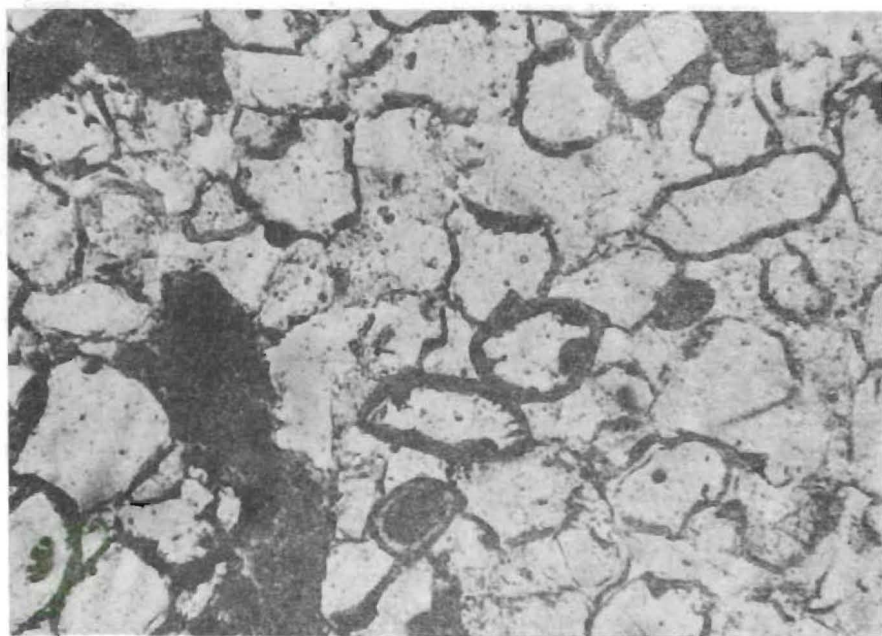
Fig.62   Spec.AP1/398/0   linear mag x 80

Encasing phosphatic pellets around quartz grains and
pyrite ooliths.
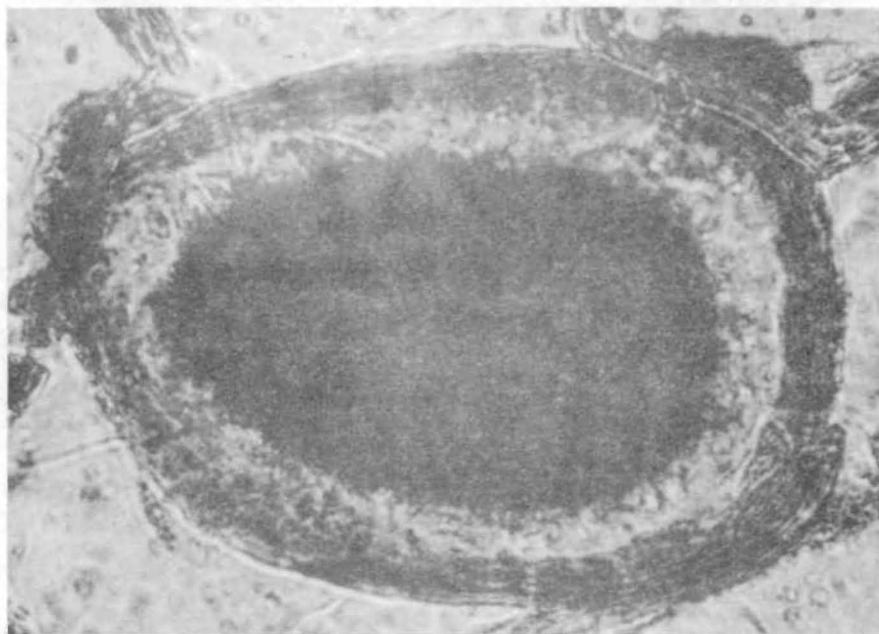
Fig.63   Spec.AP1/398/0   linear mag x 700

Encasing phosphatic pellet around a pyrite oolith.
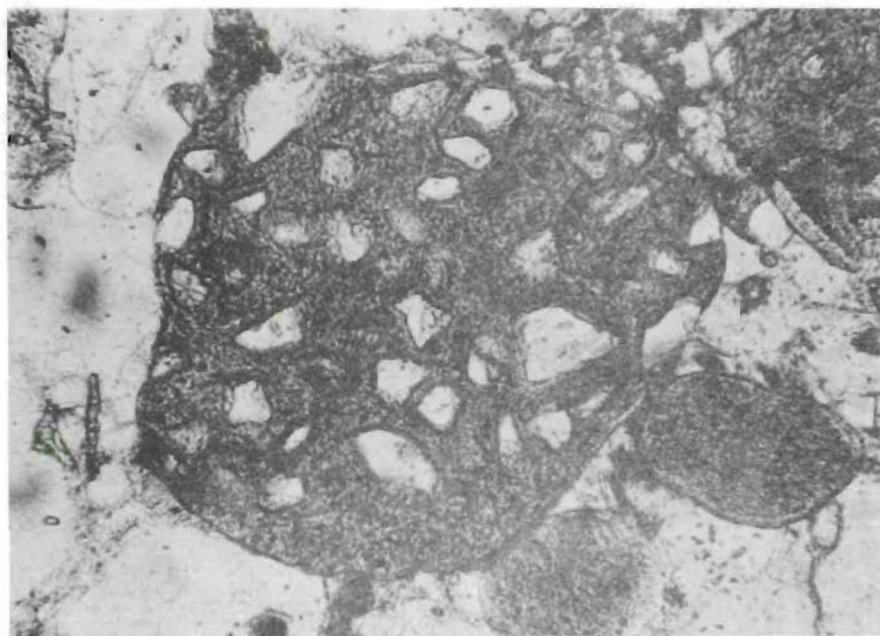
Fig.64   Spec.AP1/51/2   linear mag x 80

Sandy phosphatic pellet.
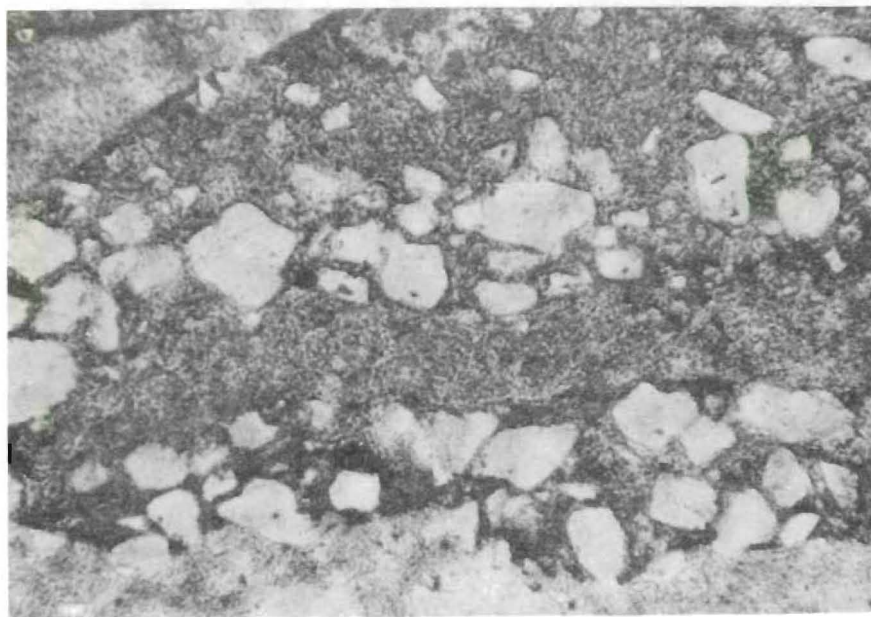
Fig.65   Spec.AP1/97/1   linear mag x 80

Sandy phosphatic pellet with relict banding shown by
the included quartz grains.
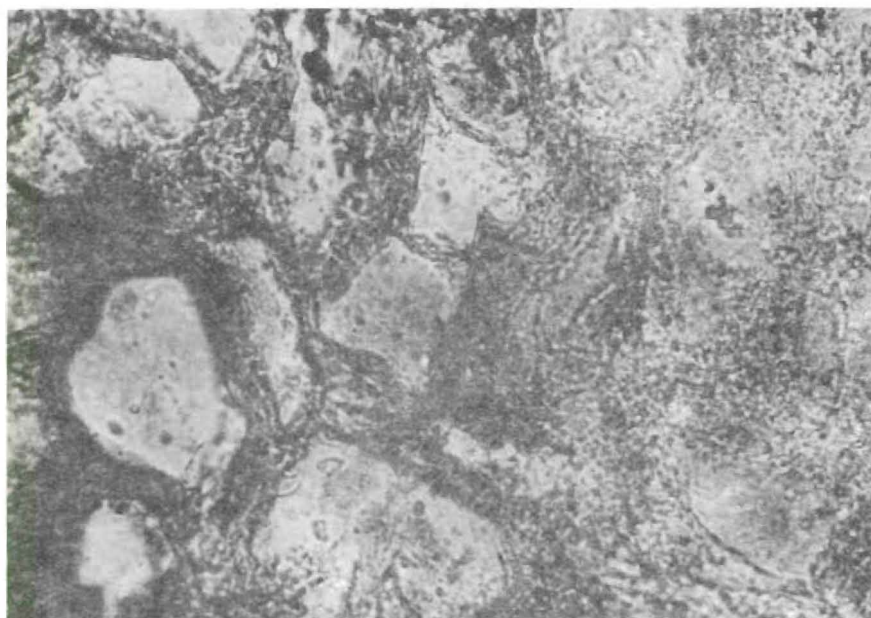
Fig.66   Spec.AP1/244/0   linear mag x 400

Cementing phosphate around quartz grains. The phosphatic
cement (dark) grades into a clayey cement (light).
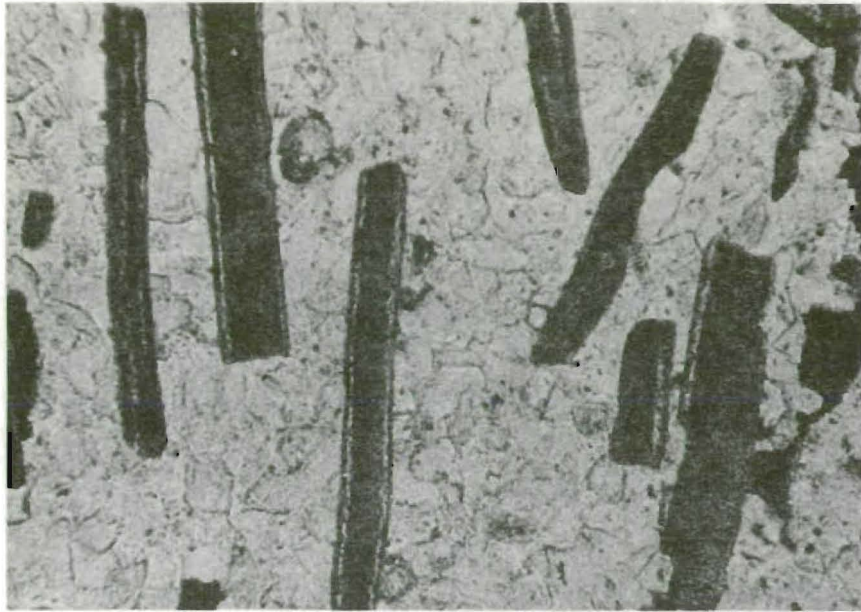
Fig.67   Spec.AP1/149/0   linear mag x 80

Laminate phosphate in quartz sandstone.
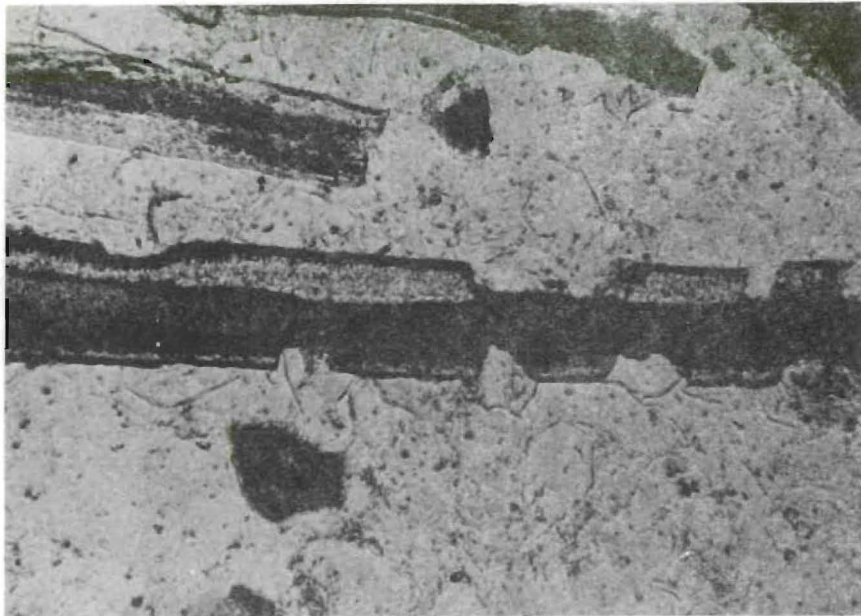
Fig.68   Spec.AP1/149/0   linear mag x 150

laminate phosphate showing the tripartite division of
the laminae and the corrosion (or erosion) of the outer
layers.
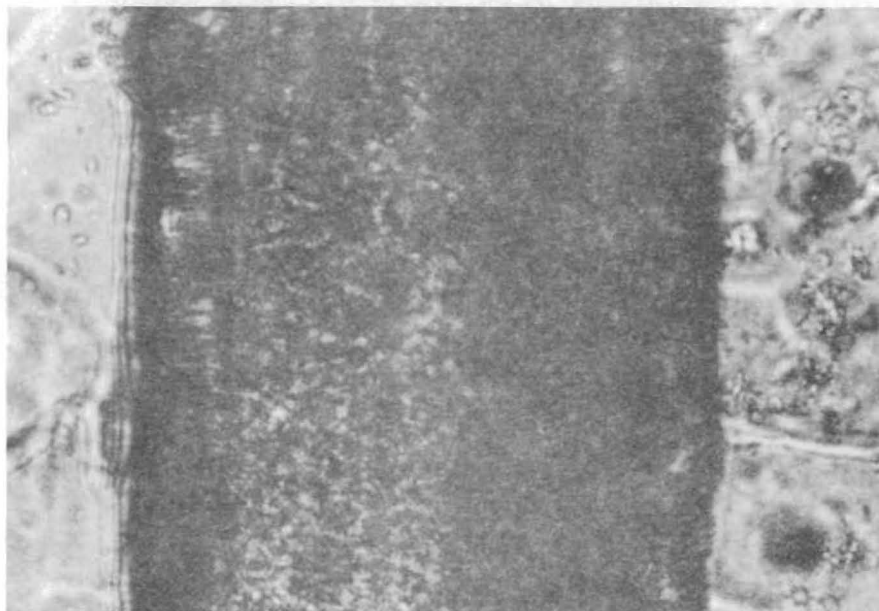
Fig.69   Spec.AP1/149/0   linear mag x 700

Laminate phosphate showing the fine rod-like structure in
the outer layer.   The "rods" have their long axes at
right angles to the long axis of the laminae.
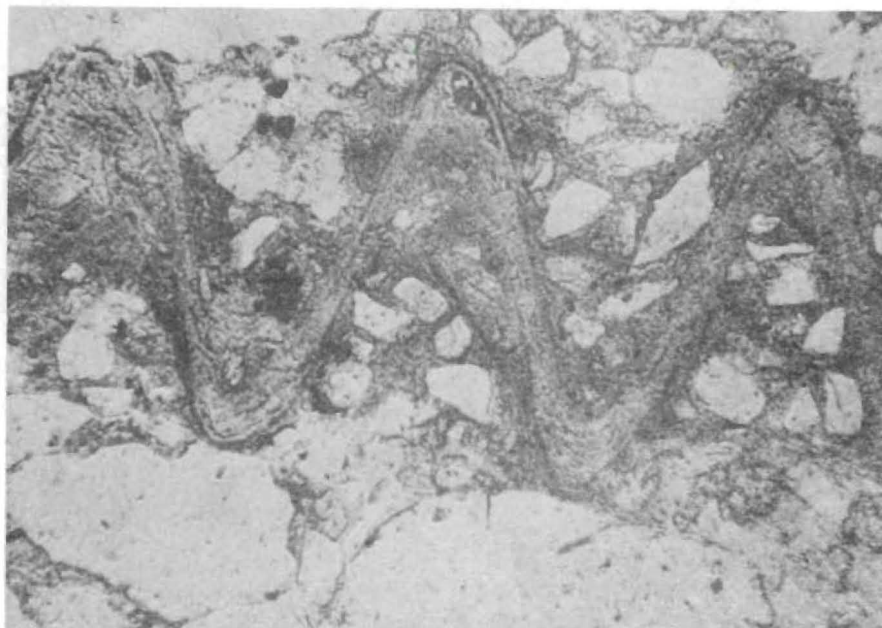
Fig.70   Spec.AP1/746/10   linear mag x 150

Phosphatized fossil - probably a fragment of an originally
calcareous brachiopod or a lamellibranch.
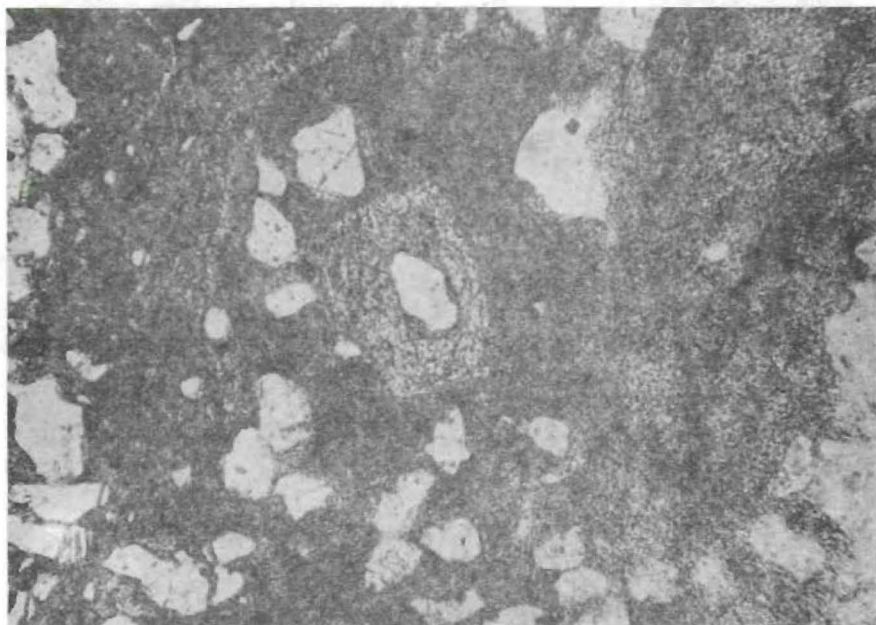
Fig.71   Spec. HY 762   linear mag x 150

Secondary corkite (fairly light outer rim) with middle
zone of crypto-crystalline apatite (dark) and a core of
?apatite (light). Some quartz grains (white).

Fig.72   Spec. HY 762   linear mag x 150

Secondary corkite (dark oolitic form) with ?apatite
cement (light, high relief). Some quartz grains (white).
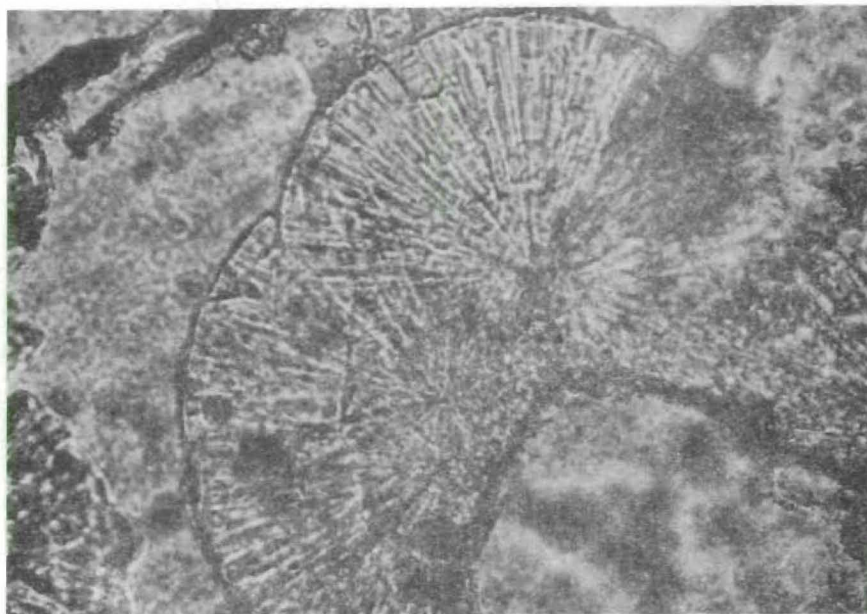
Fig.73   Spec.Rd 111   linear mag x 400

Secondary ?dahllite with an extremely well developed
spherulitic habit.
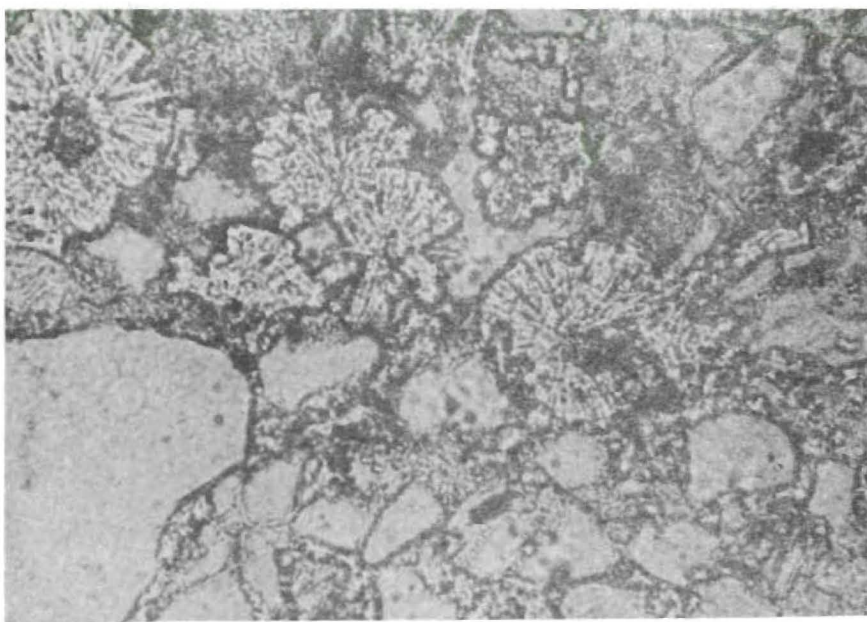
Fig.74   Spec.Rd 111   linear mag x 150

Quartz (light grey, low relief) with secondary intergranular
? dahllite (white, high relief, spherulitic form).
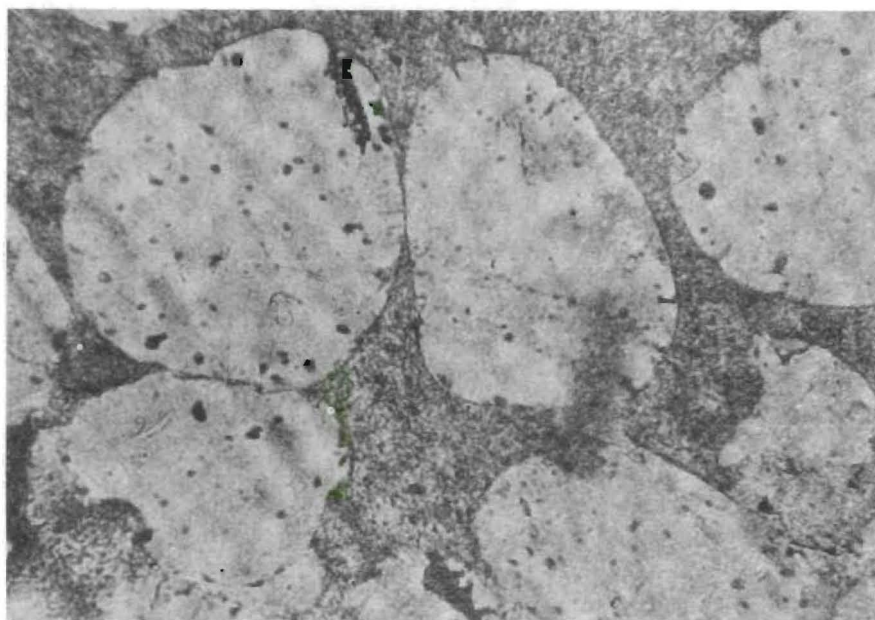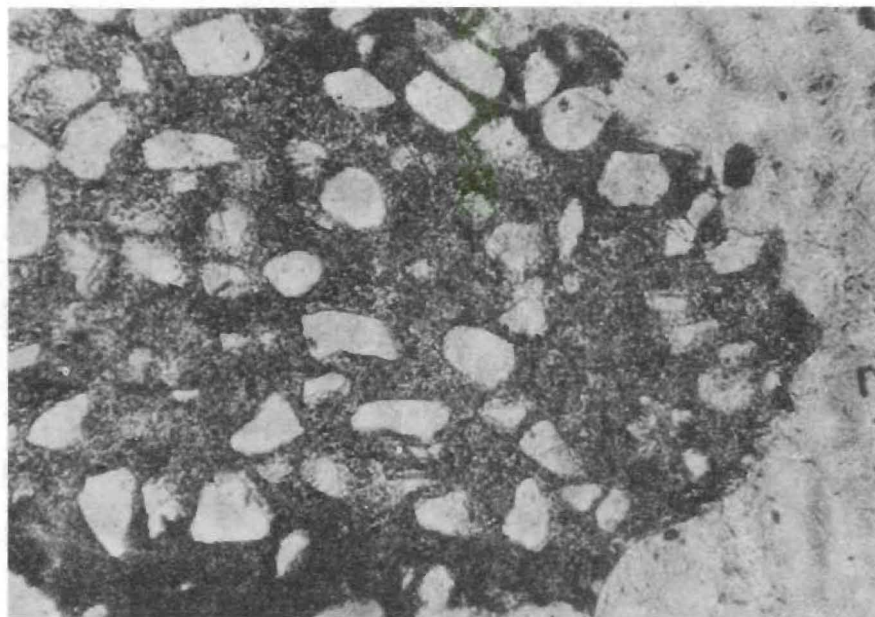
Fig.75   Spec.AP1/97/1   linear mag x 80

This figure illustrates the considerable difference in
grain size between quartz in a phosphatic pellet (upper)
and quartz (with a calcite cement) in the same thin section,
but outside the phosphatic pellets (lower).
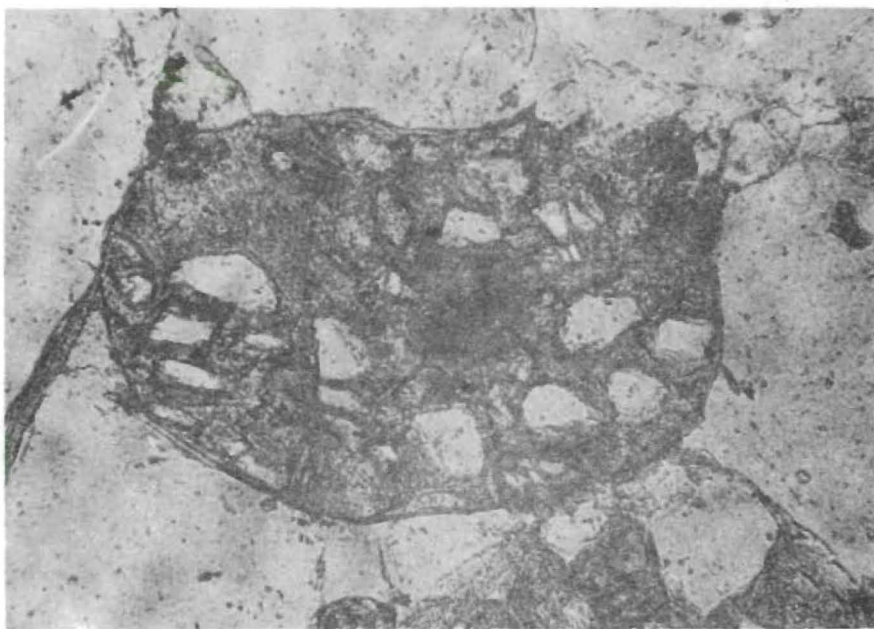
Fig.76   Spec.AP1/51/2   linear mag x 150

Sandy phosphatic pellet with an included glauconite grain
(dark) showing a very indistinct margin.

Fig.77   Spec.AP1/51/2   linear mag x 80

Phosphatic pellet (dark grey) with an included glauconite
grain (black showing a very sharp margin.
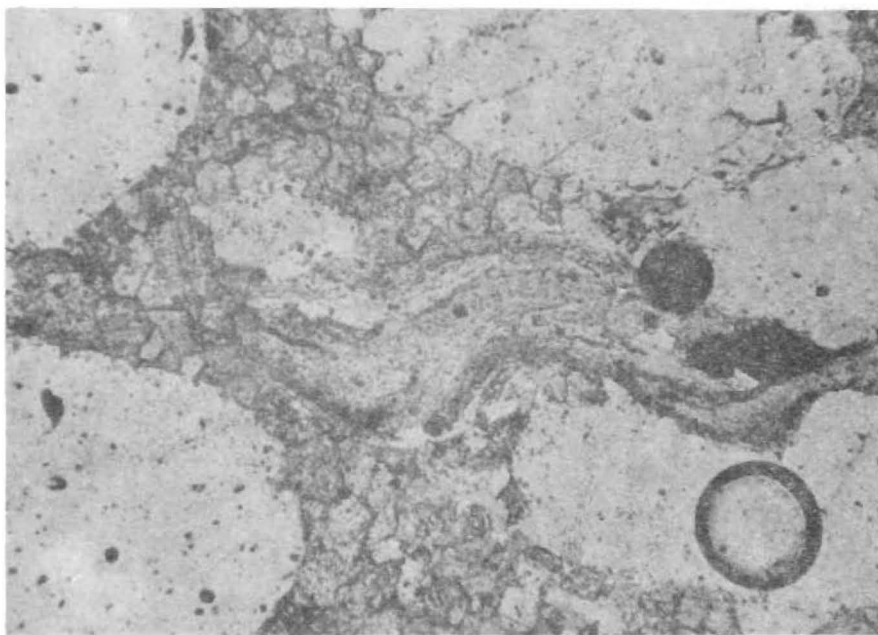
Fig.78   Spec.AP1/648/6   linear mag x 80

Coarse grains of quartz with intergranular dolomite cement.
A "wisp" of phosphatic eement with indistinct boundaries
possibly indicates some replacement of dolomite.
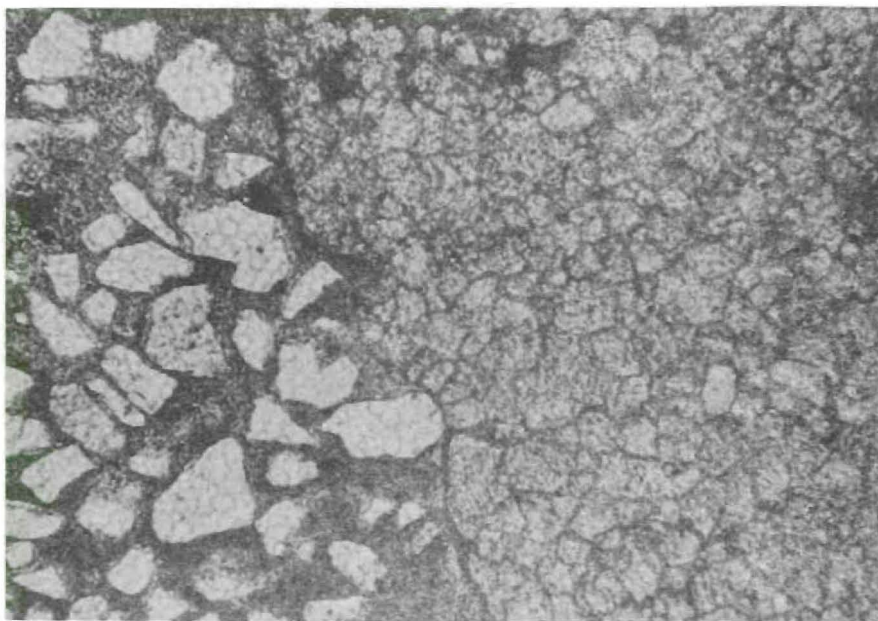
Fig.79   Spec.LA 139 (A)   linear mag x 80

Extremely sharp boundary between dolomite and the phosphate
of a sandy phosphatic pellet.   No evidence of replacement.
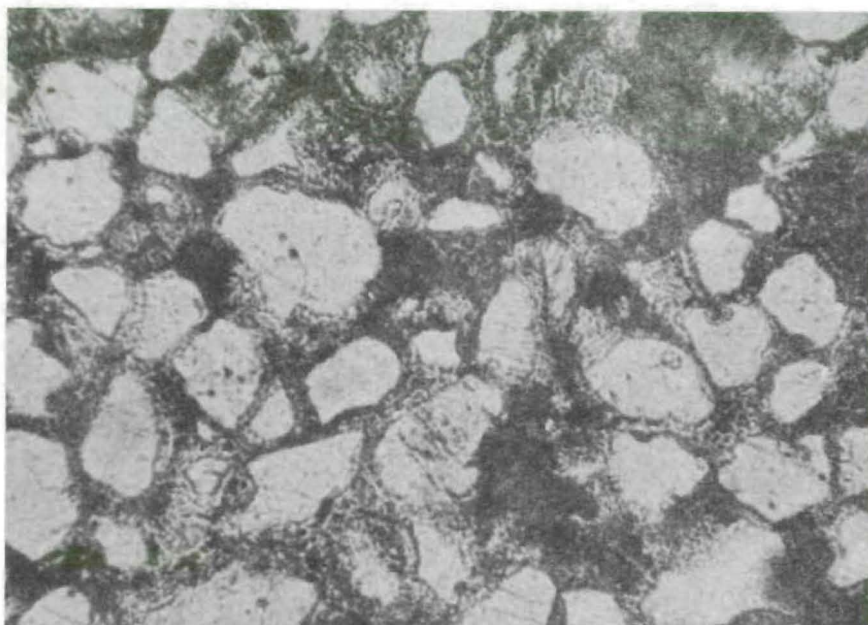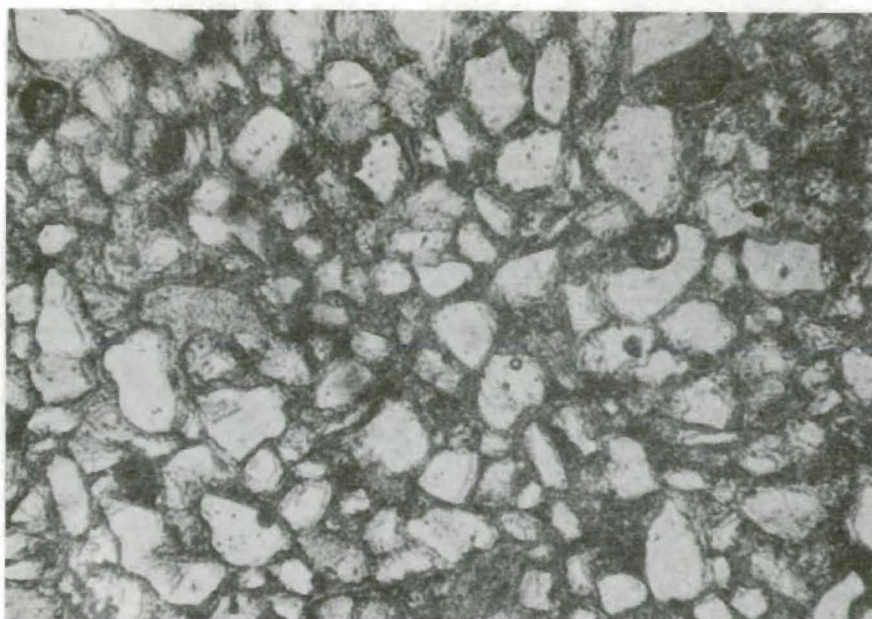
Fig.80   Spec.LA 534   linear mag x 80

This figure illustrates the difference between the grain
size of detrital quartz in grey pellets (upper) and detrital
quartz in brown pellets (lower).
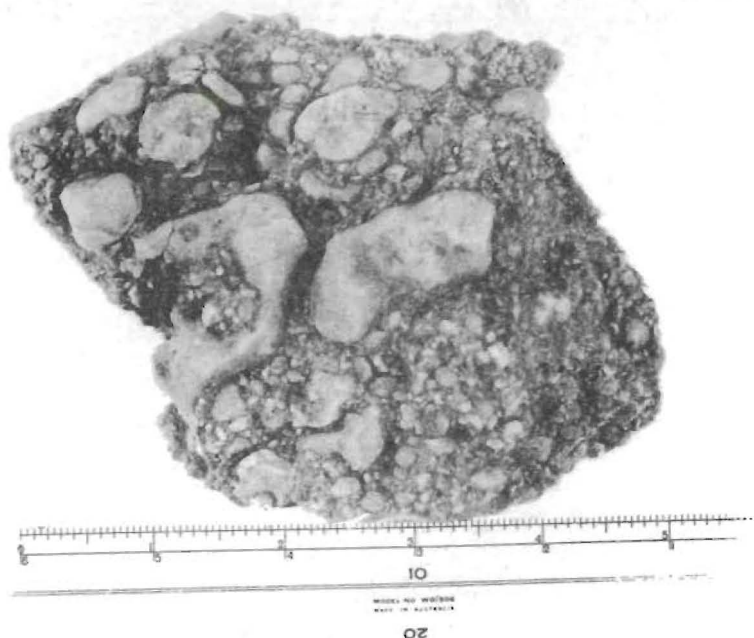
Fig. 81   Hand specimen of nodular phospherite from the
           middle Stairway, Johnny Creek
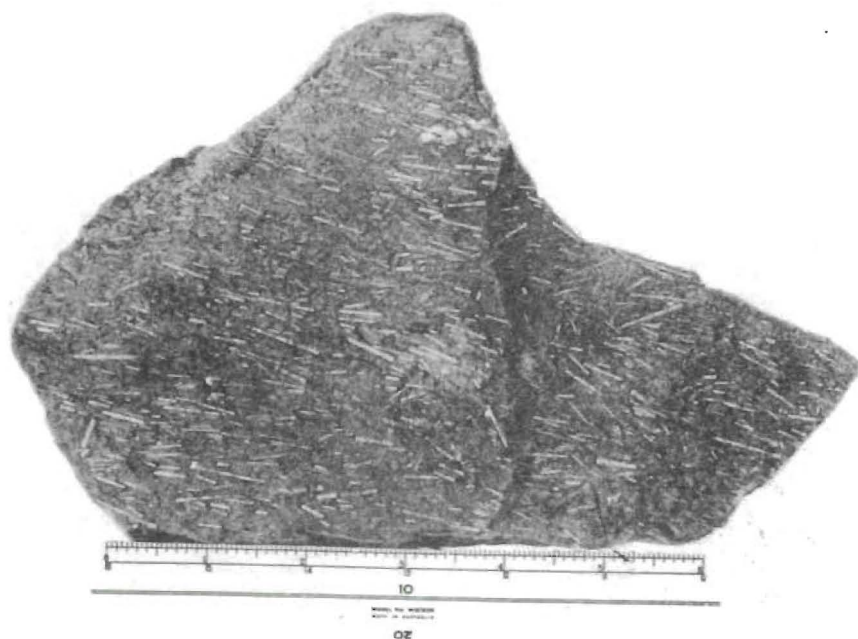
Fig. 82   Spec. LA 535/(10)

Hyalostelia australis ("sponge roots") within a slightly
phosphatic sandstone of the lower Stairway. Well developed
current lineation is visible.
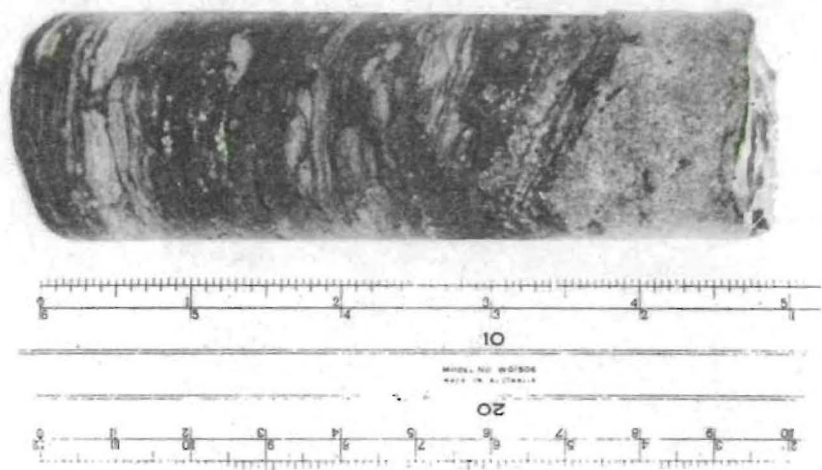
Fig.83   Disturbed laminae in sandy claystone of the
middle Stairway. Disturbance possibly due
to both "chewing" by infauna and "load-casting".
A coarse sand overlies the claystone.
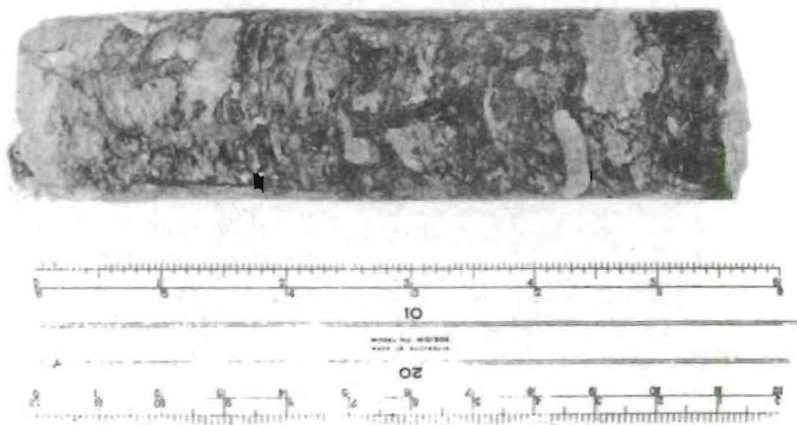
Fig.84   Strongly disturbed laminae in sandy siltstone of
the middle Stairway (due mainly to "chewing" by
infauna.
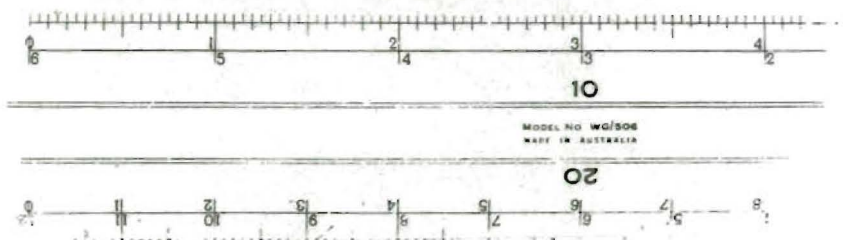
Fig.85   Strongly disturbed sandy claystone of the middle Stairway (due mainly to "chewing" by infauna).

APPENDIX II

METHODOLOGY

THIN SECTION STUDIES

(see Chapter 2)

General:

A total of 188 thin sections were examined during the course

of the investigation. Approximately half of the thin sections were

of surface samples and half of subsurface (core) samples. The

geographical distribution of the sample localities is as follows

(see Fig.1 for location of 1:250,000 sheet areas and subsurface

localities).

	No. of thin section	Locality
sub-surface	71	Johnny Creek (AP1)
	13	Mount Levi (AP2)
	16	Mount Holder (AP3)
	7	Inindia Bore (AP4)
	5	Gosses Bluff No.1 (H)
surface	37	Rodinga sheet area (Rd)
	17	Henbury sheet area (HY)
	15	Lake Amadeus sheet area (LA)
	2	Bloods Range sheet area (BR)
	2	Kulgera sheet area (K)
	1	Ayers Rock sheet area (AR)
	1	Mount Liebig sheet area (ML)
	1	Hermannsberg sheet area (H)

The samples from AP1, Gosses Bluff No.1, and the Rodinga, Henbury,

Lake Amadeus and Hermannsberg sheet areas were mainly collected by the

author. Those from AP2, AP3 and AP4 were collected by Dr.K.A.W.Crook,

and those from the remaining sheet areas were collected by A.T.Wells,

D.J.Forman, L.C.Ranford and A.J.Stewart.

Method:

Both textural and mineralogical observations were made on the thin sections: modal and maximum grain sizes (in phi units) were noted, together with roundness, and sorting. Estimates were made of the percentages of quartz (plutonic, undulose, composite and chert), feldspar, heavy minerals (tourmaline, zircon and opaques), clay, carbonate, phosphate, pyrite and glauconite; siliceous cements and quartz overgrowths were ignored. The petrography of all the specimens is summarized in Table 1, (appendix III).

Explanation of Table 1.

The purpose of Table 1 is to summarize the maximum possible amount of useful petrographic information without having to resort to detailed petrographic description. The tabulation scheme is as follows:

(a) Specimen Number

The letter prefix of a specimen number denotes the 1:250,000 sheet area or the sub-surface location from where the specimen was originally collected (see previous page). In the case of subsurface samples, the second set of numbers relates to the number of the sedimentation unit within the core (see Chapter 7) and the third set of numbers is the distance (in inches) from the top of the sedimentation unit, to the point where specimen was collected. The numbers given with surface samples are the field number by means of which the specimen can be located accurately by referring to the geological maps of the appropriate 1:250,000 sheet area, published by the Bureau of

Mineral Resources, Geology and Geophysics.

(b) Grain Size

This is expressed in phi units. Figures outside the brackets
are modal grain sizes; these are given as a single number
(e.g. 2∅) or as a range (e.g. 2∅ - 4∅) or in the case of
a bimodal sediment, as two modes, the first mode being the
major mode (e.g. 1∅ & 3∅). The figure within the bracket
is the maximum grain size.

(c) Roundness

The divisions of roundness are in accordance with the scheme
suggested by Folk (1961). Where the sediment is bimodal the
value given is that of the primary mode. The scale and the
abbreviations used are given below:

v ang	very angular
ang	angular
sub ang	sub angular
sub rnd	sub round
rnd	round
v rnd	very round

(d) Sorting

The scheme used here is that recommended by Folk (1961);
where sands are bimodal the sorting value is that of the
primary mode.

The scale and the abbreviations used are given below:

v well st	very well sorted
well st	well sorted
mod st	moderately sorted
poor st	poorly sorted
v poor st	very poorly sorted

(e) % quartz

The first value given (outside the brackets) is percentage
of quartz in the rock as a whole.   The letters within the
brackets correspond to the quartz types:

        P - plutonic (common) quartz - straight to
            slightly undulose extinction

        U - undulose quartz - strongly undulose extinction

        C - composite quartz

        Ch - chert

The number immediately after the letter gives the percentage
of that particular quartz type within the quartz group.
Hence, the meaning of 70 - 80 (P.70; U.15; C.10; Ch.5;)
is as follows: Quartz makes up 70 - 80% of the total rock
and that the composition of this quartz is 70% plutonic,
15% undulose, 10% composite and 5% chert. The letter "t"
is used to denote "trace", where there is less than 1% of
the constituent present.

(f) % Fdr

The number in this column (or the letter "t") gives the
amount of feldspar present - expressed as a percentage of
the total rock.

(g) % Heavies

The first number given (outside the brackets) is the quantity of heavy minerals present in the thin section, expressed as a percentage of the total rock. The letters within the brackets give the order of importance of the individual heavy minerals. "(O)" would mean that only opaque heavy minerals were present. "(O.T.)" would mean that major opaque minerals and minor tourmaline were present and "(T. & Z.)" would mean that tourmaline and zircon were present in approximately equal amounts.

(h) % clay, carbonate, phosphate, pyrite, glauconite.

Clay, carbonates (Carb), phosphate (Phos), pyrite (Py), and glauconite (Glauc) have their percentage expressed as a percentage of the total rock.

HEAVY MINERAL COUNTS

(see Chapter 3)

Method:

The method of obtaining the heavy mineral concentrate was as follows:-

Because of the highly indurated nature of the samples it was first necessary to carefully crush the samples using a rubber pestle. If there was a high percentage of authigenic minerals such as pyrite, the sample was also boiled in weak dilute hydrochloric acid. The sample was then added to a test-tube of bromoform and centrifuged to concentrate the heavies in the bulbous end of the test-tube. They were retained whilst the "lights" are poured off either by corking the bulbous end of the test-tube or by freezing the end with solid carbon dioxide. The heavy mineral fraction was then mounted in arochlor on a gridded slide to facilitate the location of grains under the microscope.

It was found that by far the quickest way of carrying out a heavy mineral count was by using a Dictaphone rather than noting the grains down on paper or using a point counter - this technique shortened the time to do a count to less than half the time previously taken. Wherever possible a minimum of 200 grains were counted; however in many of the slides this was not possible because of the small number of grains.

The samples were taken entirely from the AP1 core, the sample numbering system being exactly the same as that used for thin sections.

DETAILED TEXTURAL STUDIES

(see Chapter 4)

General:

A total of 18 detailed textural studies were made of 12 thin sections from core AP1. Wherever possible, specimens were chosen with only minor quartz overgrowths, to facilitate counting.

Method:

The technique of Packham (1955) was used in the textural studies. This involves the use of a Leitz integrating stage mounted onto a microscope. This stage consists of six spools, each of which can be rotated individually and on doing so will move across the slide and record the distance travelled.

Before commencing textural measurements, the slide is examined to establish the magnitude and range of the grain sizes present. The six spools on the integrating stage are then allotted various size grades (measured in phi units), with spool No.1 being allotted to all grains greater than a certain phi value; spools Nos.2-5 are allotted to equal phi unit intervals (generally $\frac{1}{2}$ phi unit intervals, unless the sediment is poorly sorted, in which case it may be necessary to use 1 phi unit intervals). Spool No.6 is allotted to all grains less than a certain phi value. Hence, a typical range for the integrating stage would be:-

Spool No.	Range
1	greater than 1ϕ
2	1ϕ to 1.5ϕ
3	1.5ϕ to 2ϕ

Spool No.	Range
4	2ϕ to 2.5ϕ
5	2.5ϕ to 3ϕ
6	less than 3ϕ

The size grades are the shortest diameters of the grains (measured by means of the calibrated cross-wires). When the centre of the cross-wires is on a grain boundary, the spool of the class into which the grain falls is rotated until the line across the grain has been traversed. The same is done for the next grain and so on, until a distance of at least 100 x's the diameter of the largest grain has been traversed.

Calculation of Results

The distances measured by the six spools are then expressed on percentages of the total distance traversed and plotted on log probability paper (Figs. 9 and 33). From the probability graph are obtained the values for the 95th percentile (ϕ_{95}), the 84th percentile (ϕ_{84}), the 75th percentile (ϕ_{75}), the 50th percentile (ϕ_{50}), the 25th percentile (ϕ_{25}), the 16th percentile (ϕ_{16}) and the 5th percentile (ϕ_5).

These values may then be used to calculate the Folk and Ward (1957) values for mean (Mz), standard deviation (d_1), skewness (Sk), and kurtosis (K_g):-

$$Mz = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3}$$

$$d_1 = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6}$$

$$Sk_1 = \frac{\phi_{16} + \phi_{84} - 2 \cdot \phi_{50}}{(\phi_{84} - \phi_{16})}$$

$$Kg = \frac{\phi_{95} - \phi_5}{2.44\,(\phi_{75} - \phi_{25})}$$

CROSS-BEDDING STUDIES

(see Chapter 5)

General:

The information noted down in the field included geographic
and stratigraphic position, the tectonic dip and the azimuth of the
tectonic dip; the dip of the cross-bed and the azimuth of the dip
of the cross-bed; the thickness of the cross-bed in inches; the
grain size of the cross-bed and the type of cross-bed.

Apparent cross-bed dips were not measured. Actual cross-bed
dips were measured by splitting the rock until a cross-bed face
was exposed or by orientating a board until it was parallel to
the cross-bed and then measuring the dip and the azimuth on the
board.

Correction for tectonic dip

Corrections were not made for plunge (Ramsay, 1961).

The normal way of correcting for tectonic dip is by a fairly
well known technique using a stereographic net.   However the
present author decided to use instead the CDC 3600 computor of
the Computing Research Centre, C,S.I.R.O., Canberra.   At various
stages in the development of the programme the author was helped
very considerably by Mr.T.Madden, Mr.T.Quinlan and Mr.J.Branson.

The programme is basically an adaptation of a programme used
by McIntyre (1963) for the rotation of spherical projections and
was particularly applied to crystallographic problems.   The
programme of McIntyre was also written for a 7090 computor and
therefore considerable adaptation was needed.   In fact if the

correction for tectonic dip had to be made by means of the
stereographic net, it probably would have been quicker for
the author than developing the programme, which took up a
great deal of time. However, the computor technique is more
accurate and also the programme is now available for general
use. The computor is able to work out about 400 corrections
in one minute - a very considerable saving in time compared with
the stereographic technique.

The method of tabulating the data for the punch-cards is given
in the "comment" section of the programme. In fact only the dip
and azimuth information is necessary for the correction - all the
other data is optional. It is recommended that this method of
tabulation is adhered to in the field so that it is unnecessary
to rewrite the data before the cards can be punched.

Symbols used in cross-bed data

(a) Geographic location

    ANG - 10 miles N.W. of Angas Downs Homestead

    AP3 - Diamond drill hole AP3 near Mt.Holder

    CHA - Chandler Range

    CSP - About 12 mils north-east of Curtin Springs Homestead

    ECK - Ellery Creek

    EGR - Eastern end of the Gardiner Range

    EJC - Eastern end of Johnny Creek Anticline

    EMC - Eastern end of the Mount Charlotte Range

    GHN - Glen Helen Gorge

    GEO - 1 ml. south of the George Gill Range

    INI - Near Inindia Bore - close to diamond drill hole AP4

LEV   -   Levi Range

MPY   -   Mount Peachy

MTE   -   Mount Ebenezer

MTS   -   Mount Sunday Range

NOM   -   2 mls north of Nomra Bore

OLF   -   Oliffe Range

RC3   -   Section RC3 - in the middle of the Mt.Charlotte Range

SEY   -   North flank of the Seymour Range

STP   -   Stokes Pass

WJC   -   Western end of Johnny Creek Anticline

WGR   -   Western end of the Gardiner Range

WMC   -   Western end of the Mt.Charlotte Range

(b) Stratigraphic Position

LST   -   Lower unit of the Stairway Sandstone

MST   -   Middle unit of the Stairway Sandstone

UST   -   Upper unit of the Stairway Sandstone

(c) Type of cross-bed

CT   -   Curved Tabular

ST   -   Straight tabular

(d) Grain Size

VF   -   Very fine grained sand

F   -   Fine grained sand

M   -   Medium grained sand

C   -   Coarse grained sand

VC   -   Very coarse grained sand

```
      PROGRAM CURRENT
C    THIS PROGRAM IS DESIGNED TO CORRECT FOR SECONDARY TILT IN CROSS-BEDS
C    THE PROGRAM IS BASED ON MCINTYRE(1963),TECHNICAL REPORT NO7 POMONA COLLEGE
C    THE PROGRAM DEPENDS ON ROTATION OF POINTS IN LOWER HEMISPHERE PROJECTIONS
C    P HAS TREND TP AND PLUNGE P.  Q HAS TREND TQ AND PLUNGE Q.
C    WHEN P IS ROTATED TO THE S POLE, Q HAS TREND TQ1 AND PLUNGE Q1.
C    IF Q IS ROTATED INTO UPPER HEMISPHERE, USE THE OPPOSITE OF Q.
C    THE RAW DATA IS PUT ON THE CARDS AS FOLLOW.
C    LOCALITY DATA  COLUMNS 3 TO 5, STRATIGRAPHIC DATA  COLUMNS 7 TO 9,
C    SECONDARY AZIMUTH (I.E. DIRECTION OF DIP) COLUMNS 20 TO 22,
C    SECONDARY DIP  COLUMNS 29 TO 30, CROSS-BED AZIMUTH  COLUMNS 36 TO 38,
C    CROSS-BED DIP  COLUMNS 45 TO 46, THICKNESS OF CROSS-BED COLUMNS 53 TO 55,
C    TYPE OF CROSS-BED  COLUMNS 58 TO 59, GRAIN SIZE COLUMNS 63 TO 64.
C    ONLY THE SECONDARY AZIMUTH AND DIP AND THE CROSS-BED AZIMUTH AND DIP
C    ARE NECESSARY FOR THE CALCULATION OF TRUE DIRECTION AND DIP
C    ALL OTHER INFORMATION IS OPTIONAL AND THESE COLUMNS MAY THEREFORE
C    BE ADAPTED AS REQUIRED
C    THE DATA CARDS MUST BE PLACED IMMEDIATELY IN FRONT OF THE CARD
C    WITH THE ROW OF NINES
C    IF THERE ARE ANY PROBLEMS P.J.COOK, D.M.R., PARKES WAY, CANBERRA, A.C.T.,
C    AUSTRALIA, MAY BE ABLE TO HELP.
C    THE BEST OF LUCK - YOU WILL PROBABLY NEED IT
C
  100 FORMAT (1X,2A4,5X,4FR,4X,I3,A4,A5)
  101 FORMAT(1X,A4,2I,A4,F14,FR,F5,F6,9X,I7,3X,A4,3X,A5,10X,F10,1,F13,1)    *001
  102 FORMAT(1X,107H LOC STRAT          SEC-AZ SEC-DIP B-AZ X-DIP          *002
     1X-THICK X-TYPE GN-SIZE          PRIMARY-AZ  PRIMARY-DIP)             *004
      PRINT 102                                                           *006
C
      PI=3.14159265358Q
      HPI=PI*0.5
      PI2=2.0*PI
      AF=PI/180.0
C
C     READ TP, P, TQ, Q IN DEGREES
C
    1 READ 100,LOC,STRAT,TP,P,TQ,Q,THICK,SHAPE,GRAIN
      TPA=TP$PA=P$TQA=TQ$QA=Q
      IF(EOF,60) 50,2                                                      *006
    2 CONTINUE                                                             *006
      IF(LOC1.NE.LOC.OR.STRAT1.NE.STRAT)PRINT 103                          *007
  103 FORMAT(1X,/)                                                         *008
      LOC1=LOC $ STRAT1=STRAT                                              *009
      IF(TP-TQ,EQ,-180.0 ,OR. TP-TQ,EQ,+180.0) 48,49                       *091
   48 Q1=Q+P $ TQ1=TQ $ GO TO 41                                          *092
   49 CONTINUE                                                             *093
      IF(TP.EQ.TQ)42,43                                                    *009
   42 Q1=Q-P $ TQ1=TQ  $ GO TO 41                                         *009
   43 IF(TP.GE.180)30,31                                                   *010
   30 TP=TP-180 $ GO TO 32                                                 *020
   31 TP=180+TP                                                            *030
   32 IF(TQ.GE.180)33,34                                                   *040
   33 TQ=TQ-180 $ GO TO 35                                                 *050
   34 TQ=180+TQ                                                            *060
   35 P=90-P $ Q=90-Q                                                      *070
C     JOB TERMINATES BY READING CARD WITH 9 IN ALL COLUMNS
C
C
      IF(TQA.EQ.9999999)14,5
    4 STOP
    5 TP=TP*AF
      P=P*AF
      ZK1=SINF(P)
      IF(ZK1.EQ.0.1)39,40                                                 *072
   39 TQ1=TQ $ Q1=Q $ GO TO 44                                            *028
   40 ZK2=COSF(P)                                                         *076
      S1=0.0
      S2=0.0
      S3=0.0
      TQ=TQ*AF
      Q=Q*AF
      SINQ=SINF(Q)
      COSQ=COSF(Q)
      T=TQ-TP
      IF (T.LT.0)6,7
    6 T=PI2+T
    7 S=AT
      IF (PI.LT.T) 8,9
    8 T=PI2-T
    9 COST=COSF(T)
      SINQ1=ZK1*SINQ+ZK2*COSQ*COST
      IF (SINQ1.LT.0) 10,12
   10 IF (HPI.LT.0) 11,12
   11 S2=PI
      SINQ1=-SINQ1
   12 Q1=ASINF(SINQ1)
      COSQ1=COSF(Q1)
      IF (S2.LT.PI) 13,15
   13 FN=SINQ-ZK1*SINQ1
      IF (FN.LT.0) 14,16
   14 FN=-FN
      S3=PI
      GO TO 16
   15 FN=SINQ-ZK1*SINQ1
   16 COSZ=FN/(ZK2*COSQ1)
      W=ASINF(COSZ)
      IF (S3.LT.PI) 17,18
   17 T1=HPI-W
      GO TO 19
   18 T1=HPI+W
   19 IF (S1.LT.PI) PI,20
   20 T1=PI2-T1
   21 TQ1=T1+TP+S2
      IF (PI2.LT.TQ1) 22,23
   22 TQ1=TQ1-PI2
   23 Q1=Q1/AF
      TQ1=TQ1/AF
   44 CONTINUE
      IF(TQ1.LE.1*0)46,37                                                 *080
   36 TQ1=TQ1+160 $ GO TO 38                                             *090
   37 TQ1=TQ1-180                                                         *100
   38 Q1=90-Q1                                                            *110
      IF(Q1.LT.0)45,41                                                    *111
   45 IF(TQ1.GT.180)46,47                                                 *113
   46 TQ1=TQ1-180 $ Q1=Q1-90 $ GO TO 41                                  *115
   47 TQ1=TQ1-180 $ Q1=90-Q1 $ GO TO 41                                  *117
   41 PRINT 101,LOC,STRAT,TPA,PA,TQA,QA,THICK,SHAPE,GRAIN,TQ1,Q1
      GO TO 1
   50 CONTINUE                                                            *018
      END
```

DETAILED GRAPHIC LOG

(see Chapter 7)

General:

A variety of types of detailed graphic logs have been
proposed in the past for the study of sedimentary sequences,
the parameters incorporated in the logs depending on the
purpose of the investigation.   Bouma (1962) summarized the
more important methods.   The basic aim of all methods is to
present in as clear a fashion as possible such features as
litholoty or sedimentary structures, so that any basic cyclicity
of sedimentary environments is apparent.   Bouma (1962) has used
the method to good effect in his investigation of turbidite
sequences of the Peira-Cava area of France.   Because of the
proven worth of the method, the comprehensiveness of its symbolism
of sedimentary structures etc., and because it is in a readily
available published form, Bouma's methods and symbols have been
used wherever possible.   Some adaptation has of course been
necessary because of particular features of the Stairway Sandstone.
Bouma was not for instance concerned with phosphorites and
therefore special columns have been added to incorporate this
additional phosphate information. Also, a major part of Bouma's
work was concerned with sections measured in the field whereas
the detailed graphic log studies in the Stairway Sandstone are
restricted to core from a continuously cored diamond drill hole.
Thus, whilst the vertical information was very much more detailed
than that which Bouma had access to, there was no lateral control
whatsoever.

The core which was studied was obtained from site AP1 on the south flank of East Johnny Creek Anticline (Fig.41). The hole, which was one of four drilled to test for phosphate in the Stairway Sandstone, was drilled to a total depth of 813 feet, but only the interval 50-700 feet was logged as it took about 1,000 working hours to obtain all the information and plot up this 650 feet of core in the necessary detail. The investigation was primarily a laboratory one and the easiest way of conducting it was by the use of a "questionnaire sheet" on which the values of the various parameters were noted. These values were then plotted up on large graphic log sheets at a scale of 1 inch to two feet. However, as this gave a graphic log over 30 feet long it was necessary to photographically reduce the logs down to a scale of 1 inch to 4 feet to make them more convenient to handle.

Graphic Presentation

1. Thickness in feet

    (a) Apparent thickness; This is the vertical distance in feet measured from the top of the hole. This thickness is noted on the graphic log at 2 foot intervals.

    (b) True thickness: This is the true thickness of the Stairway Sandstone measured from the top of the formation (situated at an apparent thickness of 69 feet 10 inches) and with a correction factor applied for the structural dip of the beds in the core. This true thickness is noted on the log at 10 foot intervals.

2. <u>Core</u>

    (a) Recovery: This is a graphical representation of information given by Barrie (1964) and is based on the footage drilled compared with the footage of core recovered.

    (b) Condition: (see Log Reference l, appendix IV). The majority of the core was in good condition but minor amounts were either lost or broken up during drilling operations. In places, half the core was taken for P_2O_5 analysis. In the more shaly units, splitting of core into many fine laminae parallel to the bedding has occurred.

3. <u>Rock type</u> (see Log Reference II, appendix IV)

    This column indicates the main rock type of the unit. Wherever possible the symbols of Bouma (1962) are used. Bouma's designation of "shale" is replaced by the more satisfactory term lutite because of the fissility implication of the name shale. In the case of the Stairway Sandstone the term "sandstone" means quartz arenite and in most cases means orthoquartzite (after Folk, 1961). Where there are two rock types present in the same unit the proportions are shown on the log.

4. <u>Bedding Plane Properties</u>

    (a) Type: (see Log Reference III, appendix IV). The symbol used for bedding plane types are identical with those used by Bouma (1962) and are essentially an

indication of the degree of sharpness of the contact

between two layers. To a certain extent the classification

into very sharp, sharp etc. is a somewhat qualitative one.

It is however of value if the classes are considered relative

to each other.

(b) Structures on the bedding plane: This column was included

should any features have been present on the small area

available on the few bedding planes visible, but in fact no

recognisable features were seen.

5. Current direction

This column was included so that should this type of information

be available from surface outcrop or from orientated core, it

can be shown on the log. In the case of the AP1 core, no such

information was available.

6. Layer Properties (see Log Reference IV, appendix IV)

The symbols used are identical with those of Bouma (1962).

The main column is in this case divided into 10 sub-columns

each of which represents a layer property or sedimentary

structure. Variations within the basic layer property are

indicated by the position of the "blocks" within the sub-column

so that in all it is possible to represent a total of 31

different layer properties by the method given on Log Reference

IV (appendix IV).

One symbol which was left out of the graphic log and which

would have been extremely useful is a sub-column for showing

the degree of churning by burrowing organisms. The lack of

such a sub-column is overcome by for instance representing

very strong churning by infauna by the "blocking in" of the
3 columns to show "strongly disturbed parallel lamination",
"strongly disturbed lenticular wavy lamination" and "tracks
and burrows in all directions".   It would however be simpler
and more correct to have had a single separate sub-column for
the purpose.

7.   Lithology

The term "lithology" is used here for uniformity with Bouma
(1962), but is somewhat unsatisfactory as "lithology" is
more normally taken to mean "rock type" and not "texture".

(a)   Texture (see Log Reference V, appendix IV)

The term texture is used here in the sense of Bouma (1962)
and may be taken to mean the modal grain size.   Bouma's
scheme has been modified so that the grain sizes of
bimodal units can be shown.   Grain size is measured under
a binocular microscope with a graduated cross-wire in
the eyepiece.   The measurement is made directly in the
phi scale by means of the conversion table given by
Folk (1961).   The grain size classes with their
equivalent on the phi scale and the Wentworth scale are
given below:-

Class	Phi Range	Wentworth Range (mms)
Coarse gravel	-2ϕ to -3ϕ	4 mm to 8 mm
Fine gravel	-1ϕ to -2ϕ	2 mm to 4 mm
V.coarse sand	0ϕ to -1ϕ	1 mm to 2 mm

* phi (ϕ) is equivalent to $-\log_2$ of the diameter in millimetres.
 (Krumbein, 1934).

Class	Phi Range	Wentworth Range (mms)
Coarse sand	1∅ to 0∅	0.5 mm to 1 mm
Medium sand	2∅ to 1∅	0.25 mm to 0.5 mm
Fine sand	3∅ to 2∅	0.125 mm to 0.25 mm
V. fine sand	4∅ to 3∅	0.0625 mm to 0.125 mm
Coarse silt	5∅ to 4∅	0.0312 mm to 0.0625 mm
Fine silt	6∅ to 5∅	0.0156 mm to 0.0312 mm
Clayey silt	7∅ to 6∅	0.0078 mm to 0.0156 mm
Mud	8∅ to 7∅	0.0039 mm to 0.0078 mm
Clay	below 8∅	below .0078 mm

    (b) Maximum Grain Size

This is given in the phi scale, the phi value being measured directly with a binocular microscope.

    (c) Calcium Carbonate (see Log Reference VI, appendix IV)

This is estimated by means of a 10% solution of hydrochloric acid and is merely a rough indication of the calcium carbonate content of the rock.

8. Porosity (see Log Reference VII, appendix IV)

The intergranular and vuggy porosity are estimated visually from inspection under the binocular microscope.

9. Induration (see Log Reference VIII, appendix IV)

Bouma (1962) proposed five grades of induration. In most of the Stairway Sandstone only grades 3 and 4 are present.

10. Supplementary Data (see Log Reference IX, Appendix IV)

The presence of pyrite, glauconite, free oil and fluorescence is noted under the heading of supplementary data. In addition, the pyrite column distinguishes between oolitic

and non-oolitic forms. The quantitative division of pyrite and glauconite into "rare", "common", and "very common", is estimated visually. "rare" implies the component is visible only with the aid of a hand lens or binocular microscope. "common" implies that the component is easily visible to the naked eye and "very common" is used when the component is considered to form a major part of the rock type.

11. Fossils

Only the presence of macrofossils is noted. Parts of the core have been submitted for microfossil examination but the results of these examinations are not available as yet.

The only fossils present are brachiopods (represented by the "triangular" symbol), gastropods, and lamellibranchs (represented by the "bomb-like" symbol. The presence of fossils in general is shown by the "ammonite symbol". A diagonal line across the fossil symbol implies that the fossils are in a fragmentary form.

12. Colour

(a) Fresh

The colour of the units is observed in artificial light, using a Geological Society of America Colour Chart (Goddard et.al., 1963) for comparison. The colours represented by the symbols used on the charts are as follows:-

N8 - very light grey

N7 - light grey

N6 - medium light grey

N5 - medium grey

N4   -   medium dark grey

N3   -   dark grey

10Y4/2 - greyish olive

5Y8/1 - yellowish grey

5Y7/2 - yellowish grey

5Y6/1 - light olive grey

5Y5/2 - light olive grey

5Y4/1 - olive grey

5G6/1 - greyish green

5GY6/1 - greenish grey

5GY5/2 - greyish green

10YR8/2- very pale orange

10YR7/4- greyish orange

10YR4/2- dark yellowish brown

(b) Weathered

Weathered colours are not in fact given for the core.

13. Properties of phosphatic material

(a) Approximate percentage of phosphatic pellets and grains.

This percentage is estimated visually and noted on the

log as one of 4 broad percentage classes 1-5%; 5-10%;

10-20%; and 20-50%.   These broad classes are used

because of the difficulty of estimating accurately the

percentage of phosphatic material. The most satisfactory

way of handling this information would in fact be to do

quantitative chemical analysis for P_2O_5 content.   This

information is available for parts of the core only, and

therefore visual estimation is used throughout the
log for consistency. The analyses would suggest the
following P_2O_5 contents for the 4 classes of visual
estimates.

% phosphatic material	% P_2O_5
1 - 5%	1 - 2%
5 - 10%	2 - 4%
10 - 20%	4 - 6%
20 - 50%	6 - 10%

(b) Textural Range

This is measured by binocular inspection as is the grain
size of the terrigenous fraction. Again, phi grain sizes
are measured directly. This column could equally well
be called "Maximum grain size" as the upper limit of the
textural range is also the maximum grain size.

(c) Roundness

The roundness is obtained from visual estimation charts
in which 5 classes of roundness are distinguished.

(d) Sphericity.

As in roundness the 5 classes of sphericity from visual
estimation charts.

(e) Colour.

As in the main rock colour, the Geological Society of
America Colour Charts (Goddard et.al., 1963) are used for
the classification of colours.

14. Number of Layers

This column heading is used by Bouma (1962) in a fairly broad

way. Here, it means the number of individual laminae
within the unit and is the smallest recognizable layer of
uniform sediment.   It does not represent a major change
in the environment of deposition but merely a momentary
small fluctuation in for instance the current velocity.
In the graphic log of the Stairway Sandstone because units
as thin as $\frac{1}{4}$ inch are considered invidually, most units
correspond to a single layer.

15.   Unit Number

Because of the detail of the work, the unit recognized in
the Stairway Sandstone corresponds to the sedimentation unit
of Pettijohn (1949), Otto (1938), and is lithologically
uniform.   The numbering of sedimentation units commences
at the first unit logged so that the numbers of the
sedimentation units increase down the core.   They range
from unit number 14 at 50 feet to number 842 at 700 feet.

16.   Remarks

This column is used for the location of samples, the letters
in this column indicating both location and reason for the
sample.

     T - thin section sample

     H - heavy mineral separation

     S - detailed size analysis carried out on the
         thin section of this sample

     M - sample submitted for microfossil determination

     C - sample for determination of clay mineralogy

     X - sample for X-ray determination of phosphate
         mineral present

The following numbering system has been adopted for specimens:-

The prefix AP1 is used in all samples to distinguish them
from subsurface samples from AP2, AP3 or AP4.   The middle
number is the unit number.   The last number signifies the
distance of the sample from the top of the unit, measured in
inches.   Hence, the number AP1/761/13 indicates that the
specimen has been collected from 13 inches below the top of
unit 761 in core AP1.

APPENDIX III

TABLES

Table 1
(Sheets i to xi)

THE PETROGRAPHY OF VARIOUS ROCK TYPES FROM THE
STAIRWAY SANDSTONE

Specimen No. AP1/	Grain size (phi)	Round-ness	Sorting	% quartz types	% Fdr.	% Heavies	% Clay	% Carb	% Phos	% Pyr	% Glau
41/2	2∅-4∅(1∅)	sub-rnd	mod st	60-70(P.70;U.25;C.5;Ch.0.)	2-3	t(T)	2-3	30-35	2-3	-	-
42/9	3∅-4∅(.5∅)	sub-rnd	poor st	85-90(P.84;U.14;C.2)	1-2	1(Z.T)	1-2	10	2-3	-	-
51/2	1∅ & 4∅(0.5∅)	v rnd	well st	70-80(P.70;U.25;C.5;Ch.t)	1	-	-	-	20-30	-	t
55/0	3∅-4∅(1.75∅)	sub ang	poor st	85-90(P.69;U.30;C.1;)	1	t(O.T.Z.)	5-10	5-10	-	-	t
61/1(ji)	1∅ & 4∅(0.5∅)	sub ang	mod st	50-60(P.64;U.35;C.1)	-	t(T.Z.)	-	-	40-50	-	-
61/1(1)	4∅(1.5∅)	ang	poor st	85-90(P.90;U.10;)	2-3	-	-	-	10-15	-	t
64/3	4∅(1.75∅)	ang	poor st	70-80(P.75;U.25;)	1	1(T.Z.)	20-30	1	20-30	-	-
73/1	1∅ & 3∅(0.5∅)	rnd	well st	60-70(P.69;U.28;C.3)	t	-	5-10	1-2	5-10	5-10	-
74/1	2∅(0.5∅)	sub-rnd	poor st	40-50(P.85;U.15;C.t;)	t	1(T & Z)	-	50-60	1	-	-
78/1	1∅ & 3∅	ang	poor st	60-70(P.65;U.35;C.0;Ch.t.)	1	1(T & Z)	-	-	25-30	5-10	-
84/1	1∅ & 4∅(0.75∅)	sub-rnd	mod st	70-80(P.60;U.36;C.2;Ch.1)	1-2	t(T)	-	-	10-15	10-15	-
93/1	3∅(0.5∅)	sub-ang	mod st	70-80(P.95;U.5;)	1	t(T)	-	-	15-20	5-10	-
96/4	5∅(3.75∅)	sub-ang	mod st	5-10	-	2(O)	20-25	70-80	-	-	-
97/1	1∅ & 4∅(0∅)	v rnd	v well st	70-80(P.85;U.15;)	t	t(T & Z)	-	5-10	10-20	-	-
97/1	8∅	-	-	-	-	-	-	100	-	-	-
101/8	3∅(1.5∅)	sub-ang	poor st	85-90(P.90;U.9;C.1;)	t	t(T.Z.)	1-2	-	10-15	-	-
105/8	6∅(2.75∅)	ang	-	5-10	-	t(O)	-	90-95	-	-	-
110/0	5∅(3∅)	ang	poor st	5-10	t	t(T)	50-60	30-40 (siderite)	-	-	-
111/4	3∅(2∅)	sub-ang	poor st	60-70(P.75;U.24;C.1;)	2	1(O.T.Z.)	5-10	10-20	10-20	-	-
112/14	3∅(1.75∅)	sub-ang	poor st	95(P.50;U.50;C.0;Ch.t;)	3-4	1(O.Z.T.)	-	-	1	-	-
112/70	3∅(1.75∅)	sub-rnd	poor st	95(P.75;U.25;C.0.;Ch.t;)	1-2	t(T.Z.)	-	-	2-3	-	-

Specimen No. AP1/	Grain Size (phi)	Round-ness	Sorting	% Quartz types	% Fdr.	% Heavies	% Clay	% Carb.	% Phos	% Pyr	(ii) % Glau
118/36	3∅(1∅)	sub-rnd	mod st	95(P.70;U.20;C.0.;Ch.10;)	5	1(0)	-	-	-	-	-
118/110	3∅(2.5∅)	sub-rnd	mod st	95(P.55;U.40;C.3;Ch.2)	2-3	1(O.T & Z)	-	-	-	-	t
122/11	4∅	sub-ang	mod st	95(P.80;U.16;C.0;Ch.4)	2-3	t(T.Z.)	-	-	-	-	-
122/11	3∅	ang	poor st	90-95(P.89;U.9;C.0;Ch.2)	5-10	t(T)	-	-	-	-	-
128/3	4∅	ang	poor st	95(P.75;U.25;)	2-3	t(T.Z.)	-	-	-	-	-
128/3	4∅(2∅)	ang	mod st	90-95	1	t(T.Z.)	-	4-5	4-5	-	-
136/0	4∅(3.75∅)	ang	mod st	5-10(P.75;U.25;)	-	t(0)	-	90-95	-	1	-
140/0	4∅(3.5∅)	ang	mod st	95(P.85;U.15;)	1	t(O.T &Z)	-	1-2	2-3	1	-
142/0	4∅(3∅)	sub-rnd	well st	90(P.45;U.55;)	2-3	t(T & Z)	-	1-2	2-3	1	-
143/0	4∅(3.5∅)	sub-ang	mod st	80-90	t	1(T.Z.)	10-20	-	-	-	-
149/0	4∅(2.5∅)	sub-ang	mod st	70-80	1-2	-	-	1-2	10-20	5	
184/0	4∅(3∅)	ang	mod st	5-10	-	t(0)	5-10	60-70	10-20	1-2	t
185/7	3∅	rnd	mod st	45-50(P.85;U.15;)	t		45-50	5			
214/2	4∅ (3∅)	sub-ang	mod st	60-70(P.85;U.15;)	t	1(O.T.)	30-40	-	1	-	-
243/27	4∅(3.75∅)	sub-rnd	mod st	20-30(P.85;U.15;)	1-2	1	70-80	-	1-2	-	-
244/0	4∅(3.5∅)	sub-ang	mod st	45-55(P.75;U.25;)	2-4	t(0)	-	-	45-55	-	-
258/0	4∅	-	-	60-70(P.55;U.45;)	2-3	1-2(O.T.Z.)	-	30-40		-	-
259/0	4∅(3.5∅)	angular	mod st	40-50	t	-	-	40-50	10-20	-	-

Specimen No.AP1/	Grain Size (phi)	Round-ness	Sorting	% quartz types	% Fdr.	% Heavies	% Clay	% Carb	% Phos	% Pyr	% Glauc.
262/0	-	-	-					98	1	1	-
272/5	3∅(1.5∅)	rnd	mod st	75-80(P.65;U.35;C.t)	t	-	5	15-20	2-3	1-2	-
398/0	3∅(2∅)	rnd	poor st	60-70(P.75;U.25;)	-	-	5	-	20-30	1-2	-
462/2	3∅(1.25∅)	sub-ang	poor st	70-80(P.85;U.15;C.t;Ch.t)	1	1(Z.T.)	10-15	-	10-15	-	t
577/5	3∅(2.25∅)	sub-ang	mod st	80-90(P.90;U.10;C.t)	t	1(0Z.T.)	5-10	5-10	-	-	-
596/0	3∅(0∅)	sub-rnd	-	70-80(P.90;U.10;)	1	-	15-20	5-10	1-2	1-2	
640/0	3∅(1∅)	sub-rnd	mod st	85-90(P.75;U.25;C.t)	1	1(Z.T.)	-	15-20	-	1	t
648/6	0∅	v rnd	mod st	75-80(P.35;U.35;C.30;Ch.t)	-	-	-	15-20	2-4	-	-
698/6	1∅(0∅)	v rnd	mod st	99(P.64;U.34;C.2;Ch.t)	-	t(0.Z.)	-	-	-	-	-
698/6	1∅(0∅)	v rnd	well st	95(P.65;U.25;C.10)		1(0.T. & Z)	2-3		1		t
704/7	3∅(2.5∅)	sub rnd	mod st	99(P.90;U.10;)	t	t(T & Z)	-	-	-	1	-
704/64	1∅ & 3∅(0∅)	sub rnd	well st	99(P.84;U.15;C.1;Ch.t)	t	t(T)	-	1	-	1	-
708/0	4∅(1.5∅)	sub-ang	poor st	30-40	1-2	t(Z)	60-70	-	-	-	t
723/57	1∅ 0∅	v rnd	mod st	99(P.84;U.15;C.1)	-	t(T & Z)	-	-	-	1	-
746/6	4∅(2∅)	sub-rnd	poor st	9)(P.85;U.15)	t	1(Z.T.)	1-2	1-2	1-2	1	1-2
746/10	2∅ & 4∅(0.75∅)	rnd	mod st	60-70(P.85;U.15;)	t	t(T &Z)	5-10	10-15	5-10	1-2	1-2
754/6	4∅(2∅)	sub rnd	mod st	70-80(P.90;U.10)	t	t(Z.T.)	10-15	-	-	1	10-15

Specimen No. AP1/	Grain size (phi)	Round-ness	Sorting	% quartz types	% Fdr.	% Heavies	% Clay	% Carb	% phos	% Pyr	% Gla.
755/0	1∅(0∅)	v rnd	well st	95(90;U.10;)	-	t(T & Z)		1-2	2-3	1	1-2
761/13	4∅(1.5∅)	Sub rnd	v poor st	85(P.65;U.35;)	t	1(Z & T)	5-10	-	-	1	5
775/14	1∅(0.75∅)	v rnd	well st	95(P.75;U.25;)	-	t(0)	-	-	-	-	-
788/20	1∅ (0∅)	v rnd	well st	99(P.84;U.15;C.1)	-	t(0.Z.&T.)	-	-	-	-	-
792/66	2∅(0.5∅)	v rnd	mod st	99(P.75;U.25;C.t)	-	t(0.T.)	-	-	-	-	-
794/8	1∅ 0∅	v rnd	v well st	100(P.85;U.15;)	-	-	-	-	-	-	-
795/5	2∅(0.5∅)	v rnd	well st	95(P.75;U.25;C.t)	-	-	-	-	-	-	-
803/5	1∅(0.5∅)	v rnd	poor st	99(P.65;U.35;C.t)	-	-	-	-	t	1-2	-
811/10	2∅ (1.75∅)	v rnd	mod st	95(P.65;U.35;)	-	t(T)	-	3-5	1	-	-
818/8	3∅(2∅)	v rnd	well st	95(P.75;U.25;C.0;Ch.t.)	t	t(T & Z)	-	-	2-3	1-2	-
AP/2 136/4	3∅(1.5∅)	sub-ang	poor st	85-90(P.90;U.10;)	-	1	5-10	-	5-10	-	-
195/2	3∅(2.75∅)	sub-ang	mod st	85-90(P.85;U.15;)	1-2	t(T.Z.)	5-10	5-10	-	-	-
314/3	3∅(2∅)	sub-ang	mod st	99(P.80;U.20;)	1-2	1(T & Z)	-	-	-	-	-
388/1	3∅	rnd	well st	80-90(P.90;U.10;)	-	1(Z)	5	-	5-10	1-2	-
505/1	3∅(2∅)	-	-	20-30(P.90;U.10;)	-	t(Z.T.)	-	70-80	1-2	1	-
549/30	4∅(2∅)	sub-rnd	v poor st	95(P.90;U.10;)	1-2	1(T & Z)	2	-	-	1	-

Specimen No AP2/	Grain Size (phi)	Round-ness	Sorting	% quartz types	% Fdr.	% Heavies	% Clay	% Carb	% Phos	% Py	% Gla.
570/1	0∅ & 3∅(0∅)	Rnd	well st	90-95(P.90;U.9;C.1)	-	1(T & Z)	1		4		
675/0	1∅ & 3∅	v rnd	well st	95(P.75;U.15;C.10;Ch.t)	1-2	-	1	-	4	-	-
740/4	1∅(0∅)	v rnd	mod st	95(P.75;U.20;C.4;Ch.1)	1	-	1-2	-	-	1-2	-
794/23	2∅	rnd	well st	95(P.85;U.15)	t	-	3-4	-	-	1-2	-
836/22	2∅(0.5∅)	rnd	well st	85-90(P.85;U.15)	-	-	5	-	1	5-10	-
858/15	4∅(3∅)	sub-rnd	well st	98(P.85;U.15)	1	t(Z)	-	-	-	1	
AP3/											
7/0	5∅(4∅)	ang	mod st	95	-	1(T.Z.)	1-2	-	-	1-2	-
44/3	2∅(2∅)	rnd	v well st	95(P.85;U.15;C.t.)		t(T)	-	-	5	-	-
140/6	4∅(3∅)	sub-ang	mod st	70-80(P.75;U.25;)	1	t(T & Z)	20-30	-	2-3	1-2	-
227/0	3∅(3∅)	sub-ang	poor st	90-95(P.75;U.25;)	1	1(Z.T.)	5	-	-	1	-
248/12	-	sub-rnd	mod st	95(P.65;U.35;)	-	t(T)	-	-	-	-	-
300/27	4∅(3∅)	sub-ang	mod st	97(P.75;U.25;)	1	t(T & Z)	2-3	-	-	-	-
419/0	3∅(2.5∅)	rnd	mod st	95(P.85;U.15)	1	t(T & Z)		1-2	2-3	-	-
488/0	3∅(2∅)	sub-rnd	mod st	75(P.90;U.10;)	-	2(T & Z)	10-20	-	-	-	3-4
710/0	3∅(1.5∅)	sub-ang	mod st	80-90(P.90;U.10;)	t	t(T & Z)	3-10		5-1)		t
799/0	4∅(3∅)	ang	mod st	60-70(P.90;U.10;)	1	1(O.T.)	30-35	5	-	-	-

Specimen No AP3/	Grain Size (phi)	Roundness	Sorting	% quartz types	% Fdr	% Heavies	% Clay	% Carb	% Phos	% Py	% Glauc.
862/0	4∅		-	80-90(P.85;U.15)	1	1(Z.T.)	5	-	-	-	-
913/0	4∅	ang	poor st	80-90(P.80;U.20;)	1	t(T)	10-15 (red)	2-3	-	-	-
967/3	0∅ & 4∅	rnd	mod st	80-90(P.75;U.15;C.10)	1	t(T)	5-10 (red)	-	5-10	-	-
1055/19	1∅(0∅)	rnd	well st	95(P.89;U.9;C.2)	-	t(T)	5	-	-	-	-
1089/8	-	rnd	well st	95(P.89;U. 9;C.2)	-	-	1-2	5	-	-	-
AP4/											
11/5	1∅ & r∅	v rnd	well st	95(P.65;U.30;C.5)	1	-	1-2	-	3-4	-	-
61/3	2∅(1.5∅)	sub-rnd	well st	80-90(P.75;U.15;C.10)	1	-	-	-	10-20	-	-
100/0	3∅	ang	mod st	80-90(P.85;U.10;C.5)	t	t(Z)	5-10	-	5-10		-
316/0	1∅(0∅)	rnd	well st	80-90(P.90;U.5;C.5;)	-	-	-	-	5-10	5-10	-
384/0	2∅(0.5∅)	sub-rnd	mod st	80-90(P.79;U.19;C.2)	1	1(0 & T &Z)	-	-	10-20	-	-
444/2	1∅ & 3∅(-2∅)	v rnd	v well st	98(P.70;U.15;C.15;)	-	-	1-2	-	-	-	-
483/2	1∅ & 3∅(-.5∅)	v rnd	poor st	95(P.70;U.20;U.10;)	-	-	-	-	1-2	1	-
HY 45	3∅	rnd	well st	90-95(P.80;U.5;C.15;Ch.t)	1	1-2(Z.T.)	1-2	-	-	-	-
HY 46	2∅(0.25∅)	rnd	mod st	95(P.95;U.5)	-	1-2(Z & T)	-	-	-	2-3	-
HY 51	3∅(2.5∅)	sub-rnd	mod st	70-80(P.95;U.2;C.2)	t	1(Z.T.)	-	2-3	20-30	2-3	-

Specimen No.	Grain Size (phi)	Round-ness	Sorting	% quartz types	% Fdr.	% Heavies	% Clay	% Carb	% Phos	% Py	% Glauc.
HY 55	3∅(1∅)	ang	mod st	60-70(P.85;U.10;C.5)	t	1(Z.T.)	-		30-35	1-2	-
HY 57	4∅(1.75∅)	sub-ang	well st	70-80(P.95;U.5)	1-2	1-2(T&Z)	-	1-2	10-15	2-3	-
HY 120(B)	3∅(1∅)	sub-ang	mod st	75-85(P.90;U.5;C.5;Ch.t)	1	2(T & Z)	-	-	-	2-3	-
HY 123(A)	3∅(2.75∅)	sub-ang	well st	90-95(P.85;)	1	1(Z)	-	-	5-10	-	-
HY 123(C)	4∅(2∅)	sub-rnd	mod st	60-70	t	1(T & Z)	-	-	30-40	1-2	1
HY132	4∅ & 2∅(0∅)	sub-rnd	poor st	60(P.95;U.2;C.2)	-	2-3(Z.T.)	-	-	30-40	5	-
HY 138	3∅(1.5∅)	sub-rnd	mod st	60-70(P.90;U.5;C.5;Ch.t)	1	1-2(Z.T.)	-	-	30-40	-	-
HY 149	3∅(1.5∅)	ang	mod st	60-70(P.95;U.5;C.1)	-	1(Z.T.)	-	-	30-40	1-2	-
HY 154	3∅(1.5∅)	sub-rnd	mod st	50-60(P.90;U.5;C.5)	-	1(Z)	-	-	35-45	5	-
HY 172	2∅(1∅)	rnd	mod st	60-70(P.70;U.20;C.10;)	-	t(T & Z)	30-40	-	30-40	1	-
HY 705(C)	3∅(1∅)	sub-rnd	mod st	70-80(P.80;U.20;)	1	1-2(Z.T.)	-	-	20-30	1	-
HY 762	3∅(0.75∅)	sub-ang	poor st	70-80(P.90;U.5;C.5)	-	1(Z.T.)	-	-	20-30	1-2	-
LA 18	3∅(2.25∅)	sub-rnd	mod st	70-80	1-2	1-2(Z.T.)	-	-	10-15	1	-
LA 54	3∅	sub-ang	poor st	50-100(P.90;U.5;C.5)	-	2(Z)	-	80-90	5-10	-	-
LA 101	3∅	ang	poor st	1	-	-	-	95	2	-	-
LA 103(A)	3∅ & 1∅(0.75∅)	sub-rnd	mod st	50-60(P.90;U.5;C.5)	t	1-2(T & Z)	-	t	40-50	1	-

Specimen No.	Grain Size (∅phi)	Round-ness	Sorting	% quartz types	% Fdr.	% Heavies	% Clay	% Carb	% Phos	% Py+	% Glauc.
LA 103(B)	4∅(3∅)	ang	mod st	10-20(P.95;U.3;C.2)	1	-	-	70-80	5-10	-	-
LA 131	1∅ & 3∅(1∅)	rnd	well st	80-90(P.95;U.5)	1	1(Z)	-	-	5-10	2-3	-
LA 133	0∅ & 3∅(-.5∅)	rnd	well st	60-70(P.75;U.15;C.10)	-	-	-	-	30-35	5-10	-
LA 139(A)	3∅(0.75∅)	sub-rnd	poor st	40-50(P.90;U.10)	t	1-2(Z)		40-50	5-10	-	-
LA 139(B)	2∅ & 4∅(0.5∅)	sub-rnd	well st	70-80(P.75;U.10;C.15)	t	1(Z)	-	-	20-30	2-3	-
LA 168	3∅ & 1∅(0.5∅)	rnd	well st	80-85(P.85;U.10;C.5)	-	1(Z)	1-2	-	10-15	2-4	-
LA 188	3∅ (2∅)	sub-rnd	well st	5-10	-	1	-	80	5-10	-	-
LA 534(A)	4∅(2.25∅)	sub-ang	mod st	70(P.65;U.35;)	1	2.3(O.Z.T.)	-	-	25-35	-	-
LA 534(B)	3∅(1.25∅)	rnd	well st	70-80(P.85;U.15;C.t.)	-	1(Z.T.)	-	-	20-30	-	-
LA 535	4∅(2.5∅)	sub-ang	mod st	60-70(P.90;U.5;C.5;)	t	2-3(Z.T.)	-	-	25-30	-	-
LA 543	4∅	sub-ang	mod st	70-80(P.95;U.3;C.2)	t	1-2(Z.T.)	-	-	20-30	-	-
Rd 103(A)	3∅ & 1∅(0∅)	sub-ang	well st	70-80(P.85;U.10;C.5)	1-2	1(Z.T.)	-	-	20-25	1	-
Rd 109	3∅(0.75∅)	ang	poor st	85-90(P.90;U.5;C.5)	2-3	1(Z.T.)	-	-	5-10	-	-
Rd 111	1∅ & 3∅(.5∅)	rnd	mod st	80-85(P.90;U.5;C.5)	t	-	-	-	1)-15	-	-
Rd 112	3∅ (2∅)	sub-rnd	mod st	98 (P.80;U.5;C.15;Ch.t)	t	1-2(Z & T)	-	-	-	-	-
Rd 117	4∅ (2∅)	ang	mod st	90(P.90;U.5;C.3;Ch.t.)	t	2.3(T.Z.)	5 (red)	-	-	-	0

Specimen No.	Grain Size (phi)	Round-ness	Sorting	% quartz types	% Fdr	% Heavies	% Clay	% Carb	% Phos	% Py	% Glau.
Rd 118	1∅ & 3∅(0.25∅)	rnd	well st	70-80(P.90;U.5;C.5)	-	1-2(T & Z)	-	-	20-30	t	-
Rd 119	3∅(2∅)	ang	mod st	85-90(P.90;U.7;C.3)	1	t(T & Z)	-	-	10-15	-	-
Rd 120	4∅(1.5∅)	ang	mod st	90-95(P.90;U.5;C.5)	-	1(Z)	5-10 (red)	-	-	-	-
Rd 130	1∅ & 3∅(-1.5∅)	rnd	well st	99(P.70;U.10;C.20)	-	t(Z)	-	-	-	-	-
Rd 131	2∅(0.5∅)	v rnd	poor st	99(P.95;U.2;C.2)	-	t(O.Z.)	-	-	-	-	-
Rd 134	0∅ & 3∅(-.25∅)	v rnd	v well st	99(P.85;U.5;C.10;)	-	1(O)	-	-	-	-	-
Rd 135	3∅(0∅)	-	-	90-95(P.70;U.15;C.15)	-	2-3(O.Z.T.)	1-2 (red)	-	-	-	-
Rd 137	3∅(2∅)	ang	mod st	90-95(P.70;U.10;C.20;)	1	2-3(O.T.Z.)	1-2	-	-	2-4	-
Rd 138	3∅(2∅)	sub-ang	mod st	98(P.90;U.7;C.3)	-	2(O.T.&Z.)	-	-	-	1	-
Rd 139	3∅(0.75∅)	sub-ang	mod st	70-80(P.8-;U.10;C.10)	-	2(O.Z.T.)	-	-	20-25	1	-
Rd 140	4∅ (2.25∅)	ang	poor st	70-80(P.90;U.5;C.5)	-	3(O.T.Z.)	5-10	-	10-20	-	-
Rd 141	4∅(3∅)	sub-ang	mod st	80-90(P.90;U.5;C.5)	-	2(O.T.& Z.)	5-15	-	5	-	-
Rd 145	4∅ & 1∅(0.5∅)	rnd	mod st	80-85(P.80;U.10;C.10)	1	2(O.Z.)	5	-	10	-	-
Rd 146	3∅(1.75∅)	sub-rnd	mod st	85-90(P.90;U.5;C.5;Ch.t)	-	2(O.T & Z)	5-10	-	-	-	-
Rd 147	2∅(0.5∅)	v rnd	poor st	95(P.75;U.15;C.10)	-	2(O.Z.T.)	1-2	-	-	-	-
Rd 148	4∅(2.25∅)	ang	mod st	80-90(P.90;U.8;C.2)	1	1-2(O.Z.T.)	10-20	-	-	-	-

Specimen No.	Grain Size	Round-ness	Sorting	% Quartz types	% Fdr	% Heavies	% Clay	% Carb	% Phos	% Py	% Glauc.
Rd 149	4∅(2.5∅)	ang	poor st	85-90(P.90;U.9;C.1)	2	1(O.T.&Z)	5-10 (red)	-	-	-	-
Rd 150	3∅(2.5∅)	ang	mod st	95(P.90;U.19;C.1)	t	1-2(Z.T.)	1-2	-	-	2	-
Rd 151	4∅(1.5∅)	-	-	85-90(P.90;U.5;C.5)	t	2-3(T.Z.&O.)	5-10	-	-	2	-
Rd 152	4∅(2∅)	-	-	90(P.85;U.10;C.5)	1-2	1-2(O.T.Z.)	5	-	-	-	-
Rd 153	1∅ & 4∅(0.5∅)	sub-ang	mod st	85-90(P.85;U.10;C.5)	-	2(Z.& O.T.)	10-15	-	-	-	-
Rd 154	2∅ & 4∅(0.25∅)	rnd	mod st	75(P.80;U.15;C.5)	2-3	2-3(O.Z.T.)	-	-	20	-	-
Rd 155	4∅(1∅)	ang	mod st	98(P.95;U.5;C.0;Ch.t)	t	2(O & T)	-	-	-	-	-
Rd 157	4∅(2.5∅)	ang	mod st	80-90(P.95;U.5)	-	t(T & Z)	10-20 (red)	-	-	-	-
Rd 158	4∅	ang	poor st	90-95(P.95;U.5)	-	1-2(O.T.&Z)	5-10 (red)	-	-	-	-
Rd 162	0∅ & 3∅(-2∅)	v rnd	well st	90-95(P.60;U.15;C.25;)	-	1-2(Z.T.)	5-10 (red)	-	-	-	-
Rd 163		v rnd	mod st	99(P.80;U.10;C.10;Ch.t)	-	1(T.& Z.)	-	-	-	-	-
Rd 165	4∅(2.75∅)	ang	mod st	95(P.90;U.5;C.5)	-	2(T & Z)	2-2 (red)	-	-	1-2	-
Rd 168	3∅	sub-ang	mod st	95(P.96;U.2;C.2)	-	1-2(T & Z)	5 (red)	-	-	1-2	-
Rd 177	0∅ & 3∅(-.7∅)	v rnd	well st	99(P.80;U.10;C.10;Ch.t)	-	t(T &Z)	-	-	-	t	-
Rd 178	5∅(3∅)	ang	poor st	45-50	-	1(T & Z)	50	-	-	1-2	-
Rd 179	4∅(2.5∅)	ang	poor st	99	-	t(O & Z.)	-	-	-	-	-
BR 15(1)	3∅(1.25∅)	sub-ang	mod st	70-80(P.85;U.15)	-	2-3(O.&Z.T)	.5	-	10-20	-	-

Specimen No.	Grain Size	Round-ness	Sorting	% quartz types	% Fdr	% Heaview	% Clay	% Carb	% Phos	%Py	% Glau
BR 15(2)	4∅	ang	mod st	60-70	t	1-2(O.T&Z)	5		25-35	-	-
H 1	1∅ & 4∅(0∅)	v rnd	well st	80-90(P.45;U.50;C.5)	-	1-2(O)	-	2-3	10-20	-	-
H 2	3∅(1.75∅)	ang	mod st	95(P.25;U.75)	t	t(Z)	3-4	1-2	-	-	-
H 3	4∅(3∅)	ang	mod st	96(P.35;U.65)	t	1(O.T.&Z.)	-	2-3	-	-	-
H 4	3∅(2∅)	ang	mod st	99(P.25;U.75)	t	t(Z.T.)	-	-	-	-	-
H 5	4∅(3∅)	ang	-	80-90(P.45;U.55)	-	1(O.Z.)	-	10-20	-	-	-
K28A	3∅(0.5∅)	rnd	v poor st	90-95(P.30;U.25;C.25;Ch.20)	-	1-2(O)		5	5	-	-
K106(ii)	2∅	sub-rnd	well st	99(P.65;U.35;)	-	t(T)	-	-	-	-	-
ML 37	3∅81∅	rnd	well st	80-90(P.80;U.10;C.10)	t	t(T & Z)	-	-	10-15	-	-

Table 2

PERCENTILE VALUES IN THE STAIRWAY SANDSTONE

Specimen No AP1/	Lith charact of material counted	Phi values for given percentiles						
		95	84	75	50	25	16	5
51/2	Pellets inc in grain count	3.46	2.76	1.63	0.72	0.17	-0.10	-0.61
108/110	Indurated sand-stone	4.33	3.76	3.68	3.20	2.83	2.67	2.34
112/70 (a)	Indurated sand-stone	4.17	3.77	3.57	3.12	2.70	2.50	1.95
112/70 (b)	Within phos pellets only	4.70	4.38	4.23	3.86	3.45	3.29	1.95
122/108	Indurated sand-stone	4.71	4.27	4.09	3.78	3.47	3.26	2.87
243/27	Sandy-silty claystone	5.38	4.80	4.46	3.85	3.55	3.43	3.17
472/18	Bimodal sand	5.25	4.20	3.78	3.17	2.83	2.72	2.54
601/0(b)	Grains within phos pellets	4.60	4.18	3.94	3.37	3.03	2.88	2.70
601/0 (c)	Phos pellets & detrital gns	1.52	0.93	0.75	0.31	-0.83	-1.20	-1.79
601/0 (d)	Only phos pellets	1.15	0.43	0.10	-0.83	-1.40	-1.60	-1.93
648/6	Lower Stairway	1.33	0.55	0.25	-0.33	-0.87	-1.20	-2.30
755/0	Grains outside phos pellets	1.67	1.07	0.90	0.65	0.37	0.26	0.07
755/0	Grains within phos pellets	4.55	4.17	3.99	3.60	3.20	3.00	2.62
755/0(c)	Phos pellets & detrital gns	1.20	0.68	0.50	0.03	-0.79	-1.12	-1.76
761/13	Lower Stairway	3.95	3.48	3.30	2.85	2.40	2.18	1.60
792/66	Lower Stairway	2.45	1.65	1.30	0.80	0.40	0.20	-0.10
803/5	Lower Stairway	2.53	2.05	1.84	1.35	0.85	0.65	0.55
601/0(a)	Only grains outside phos pellets	1.90	1.46	1.25	0.97	0.73	0.58	0.37

Table 3

NUMERICAL VALUES OF TEXTURAL PARAMETERS

(after Folk and Ward, 1957)

Specimen No.	Median Diam. (phi)	Mean Diam. (phi)	Standard Devn (phi)	Skewness	Kurtosis
1. 51/2	0.72	1.13	1.34	0.33	0.93
2. 112/70(a)	3.12	3.13	0.66	-0.02	1.05
3. 112/70(b)	3.86	3.84	0.54	-0.01	0.93
4. 118/110	3.20	3.21	0.57	0.08	0.96
5. 112/108	3.78	3.77	0.53	-0.01	1.21
6. 243/27	3.85	4.03	0.67	0.39	1.00
7. 472/18	3.17	3.36	0.78	0.47	1.17
8. 601/0(a)	0.97	1.00	0.45	0.17	1.20
9. 601/0(b)	3.38	3.48	0.63	0.27	0.90
10. 601/0(c)	0.31	0.01	1.03	-0.35	0.86
11. 601/0(d)	-0.85	-0.67	0.98	0.28	0.84
12. 648/6	-0.33	-0.33	0.99	-0.05	1.33
13. 755/0(a)	0.65	0.66	0.44	0.16	1.24
14. 755/0(b)	3.60	3.59	0.58	-0.02	1.00
15. 755/0(c)	0.03	-0.14	0.90	-0.25	0.94
16. 761/13	2.85	2.84	0.68	-0.05	1.07
17. 792/66	0.80	0.88	0.75	0.23	1.15
18. 803/5	1.35	1.35	0.67	0.07	0.90

Table   4

VERBAL EXPRESSION OF TEXTURAL PARAMETERS
(after Folk and Ward, 1957)

Specimen No. AP1/	Mean Diameter	Standard Devn	Skewness	Kurtosis
51/2	Med sand	Poorly sorted	Strongly fn skewed	Mesokurtic
112/70(a)	Very fn sand	Mod well sorted	Near symmet	Mesokurtic
112/70(h)	Very fn sand	Mod well sorted	Near symmet	Mesokurtic
118/110	Very fn sand	Mod well sorted	Near symmet	Mesokurtic
122/108	Very fin sand	Mod well sorted	Near symmet	Leptokurtic
243/27	Coarse silt	Mod well sorted	Strongly fn skewed	Mesokurtic
472/18	Very fn sand	Mod sorted	Strongly fn skewed	Leptokurtic
601/0(a)	Coarse=med sand	Well sorted	Fn skewed	Leptokurtic
601/0(b)	Very fn sand	Mod well sorted	Fn skewed	Platy/ Mesokurtic
601/0(c)	Coarse sand	Poorly sorted	Strongly coarse skewed	Platykurtic
601/0(d)	Very coarse sand	Mod sorted	Fine skewed	Platykurtic
648/6	Very coarse sand	Mod sorted	Near symmet	Leptokurtic
755/0(a)	Coarse sand	Well sorted	Fn skewed	Leptokurtic
755/0(b)	Very fine sand	Mod well sorted	Near symmet	Mesokurtic
755/0(c)	Very coarse sand	Mod sorted	Coarse skewed	Mesokurtic
761/13	Fn sand	Mod well sorted	Near symmet	Mesokurtic
792/66	Coarse sand	Mod sorted	Fn skewed	Leptokurtic
803/5	Med sand	Mod well sorted	Near symmet	Platy/ Mesokurtic

Table 5

DETERMINATION OF DEPOSITIONAL ENVIRONMENTS
(after Sahu, 1964)

Specimen No. AP1/	Values obtained for discriminant functions			Inferred environment
	Yu beach: aeolian	Yu beach: sh marine	Yu sh marine: fluviatile	
51/2	-1.3270	159.1490	-17.0159	Beach
112/70(a)	-6.2310	96.9745	-2.8134	Sh marine
112/70(b)	-9.7142	96.1936	-1.4494	Sh marine
118/110	-7.4484	90.4870	-1.6320	Sh marine
122/108	-8.6715	99.6209	-1.2705	Sh marine
243/27	-10.4130	118.2148	-4.6529	Sh marine
472/18	-7.0664	123.5812	-6.6289	Indet
601/0(a)	0.5547	54.0786	-2.2409	Beach
601/0(b)	-8.6973	102.3000	-3.7895	Sh marine
601/0(c)	7.2924	79.3843	-9.1110	Fluviatile
601/0(d)	7.9785	73.2065	-9.9307	Fluviatile
648/6	12.4483	85.4085	-8.2647	Fluviatile
755/0(a)	1.8764	48.6583	-2.1396	Beach
755/0(b)	-8.4097	96.4243	-1.9137	Sh marine
755/0(c)	6.9438	63.9000	-5.8672	Sh marine
761/13	2.0799	93.5761	-3.2087	Sh marine
792/66	2.0353	76.0166	-5.7368	Sh marine
803/5	-1.3185	59.6551	-3.8563	Beach/ sh marine

Table 6

CROSS-BED DIP VALUES FOR THE STAIRWAY SANDSTONE

LOCALITY	NO OF READINGS	AVERAGE DIP OF CROSS BEDS
ANG	(18)	22.1°
AP3	(18)	14.0°
CHA	(15)	21.8°
CSP	(22)	25.7°
ECK	(6)	23.5°
EGR	(14)	21.4°
EJC	(34)	20.0°
EMC	(12)	18.1°
GHN	(4)	11.7°
GEO	(23)	18.8°
INI	(20)	21.8°
LEV	(11)	16.2°
MPY	(23)	19.3°
MTE	(24)	18.1°
MTS	(18)	18.7°
NOM	(25)	19.7°
OLF	(26)	21.0°
RC3	(29)	19.0°
SEY	(24)	22.8°
STP	(12)	16.5°
WJC	(25)	19.8°
WGR	(27)	17.7°
WMC	(24)	19.5°
Average value throughout the basin		18.0°

Table 7

VARIATION OF THE THICKNESS OF CROSS-BED SETS WITH
GRAIN SIZE AND LOCALITY

LOC.	FINE AND VERY FINE GRAINED SAND		MEDIUM GRAINED SAND		COARSE AND VERY COARSE GRAINED SAND		WHOLE FORMATION
	A	B	A	B	A	B	
ANG	(9)	5.2			(7)	(7.2)	6.2
AP3	(18)	6.4			(1)	4.0	5.2
CHA	(8)	7.3	(2)	8.0	(5)	5.2	6.8
CSP	(13)	3.9			(8)	13.8	8.9
ECK	(11)	6.3					
EGR	(5)	5.6			(15)	15.0	10.3
EJC	(10)	2.5	(6)	5.1	(19)	24.1	10.6
EMC							
GHN	(3)	6.3					
GEO	(15)	9.4	(2)	4.5	(5)	7.6	7.2
INI					(20)	7.3	
LEV	(4)	3.2	(1)	3.0	(5)	10.2	5.5
MPY	(18)	5.6	(3)	6.3	(1)	4.0	5.3
MTE	(23)	4.5			(1)	12.0	8.3
MTS	(2)	3.0	(3)	12.0	(13)	14.7	9.9
NOM	(16)	4.7	(4)	6.0	(3)	13.3	8.0
OLF	(10)	6.1	(13)	7.6	(1)	3.0	5.6
RC3	15	5.9					

Table7 (continued)

LOC.	FINE AND VERY FINE GRAINED SAND		MEDIUM GRAINED SAND		COARSE AND VERY COARSE GRAINED SAND		WHOLE FORMATION
	A	B	A	B	A	B	
SEY	(14)	5.9	(3)	7.0	(7)	9.8	7.6
STP	(4)	8.5					
WJC	(14)	3.7	(4)	8.5	(9)	11.1	7.8
WGR	(5)	4.0			(11)	6.0	8.0
WMC	(15)	5.4			(4)	6.2	5.8
Average value for all localities	5.4		6.8				7.5

A - number of readings available at the locality

B - average thickness of cross-bed sets, in inches

Table 8

VARIATION OF THE THICKNESS OF CROSS-BED SETS
WITH STRATIGRAPHIC POSITION AND LOCALITY

LOC.	LOWER STAIRWAY		MIDDLE STAIRWAY		UPPER STAIRWAY		WHOLE FORMATION
	A	B	A	B	A	B	
ANG	(6)	7.3			(5)	2.6	5.0
AP3	(3)	3.0			(11)	7.6	5.3
CHA	(8)	6.3			(7)	7.1	6.7
CSP	(10)	12.4			(12)	3.7	8.1
ECK	(4)	5.7	(2)	5.0			5.4
EGR	(18)	13.6			(3)	1.7	7.7
EJC	(24)	19.2			(9)	2.5	10.9
EMC							
GHN					(3)	6.3	6.3
GEO	(13)	5.2			(7)	17.1	11.2
INI	(20)	7.3					7.3
LEV	(7)	8.0			(4)	2.7	5.4
MPY	(12)	5.5			(10)	5.8	5.7
MTE	(25)	4.6					4.6
MTS	(12)	17.9			(6)	3.1	10.5
NOM	(11)	7.4	(6)	3.5	(6)	6.1	5.7
OLF	(17)	6.7	(6)	6.6	(1)	9.0	5.4
RC3	(10)	6.5	(1)	6.0	(4)	4.5	5.7
SEY	(14)	8.3			(10)	5.6	7.0

Table 8 (continued)

LOC.	LOWER STAIRWAY A	B	MIDDLE STAIRWAY A	B	UPPER STAIRWAY A	B	WHOLE FORMATION
STP	(4)	8.5			(2)	8.0	8.3
WJC	(15)	9.5			(12)	3.6	6.6
WGR	(15)	5.2			(4)	5.0	5.1
WMC	(4)	6.0	(9)	5.7	(6)	5.0	8.4
Average value for all localities		8.3		5.4		5.6	6.9

A - number of readings available at the locality

B - average thickness of cross-bed sets, in inches

Table 9

CROSS-BED FIELD DATA AND VALUES AFTER

CORRECTION FOR TECTONIC DIP

(see over)

Column 1   - Locality

Column 2   - Stratigraphy

Column 3   - Tectonic azimuth

Column 4   - Tectonic dip

Column 5   - Cross-bed azimuth

Column 6   - Cross-bed dip

Column 7   - Thickness of cross-bed set in inches

Column 8   - Type of cross-bed

Column 9   - Grain size

Column 10   - Corrected (i.e. true) cross-bed azimuth.

Column 11   - Corrected (i.e. true) cross-bed dip.

Table 9 (sheet 1).

LOC	STRAT	SEC-AZ	SEC-DIP	X-AZ	X-DIP	X-THICK	X-TYPE	ON-SIZE	PRIMARY-AZ	PRIMARY-DIP
NOM	UST	350	15	290	27	-0	CT	F	258.3	23.3
NOM	UST	360	17	210	1	4	CT	F	182.2	12.9
NOM	UST	10	24	140	18	4	CT	F	234.1	13.8
NOM	UST	10	15	310	33	12	CT	F	285.6	28.3
NOM	UST	290	11	210	28	5	CT	F	183.5	28.5
NOM	UST	255	13	140	15	6	CT	F	108.7	22.9
NOM	UST	15	24	70	11	4	CT	F	167.4	18.7
NOM	UST	10	15	50	10	-0	CT	F	148.6	9.7
NOM	MST	10	17	105	5	2	CT	F	173.8	18.1
NOM	MST	10	17	350	29	4	CT	F	318.5	10.6
NOM	MST	10	21	315	33	4	CT	F	355.3	20.0
NOM	MST	25	11	330	24	2	CT	F	304.3	19.7
NOM	MST	5	13	245	38	1	CT	F	260.5	26.5
NOM	MST	25	9	10	21	3	CT	F	359.7	12.5
NOM	LST	10	22	240	24	5	CT	M	248.3	30.9
NOM	LST	10	7	305	22	8	CT	M	287.4	20.9
NOM	LST	10	7	305	20	3	CT	F	285.3	18.1
NOM	LST	10	24	315	25	6	CT	M	263.6	23.6
NOM	LST	20	10	315	32	12	CT	C	280.1	19.8
NOM	LST	25	14	240	18	8	CT	C	225.4	30.5
NOM	LST	25	13	330	34	3	CT	M	301.4	21.2
NOM	LST	10	10	5	32	20	CT	C	2.9	22.1
NOM	LST	25	30	50	33	6	CT	F	142.0	13.4
NOM	LST	15	16	355	29	7	CT	F	334.9	14.9
NOM	LST	30	8	40	21	3	CT	F	51.1	18.7
OMN	UST	187	89	165	95	50			168.6	6.3
OMN	UST	187	89	185	85	40			33.5	4.5
OMN	UST	187	89	195	76	30			336.0	19.2
OMN	UST	187	89	195	104	20			211.6	18.7
WMC	UST	360	0	135	20	5	CT	F	135.0	20.0
WMC	UST	60	3	185	13	4	CT	F	194.3	14.9
WMC	UST	140	13	160	29	6	CT	F	173.9	17.3
WMC	UST	140	10	180	27	5	CT	F	62.5	20.2
WMC	UST	160	13	190	21	2	CT	F	222.7	11.6
WMC	UST	158	10	190	15	-0		VF	226.6	0.4
WMC	UST	158	15	205	37	-0		VF	224.7	28.6
WMC	UST	158	15	210	30	-0		VF	256.4	15.8
WMC	UST	158	15	205	20	-0		VF	292.1	14.5
WMC	UST	160	0	190	14	3	CT	F	221.8	10.7
WMC	MST	130	7	185	18	5	CT	F	206.7	15.1
WMC	MST	140	16	285	17	5	CT	F	301.2	31.4
WMC	MST	135	9	70	13	6	CT	F	29.0	12.2
WMC	MST	140	10	95	14	6	CT	F	62.9	13.0
WMC	MST	165	7	225	21	4	CT	F	243.3	18.5
WMC	MST	170	12	220	18	5	CT	F	270.0	14.4
WMC	MST	145	3	300	8	6	CT	F	306.7	10.8
WMC	MST	130	10	215	18	3	CT	F	244.2	19.7
WMC	MST	165	2	275	19	5	CT	F	230.3	18.1
WMC	LST	158	10	350	11	-0		VC	344.4	20.9
WMC	LST	140	11	200	13	6	CT	C	251.2	12.1
WMC	LST	145	23	290	13	5	ST	C	311.8	34.4
WMC	LST	140	17	150	40	5	CT	C	158.3	23.4
WMC	LST	140	35	300	3	-0	CT	C	315.3	37.8
WMC	LST	125	12	270	14	9	CT	C	285.7	24.8
MTE	UST	125	7	60	17	7	CT	F	36.3	15.4
MTE	UST	170	5	275	10	5	CT	F	297.9	12.1
MTE	UST	105	17	125	34	3	CT	F	141.3	18.8
MTE	UST	160	22	200	10	1	CT	F	315.6	15.6
MTE	UST	140	18	110	20	5	CT	F	47.1	9.9
MTE	UST	120	20	210	25	3	CT	F	246.3	31.6
MTE	UST	115	15	150	13	3	CT	F	234.9	8.4
MTE	UST	140	15	85	27	4	CT	F	53.2	21.9
MTE	UST	165	18	295	6	2	CT	F	332.8	22.3
MTE	UST	140	0	30	20	9	CT	F	55.0	15.7
MTE	UST	180	15	130	16	3	CT	F	69.8	13.0
MTE	UST	200	10	215	17	4	CT	F	234.0	7.8
MTE	UST	140	13	115	20	3	CT	F	82.1	9.8
MTE	UST	140	3	290	31	5	CT	F	285.4	18.8
MTE	UST	155	11	305	9	9	CT	F	321.3	19.3
MTE	UST	75	18	90	38	6	ST	F	101.1	21.1
MTE	UST	135	29	279	11	3	CT	F	303.5	36.0
MTE	UST	145	21	225	28	2	CT	F	262.5	31.4
MTE	UST	150	8	310	29	12	CT	C	313.9	36.6
MTE	UST	145	16	130	12	6	CT	F	117.0	17.0
MTE	UST	140	17	115	10	2	CT	F	348.1	9.9
MTE	UST	145	13	80	30	14	CT	F	66.2	24.7
MTE	UST	130	10	100	21	3	CT	F	78.7	13.3
MTE	UST	170	22	210	34	3	CT	F	246.5	21.7
MTE	UST	360	0	295	12	33	CT	C	295.0	12.0

Table 9 (sheet 2).

GEO	UST		5	26	65	30	29	ST	VF	114.7	27.4
GEO	UST		10	0	0	18	6	ST	VF	350.5	9.3
GEO	UST		11	11	335	26	12	ST	VF	309.5	17.5
GEO	UST		350	14	340	18	10	ST	VF	310.5	4.8
GEO	UST		7	17	325	25	0	CT	VF	284.1	16.6
GEO	UST		4	17	325	35	3	CT	VF	301.4	24.0
GEO	UST		10	24	325	45	24	CT	VF	295.6	31.3
GEO	UST		360	33	330	49	9		VF	296.8	25.0
GEO	UST		5	14	65	30	29	ST	VF	94.8	25.7
GEO	UST		25	23	325	19	30	CT	VF	257.1	70.9
GEO	UST		10	9	340	18	6	ST	VF	350.5	9.3

GEO	LST		7	31	35	25	3	CT	F	133.5	14.3
GEO	LST		12	25	40	24	6	CT	M	119.6	11.6
GEO	LST		12	25	35	20	3	CT	M	141.9	10.0
GEO	LST		20	26	50	24	4	CT	F	132.4	12.7
GEO	LST		5	34	50	15	3	CT	C	159.8	25.4
GEO	LST		12	13	350	34	3	CT	C	382.1	12.1
GEO	LST		360	27	63	13	=0	CT	C	150.3	23.9
GEO	LST		360	24	105	1		CT	C	180.5	39.0
GEO	LST		20	28	70	29	2	CT	F	130.0	23.3
GEO	LST		12	25	185	28	3	CT	F	205.8	8.1
GEO	LST		15	32	20	38	6	CT	F	42.6	6.6
GEO	LST		15	13	330	33	3	CT	F	268.0	23.7
GEO	LST		5	34	310	51	22	CT	C	276.6	39.6
GEO	LST		20	30	50	28	4		C	130.8	14.5

EQR	UST		200	50	195	52	6	CT	F	135.6	4.4
EQR	UST		192	51	115	58	4	CT	F	82.6	61.2

EQR	LST		220	25	45	1	18		VC	40.2	26.0
EQR	LST		225	44	225	16	18		C	225.0	-28.0
EQR	LST		205	45	250	29	24		VC	342.6	30.6
EQR	LST		205	45	240	35	18		C	331.9	24.3
EQR	LST		195	43	200	25	12		VC	8.2	18.2
EQR	LST		220	41	255	28	10		C	357.0	23.3
EQR	LST		220	41	225	30	=0		M	27.3	41.4
EQR	LST		190	55	205	19	=0		M	1.9	36.9
EQR	LST		205	39	250	33	6	CT	C	325.7	26.6
EQR	LST		215	36	265	51	8	CT	C	335.9	27.4
EQR	LST		225	38	245	20	=0		VC	35.2	30.2
EQR	LST		225	31	230	34	=0		M	269.0	4.0

EJC	UST		75	9	10	20	2	CT	VF	344.2	18.2
EJC	UST		60	8	20	15	2	CT	VF	350.4	10.2
EJC	UST		45	8	160	14	4	CT	F	326.4	10.6
EJC	UST		65	14	15	14	2	CT	VF	310.7	11.7
EJC	UST		55	9	18	5	1	CT	F	346.1	5.6
GJC	UST		45	29	10	31	2		F	306.0	17.4
EJC	UST		60	13	5	20	2	CT	F	325.9	16.3
EJC	UST		60	21	25	24	4	CT	VF	326.0	13.5
EJC	UST		35	13	10	20	4	CT	F	341.7	10.4
EJC	UST		360	0	295	17	5	CT	F	295.0	17.0

EJC	LST		242	12	50	13	72	CT	C	55.5	24.8
EJC	LST		215	7	30	18	20	CT	C	31.3	25.0
EJC	LST		215	7	15	13	15	CT	C	21.6	19.7
EJC	LST		215	7	10	26	12	CT	C	14.8	32.5
EJC	LST		45	8	340	24	30	CT	C	321.7	21.6
EJC	LST		360	0	310	18	33	CT	C	310.0	18.0
EJC	LST		235	7	310	21	45	CT	C	328.6	20.3
EJC	LST		30	8	295	23	10	CT	C	277.4	24.9
EJC	LST		40	1	310	24	20	CT	C	303.3	26.3
EJC	LST		360	0	5	18	5	CT	M	5.0	18.0
EJC	LST		320	2	345	26	12	CT	C	346.9	24.2
EJC	LST		360	0	360	20	9	CT	M	360.0	20.0
EJC	LST		360	0	325	24	5	CT	M	325.0	24.0
EJC	LST		360	0	360	22	4	CT	M	360.0	72.0
EJC	LST		320	2	245	26	10	CT	C	241.0	25.0
EJC	LST		265	3	10	25	6	CT	M	16.0	25.9
EJC	LST		5	4	40	32	2	CT	M	50.9	17.4
EJC	LST		350	4	245	23	5	CT	C	236.4	24.3
EJC	LST		195	8	350	32	10	CT	C	356.2	29.4
EJC	LST		45	8	340	24	30	CT	C	321.7	21.6
EJC	LST		45	10	280	13	24	CT	C	268.2	21.9
EJC	LST		360	0	260	28	14	CT	VC	260.0	28.0
EJC	LST		363	0	10	27	14	CT	C	10.0	27.0
EJC	LST		360	0	330	18	90	CT	C	330.0	18.0
EJC	LST		242	5	205	35	12	CT	C	304.6	22.3
EJC	LST		50	4	5	26	18	CT	C	358.9	23.3

MJC	UST		40	14	320	17	3	CT	F	333.7	19.9
MJC	UST		30	10	75	35	2	ST	F	87.6	28.7
MJC	UST		25	11	10	14	4	CT	F	330.2	4.4
MJC	UST		40	8	15	23	3	ST	F	3.4	16.1

MJC	UST		40	12	20	12	3	ST	VF	300.2	4.1
MJC	UST		40	12	320	12	2	CT	VF	270.6	15.4
MJC	UST		40	12	15	13	3	CT	VF	308.1	5.5
MJC	UST		50	12	10	21	2	CT	VF	317.4	13.3
MJC	UST		35	15	330	24	5	CT	VF	294.2	22.0
MJC	UST		30	14	335	17	0	CT	F	284.0	14.4
MJC	UST		45	14	325	24	6	CT	F	294.2	25.4
MJC	UST		50	10	340	22	4	ST	F	334.9	17.3

Table 9 (sheet 3).

WJC	LST	35	19	35	48	6	CT	N	35.0	29.0
WJC	LST	40	18	135	9	4	CT	N	193.9	20.4
WJC	LST	30	12	50	38	8	CT	C	57.6	97.0
WJC	LST	30	12	15	22	12	CT	N	350.0	16.8
WJC	LST	25	13	15	32	12	CT	N	6.8	19.3
WJC	LST	50	16	330	34	12	ST	C	324.8	29.1
WJC	LST	20	23	15	45	16	ST	C	10.6	22.2
WJC	LST	320	10	345	31	6	ST	C	335.0	72.3
WJC	LST	75	8	245	28	5	CT	F	247.0	35.9
WJC	LST	80	26	100	40	4	ST	F	136.7	17.6
WJC	LST	360	0	137	23	6	ST	C	137.0	23.0
WJC	LST	93	10	148	32	13	ST	C	147.4	34.3
WJC	LST	55	18	155	21	13	CT	C	189.6	29.7
WJC	LST	35	19	35	44	4	CT	N	35.0	29.0
WJC	LST	50	13	390	30	15	ST	C	326.4	29.6
WJC	LST	35	14	50	17	11	ST	C	57.8	23.7

LGV	UST	20	9	90	16	9	CT	F	107.8	15.0
LGV	UST	235	7	210	18	3	CT	VF	197.3	13.0
LGV	UST	360	0	320	29	2	CT	VF	320.8	29.0

LGV	LST	15	14	41	25	2	CT	C	44.1	13.0
LGV	LST	10	23	320	24	3	CT	C	299.5	19.4
LGV	LST	35	17	8	30	12	CT	C	310.4	7.0
LGV	LST	20	20	325	35	30	CT	C	293.5	28.1
LGV	LST	360	7	205	2	2	CT	C	185.5	8.8
LGV	LST	355	7	199	12	3	CT	N	187.8	18.7
LGV	LST	50	15	70	31	4	CT	C	85.4	17.4
LGV	LST	15	14	41	29	2	CT	C	66.1	13.6
LGV	LST	340	17	340	31	4	CT	F	42.3	7.6

ANO	UST	155	26	113	24	7	CT	F	40.3	16.7
ANO	UST	162	30	105	16	3	CT	F	267.1	10.2
ANO	UST	225	7	30	18	-0	CT	F	34.0	24.8
ANO	UST	160	3	125	11	4	CT	F	327.3	12.8
ANO	UST	360	0	30	11	12	CT	F	30.0	11.0
ANO	UST	140	6	270	32	9	CT	F	240.3	71.0
ANO	UST	360	0	350	20	6	CT	C	350.0	20.0
ANO	UST	360	0	340	15	4	CT	VC	310.0	15.0
ANO	UST	360	0	360	20	-0	CT	C	360.0	20.0
ANO	UST	180	9	35	10	3	CT	C	18.3	18.1
ANO	UST	180	9	20	26	12			17.1	30.7
ANO	UST	180	9	20	26	12	CT	C	17.1	30.7
ANO	UST	170	35	200	37	6	CT	C	265.9	17.6
ANO	UST	160	6	130	23	3	CT	F	123.3	16.8
ANO	UST	360	0	180	23	3	CT	F	180.0	23.0
ANO	UST	160	28	230	20	2	CT	F	202.4	43.4
ANO	UST	360	6	225	33	3	CT	F	219.3	37.5
ANO	UST	360	0	215	19	3	CT	F	215.0	19.0

CSP	UST	185	20	290	24	6	ST	F	297.3	23.5
CSP	UST	190	22	315	2	4	CT	F	5.8	23.2
CSP	UST	65	14	50	24	4	CT	F	31.7	11.1
CSP	UST	115	26	295	15	2	ST	F	295.0	41.0
CSP	UST	191	15	280	21	4	CT	F	313.4	24.5
CSP	UST	150	21	245	19	2	CT	F	288.4	29.2
CSP	UST	195	18	200	12	3	CT	F	342.0	22.4

INI	UST	200	8	20	19	10	CT	C	20.0	77.0
INI	UST	185	7	360	24	9	CT	C	1.1	31.0
INI	UST	185	7	30	14	2	CT	C	21.9	70.6
INI	UST	185	7	130	18	4	CT	VC	108.3	15.1
INI	UST	185	7	70	23	9	CT	VC	57.1	26.7
INI	UST	188	7	20	16	4	CT	C	15.4	22.8
INI	UST	185	7	10	22	9	CT	C	8.9	29.0
INI	UST	185	7	350	12	3	CT	C	352.8	25.8
INI	UST	180	7	335	11	3	CT	C	344.5	17.6
INI	UST	185	7	20	8	4	CT	C	13.1	14.9
INI	UST	185	7	35	7	9	CT	C	20.1	13.5
INI	UST	188	7	85	67	24	ST	VC	60.8	66.0
INI	UST	185	7	325	13	0	ST	C	338.5	18.9
INI	UST	185	7	40	11	4	CT	VC	24.7	17.2
INI	UST	220	7	245	31	12	CT	C	251.8	24.8
INI	UST	220	7	50	9	4	CT	C	48.7	16.8
INI	UST	220	4	15	22	9	CT	C	18.6	25.7
INI	UST	220	7	330	15	4	CT	C	343.8	17.6
INI	UST	220	8	305	23	12	CT	C	323.6	73.6
INI	UST	220	8	340	31	9	CT	C	354.7	26.0

MST	UST	360	0	15	17	3	CT	C	15.0	17.0
MST	UST	360	0	325	21	24	CT	C	325.0	21.0
MST	UST	360	0	340	17	30	CT	C	340.0	17.0
MST	UST	360	0	325	18	30	CT	C	325.0	45.0
MST	UST	360	0	285	18	26	CT	C	285.0	18.0
MST	UST	360	0	255	18	12	CT	C	255.0	18.0
MST	UST	220	13	285	21	3	CT	C	320.9	19.3
MST	UST	360	0	360	23	16	CT	C	360.0	23.0
MST	UST	360	0	300	19	12	CT	N	300.0	19.0
MST	UST	360	0	300	24	12	CT	N	300.0	24.0
MST	UST	360	0	255	21	12	CT	N	255.0	21.0
MST	UST	195	6	360	0	4	CT	F	5.9	16.9
MST	UST	325	3	305	11	2	CT	F	297.9	8.2
MST	UST	360	0	290	26	3	CT	C	290.2	50.9
MST	UST	245	13	290	27	2	CT	C	315.7	19.9
MST	UST	295	7	350	28	3	CT	C	316.4	30.4
MST	UST	130	6	295	20	5	CT	C	298.3	25.8

Table 9 (sheet 4).

CSP	UST	210	20	360	35	24	CT	0	340.4	40.0
CSP	UST	235	8	250	30	15	ST	C	254.9	72.4
CSP	UST	240	14	355	20	99	GT	G	277.6	14.9
CSP	UST	189	13	90	10	8	CT	C	97.0	23.0
CSP	UST	185	13	260	21	6	GT	F	274.1	21.3
CSP	UST	105	18	40	42	5	CT	F	21.3	37.0
CSP	UST	195	20	230	34	3	CT	F	245.4	12.9
CSP	UST	170	15	220	47	3	ST	F	253.6	38.7
CSP	UST	155	8	360	12	3	ST	C	340.5	70.2
CSP	UST	170	15	330	7	7	CT	C	343.5	21.7
CSP	UST	45	21	170	10	0	CT	C	200.9	31.2
CSP	UST	200	17	350	25	12	CT	C	1.0	40.6
CSP	UST	210	11	300	99	10	ST	C	306.9	59.6
CSP	UST	189	64	210	59	4	CT	F	293.7	22.9
CSP	UST	165	44	185	51	3	CT	F	230.7	18.3
EMC	LST	180	3	30	28	0			27.4	30.4
EMC	LST	180	3	205	14	0			304.9	15.9
EMC	LST	180	3	275	14	0			288.6	14.6
EMC	LST	180	3	10	23	0			8.9	76.0
EMC	LST	180	3	15	29	0			13.2	31.0
EMC	LST	180	3	50	11	0			40.1	13.1
EMC	LST	150	3	20	3	0			10.0	9.9
EMC	LST	160	3	35	6	0			23.6	8.6
EMC	LST	180	3	290	24	0			226.0	29.2
EMC	LST	180	3	270	18	0			270.2	16.2
EMC	LST	180	3	100	12	0			90.1	14.2
EMC	LST	180	30	360	12	0			360.0	42.0
SEY	UST	15	38	330	38	6	CT	C	364.0	24.3
SEY	UST	15	53	5	63	2	ST	M	331.0	13.1
SEY	UST	55	53	345	56	3	CT	C	245.7	44.9
SEY	UST	19	39	350	47	4	CT	M	311.2	20.1
SEY	UST	15	28	355	55	19	CT	M	343.4	12.3
SEY	UST	25	47	345	41	9	CT	C	366.6	26.1
SEY	UST	20	53	340	50	10	CT	C	372.0	31.3
SEY	UST	15	44	335	41	14	ST	C	263.9	26.9
SEY	UST	8	43	330	41	43	ST	C	248.8	34.8
SEY	UST	10	43	310	31	19	CT	C	239.4	36.6
SEY	UST	300	16	305	17	9	CT	F	304.4	24.1
SEY	UST	35	47	10	42	2	CT	F	280.3	16.1
SEY	UST	15	41	340	31	6	ST	F	249.5	72.8
SEY	UST	355	48	330	43	10	CT	F	246.4	17.7
SEY	UST	245	11	330	30	9	CT	F	343.4	39.3
SEY	UST	10	23	370	28	3	CT	F	269.4	21.5
SEY	UST	30	38	360	47	3	CT	F	316.4	44.2
SEY	UST	30	37	10	24	6	CT	F	239.6	16.3
SEY	UST	20	38	5	38	4	ST	F	278.0	0.4
SEY	UST	30	43	10	42	12	CT	F	326.2	19.0
SEY	UST	15	33	5	43	6	CT	F	339.3	11.7
SEY	UST	10	28	45	36	9	CT	F	92.3	19.9
SEY	UST	15	42	95	28	3	CT	F	158.0	30.4
SEY	UST	40	37	360	47	9	CT	F	314.9	28.1
ECK	UST	195	56	225	25	9			337.2	59.0
ECK	UST	185	52	225	40	9			273.9	33.8
ECK	UST	175	48	175	42	0			175.0	3.0
ECK	MST	190	44	165	97	0	CT		125.4	23.1
ECK	LST	175	38	180	44	3	CT	F	89.2	19.2
ECK	LST	190	55	45	70	7	CT		226.8	25.7
ECK	LST	10	18	225	20	7	CB		204.3	42.8
ECK	LST	190	55	45	70	7	CR		226.8	75.7
HPV	UST	340	18	300	18	4	CT	F	343.0	41.8
HPV	UST	355	14	305	24	9	CT	F	271.0	18.3
HPV	UST	360	27	120	6	4	CT	F	161.1	31.2
HPV	UST	395	24	290	19	5	CT	F	223.7	23.1
HPV	UST	9	45	40	10	4	CT	F	174.2	32.2
HPV	UST	345	23	300	25	12	CT	F	240.2	16.0
HPV	UST	330	18	235	11	4	CT	F	183.4	70.1
HPV	UST	15	24	200	6	0	CT	F	186.0	30.0
HPV	UST	15	24	20	29	4	CT	F	41.3	5.5
HPV	UST	360	19	300	28	6	CT	F	223.7	31.1
HPV	LST	350	20	350	38	2	CT	M	350.0	16.0
HPV	LST	360	18	130	35	4	CT	F	394.1	33.8
HPV	LST	360	18	370	28	7	CT	F	782.9	18.0
HPV	LST	390	24	340	27	8	CT	F	380.3	9.3
HPV	LST	10	13	45	36	12	CT	M	59.6	26.3
HPV	LST	5	22	35	24	3	CT	F	99.4	11.0
HPV	LST	10	13	45	36	12	CT	M	59.6	26.3
HPV	LST	10	33	360	51	4	CT	C	345.7	10.3
HPV	LST	10	33	5	51	4	CT	F	357.5	16.3
HPV	LST	40	21	330	28	3	CT	F	290.2	33.8
HPV	LST	25	18	15	43	5	CT	F	11.9	25.1
HPV	LST	20	18	35	24	9	CT	M	73.4	7.2
HPV	LST	360	25	340	32	7	CT	F	297.1	11.0
HPV	LST	185	21	355	24	0	CT	0	385.4	11.0

Table 9 (sheet 5).

EGR	LST	205	41	170	46	-0		F	113.5	24.4
EGR	LST	220	10	385	40	6		VF	309.3	35.6
EGR	LST	210	34	200	52	-0		F	179.5	15.7
EGR	LST	205	50	235	38	13		3	342.4	84.0
EGR	LST	225	32	240	42	-0		VC	273.3	13.4
EGR	LST	335	34	350	30	-0		G	18.5	12.2
EGR	LST	200	54	215	41	9		F	344.5	17.0
EGR	LST	210	48	170	35	-0		VF	70.8	20.0
EGR	LST	210	48	190	79	-0		F	174.8	35.0
EGR	LST	215	43	180	50	3		VF	145.5	22.9
WGR	UST	200	34	210	35	6	ST	F	284.1	5.7
WGR	UST	195	28	165	14	3	ST	F	112.5	16.4
WGR	UST	193	35	230	21	4	ST	F	337.4	21.7
WGR	UST	193	35	207	44	-0		F	211.2	50.3
WGR	UST	193	35	207	23	7	3Y	F	349.5	13.7
WGR	UST	195	28	208	33	1	CR	F	283.4	8.3
WGR	LST	203	36	255	13	12	CT	C	2.0	29.6
WGR	LST	203	40	245	45	3	CT		276.0	24.3
WGR	LST	190	36	185	55	6	ST		177.5	19.3
WGR	LST	187	38	183	70	3	ST		197.6	32.3
WGR	LST	187	32	202	49	3	ST		222.8	19.5
WGR	LST	180	72	200	88	4	ST		329.3	31.7
WGR	LST	296	47	215	56	3	ST		185.5	82.9
WGR	LST	195	50	260	88	0	CT	8	132.6	7.4
WGR	LST	208	51	192	50	2	CT	C	106.3	12.4
WGR	LST	203	93	250	40	3	CT	G	195.3	10.1
WGR	LST	223	48	245	65	3	CT	C	276.8	24.9
WGR	LST	230	50	265	55	-0	ST	C	88.5	43.8
WGR	LST	222	31	240	60	-0	BT	C	252.8	31.5
WGR	LST	185	46	232	38	6	ST	C	309.1	32.0
WGR	LST	220	60	213	58	10	3Y	C	109.8	5.3
WGR	LST	218	53	228	51	-0	ST	C	311.2	7.8
WGR	LST	210	31	245	32	2	ST	C	312.0	16.1
WGR	LST	192	26	247	45	12	8T	G	276.0	35.0
WGR	LST	192	29	240	36	3	CT	C	284.7	27.3
WGR	LST	230	41	260	39	-0		C	337.4	19.3
WGR	LST	230	41	260	39	-0	8T	C	337.4	19.3
WGR	LST	220	44	240	55	8		C	281.0	16.7
WGR	LST	195	36	230	52	-0		C	265.5	28.7
WGR	LST	203	36	255	13	12	CT	C	2.0	29.6
STP	UST	195	70	180	70	-0		VC	74.1	16.5
STP	UST	195	64	205	61	-0		VC	306.0	9.4
STP	UST	200	70	10	84	6			173.0	67.7
STP	UST	190	75	200	81	10			249.6	11.5
STP	MST	225	55	225	62	-0		VF	225.0	7.0
STP	MST	200	49	210	62	-0		VF	235.3	15.4
STP	MST	215	33	225	80	-0		VF	233.3	27.9
STP	MST	187	50	175	50	-0		VF	93.1	9.2
STP	MST	185	40	215	39	-0		VF	343.1	36.8
STP	LST	193	67	3	84	6	CT	VF	173.2	99.4
STP	LST	200	74	200	88	5	CT	VF	200.0	43.0
STP	LST	195	78	207	82	5	CT	VF	115.5	9.9
CHA	UST	220	13	15	19	5	CT	F	24.3	30.3
CHA	UST	265	13	270	31	9	CT	F	248.5	18.7
CHA	UST	285	13	340	30	8	CT	F	344.4	40.0
CHA	UST	325	9	315	16	3	CT	F	302.9	7.3
CHA	UST	310	6	300	33	8	CT	F	298.2	27.1
CHA	UST	220	17	255	24	3	CT	F	297.5	13.8
CHA	UST	345	8	245	33	5	CT	F	345.1	22.0
CHA	UST	290	12	309	35	20	CT	F	311.8	23.6
CHA	LST	80	34	345	30	6	CT	F	310.0	31.0
CHA	LST	360	38	15	38	12	CT	C	95.9	9.2
CHA	LST	10	16	340	42	4	CT	C	326.3	29.1
CHA	LST	15	9	75	16	11	CT	M	108.4	13.8
CHA	LST	10	11	330	19	5	CT	M	318.8	31.3
CHA	LST	34	33	200	7	3	CT	F	211.4	39.8
CHA	LST	6	17	350	30	2	CT	C	228.7	10.8
RC3	UST	140	23	180	26	5	CT	F	238.5	16.6
RC3	UST	150	30	170	29	5	CT	F	228.1	19.1
RC3	UST	180	24	230	29	4	CT	F	280.6	22.2
RC3	UST	150	24	255	15	3	CT	F	301.2	31.2
RC3	UST	158	10	305	22	-0		VF	314.6	30.8
RC3	UST	158	10	100	10	-0		VF	263.8	5.5
RC3	UST	158	10	330	8	-0		VF	334.4	18.0
RC3	UST	158	10	245	8	-0		VF	305.2	14.8
RC3	UST	158	10	260	27	-0		VF	277.2	30.6
RC3	UST	158	10	270	13	-0		VF	281.4	39.7
RC3	UST	158	10	280	13	-0		VF	304.4	70.1
RC3	MST	158	8	83	23	-0		F	33.5	21.6
RC3	MST	315	9	265	17	-0	CT	F	234.1	13.1
RC3	MST	360	9	230	36	6	CT	F	330.0	36.0

Table 9 (sheet 6).

RC3	LST	140	8	40	25	8	CT	F	24.5	27.5
RC3	LST	360	0	10	9	2	CT	F	10.0	9.0
RC3	LST	360	0	55	19	4	CT	F	55.0	19.0
RC3	LST	140	5	255	3	6	CT	F	296.5	6.8
RC3	LST	100	4	180	15	4	CT	F	105.1	14.8
RC3	LST	100	4	49	19	4	CT	F	34.3	17.0
RC3	LST	140	5	50	29	8	CT	F	41.1	29.4
RC3	LST	115	4	65	17	12	CT	F	53.3	14.7
RC3	LST	115	2	160	12	11	CT	F	167.5	10.7
RC3	LST	158	10	210	9	-0		F	279.9	8.3
RC3	LST	158	10	250	11	-0		F	290.9	15.1
RC3	LST	140	5	240	16	2	CT	F	255.8	17.6
RC3	LST	158	10	20	6	-0		F	353.7	15.0
RC3	LST	158	10	270	6	-0		F	308.0	14.9
RC3	LST	158	10	250	23	-0		F	371.9	25.3
RC3	LST	158	10	255	9	-0		F	298.8	14.2
AP3	UST	5	13	310	14	6	CT	F	366.4	42.1
AP3	UST	355	8	320	17	4	CT	F	296.8	11.4
AP3	UST	25	10	35	17	8	CT	F	48.4	7.4
AP3	UST	350	13	315	21	8	CT	F	280.3	12.7
AP3	UST	5	12	340	19	2	CT	F	372.0	15.9
AP3	UST	360	4	310	12	6	CT	F	292.2	9.9
AP3	UST	5	0	105	3	3	CT	F	166.6	11.0
AP3	UST	35	14	220	14	17	CT	F	217.6	20.0
AP3	UST	10	19	155	16	12	CT	F	160.4	26.7
AP3	UST	10	12	105	22	16	CT	F	131.1	25.8
AP3	UST	60	4	170	11	6	CT	F	166.7	13.9
AP3	LST	360	21	210	28	4	ST	C	198.6	47.3
AP3	LST	20	14	40	24	3	CT	F	357.2	10.5
AP3	LST	360	19	350	29	2	CT	F	340.3	14.4
AP3	UST	10	14	10	12	8	ST	F	266.5	4.9
AP3	UST	40	9	90	8	6		F	128.5	6.1
AP3	UST	40	5	90	8	4	CT	F	128.5	6.1
AP3	UST	15	7	10	24	4	CT	F	8.1	17.0
OLF	UST	340	27	285	39	0	CT	F	329.4	25.1
OLF	MST	345	37	335	49	4	ST	F	311.6	13.6
OLF	MST	325	31	5	62	10	CT	VF	67.6	20.0
OLF	MST	350	31	15	24	15	CT	VF	122.0	13.4
OLF	MST	345	33	345	54	2	CT	VF	345.0	17.0
OLF	MST	345	28	350	42	6	CT	VF	358.7	14.3
OLF	MST	340	31	140	46	-0	CT	VF	38.0	19.3
OLF	MST	345	37	360	42	3	ST	F	53.3	10.7
OLF	LST	335	12	285	33	4	CT	M	266.9	26.7
OLF	LST	335	12	270	16	3	ST	M	226.0	15.3
OLF	LST	335	12	270	28	2	ST	M	246.4	25.2
OLF	LST	335	12	360	25	6	CT	M	16.8	15.0
OLF	LST	345	12	340	28	3	ST	F	256.4	25.2
OLF	LST	345	12	70	42	5	CT	F	30.2	32.8
OLF	LST	360	8	200	24	5	CT	M	271.6	22.5
OLF	LST	235	14	310	36	6	CT	M	329.6	34.7
OLF	LST	235	14	320	20	4	CT	M	344.5	30.8
OLF	LST	235	14	270	20	6	CT	M	312.2	11.6
OLF	LST	360	45	60	22	-0	CT	M	148.2	38.0
OLF	LST	335	14	270	30	6	CT	M	229.3	18.6
OLF	LST	30	13	230	27	4	CT	M	224.1	39.4
OLF	LST	355	11	285	35	6	CT	M	268.8	32.7
OLF	LST	355	11	315	24	8	CT	M	291.7	17.0
OLF	LST	350	10	305	15	10	CT	M	292.4	29.7
OLF	LST	335	15	305	33	4	CT	F	286.2	21.2
OLF	LST	335	9	360	11	3	ST	C	52.9	4.7
OLF	LST	360	14	310	27	14	CT	M	281.6	20.7
99	9999	999999999999999999999aaaaaaaaaaa				999	9999	99999	99999999.0	0.0

		Thickness	% Sed. structures present			Grain Size		Carb.	Porosity		Degree of Indurn.	Pyrite	Phos. material	
			Churning by infauna	Cross-bedding	Graded bedding	Mode	Max. diam. (phi)		Intergr.	Vuggy			% pres.	Max. diam. pellets (phi)
F	Upper	$1\frac{1}{4}'$	58%	0	0	fn silt	2.8φ	Nil	Low	Nil	4	Rare	Nil	-
	Lower	$2\frac{3}{4}'$	55%	0	0	clayey silt	2.1φ	Nil	Low	Nil	4	Rare	4.46	-2.3φ
E	Upper	$7\frac{3}{4}'$	72%			clayey silt	3.3φ	Nil	Low	Nil	4	Rare	Nil	-
	Lower	$2\frac{3}{4}''$	10%	0	0	V fn sand	2.5φ	Nil-low	Low	Nil	4	Rare-Comm.	13.8%	2.5φ
D	Upper	$5\frac{1}{2}''$	45%	0	0	Clayey silt	3.3φ	Nil	Nil	Nil	4	Rare	Nil	-
	Lower	2"	20%	0	0	fn sand	1.7φ	Nil-low	Low	Nil-rare fn	4	Rare-comm.	11.8%	-1.1φ
C	Upper	11"	55%	0	10%	V fn sand	2.1φ	Nil-low	Low-mod	Nil-rare fn	4	Rare	Nil	-
	Lower	$6\frac{1}{2}''$	28%	0	0	Med	1.3φ	Nil	Low-mod	Nil-rare fn	3-4	Rare	7.2%	-1.5φ
B	Upper	$11\frac{1}{2}''$	16%	7%	0	Fn sand	1.5φ	Low	Low-mod	Rare fn-comm fn	4	Rare	Nil	-
	Lower	5"	0	0	0	Med sand	0.4φ	Nil	Low	Nil	4	Rare-comm.	7.1%	-1.3φ
A	Upper	$1\frac{1}{4}'$	33%	0	30%	Fn sand	1.5φ	Nil	Mod	Rare-fn	4	Rare	Nil	-
	Lower	$4\frac{1}{4}'$	35%	24%	30%	Med sand	0.5φ	Nil	Mod	Comm. fn	3-4	Rare	2.8%	-2.1φ

Table 10

AVERAGE VALUES OF LITHOLOGICAL PARAMETERS

IN THE COMPOUND SEDIMENTATION UNIT

(See Fig.27)

Table 11

Specific gravity determinations on nodules

A. Brown nodules

1	2.61 gms/cc
2	2.52 gms/cc
3	2.70 gms
Average for brown nodules	<u>2.61 gms/cc</u>

B. Grey nodules

4	2.76 gms/cc
5	2.59 gms/cc
6	2.67 gms/cc
Average for grey nodules	<u>2.67 gms/cc</u>

APPENDIX IV

DETAILED GRAPHIC LOGS

LOG REFERENCE I

Core Condition

core in good condition - no gaps

core has split into many laminae parallel
to the bedding

core broken into irregular fragments
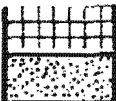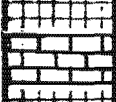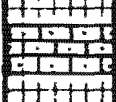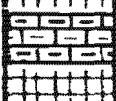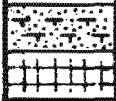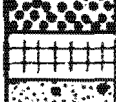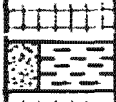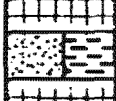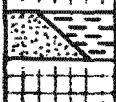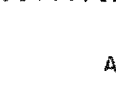
half the core has been removed for deter-
mination of P_2O_5 content.

core missing (lost during drilling
operations)

LOG REFERENCE II

Rock Type

sandstone

lutite

limestone

sandy limestone

lutaceous limestone

calcareous sandstone

calcareous lutite

phosphorite

phosphatic sandstone

phosphatic lutite

phosphatic limestone

oolitic pyrite

minor sandstone with major lutite (strata
either alternating or interfingering)

equal sandstone and lutite

major sandstone with minor lutite

alternating or interfingering sandstone and lutite, but
with the proportions varying from top to bottom.

Bedding Plane Types

very sharp flat contact

sharp flat contact

distinct flat contact

transition gradual but rapid (range of transition <0.5cm)

transition gradual but fairly rapid (range of transition
0.5-1cm)

transition gradual and slow, hardly visible

undulating contact; gradations distinguished as above

irregular contact; gradations distinguished as above

Layer Properties

graded bedding (negative (bottom fine) ⎯••
(positive(bottom coarse)••_

parallel lamination (coarse grained laminae predominate
(equal coarse and fine grained laminae
(fine grained laminae predominate

slightly disturbed
parallel lamination (coarse grained laminae predominate
(equal coarse and fine grained laminae
(fine grained laminae predominate

strongly disturbed
parallel lamination (predominating grain size not indicat-
(ed

wavy lamination (predominating grain size indicated
(as above

lenticular wavy
lamination (predominating grain size indicated
(as above

cross bedding

tracks and burrows in all directions

bed pulled apart

lens (coarser than surroundings
(finer than surroundings

irregular inclusions (coarser than surroundings
(finer than surroundings

clay pellets

Textural representation

fine grained sandstone

equal very fine grained sandstone and
silty lutite

very fine grained sandstone and minor
muddy lutite

silty muddy lutite and minor very fine
grained sandstone

bimodal coarse and fine grained sandstone

silty lutite with very fine laminae of
very fine grained sandstone

fine grained sandstone with very fine
silty laminae

sandstone grading from very fine to
coarse grained.
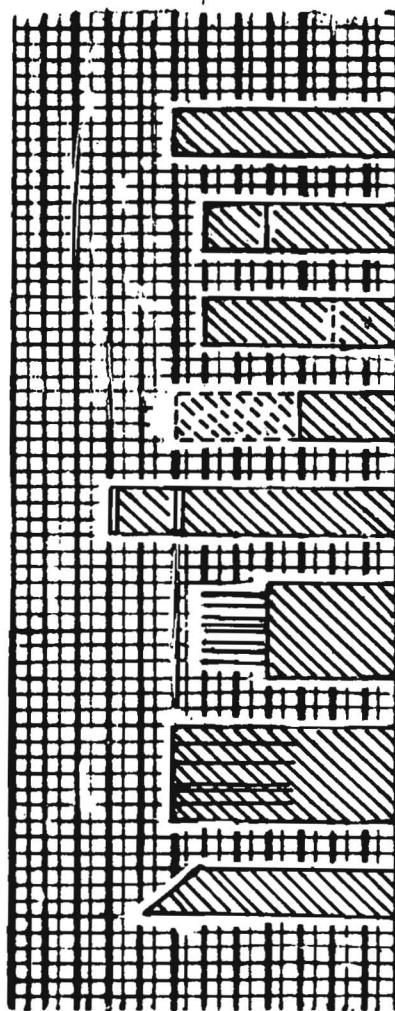
LOG REFERENCE VI

Calcium Carbonate Content

low (effevescence very weak)

moderate (effevescence fairly strong)

high (effevescence very strong)
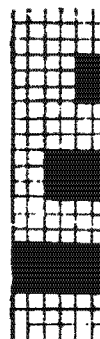
LOG REFERENCE VII

Porosity

```
                         (            low (approx. 1-5%)
                         (
                         (
intergranular( moderate (approx.5-15%)
                         (
                         (
                         (         high ( > 15%)
```

```
         (common fine (1mm or less)
         (
         (
         (common coarse (1-10mm)
         (
         (
         (common very coarse ( > 10 mm)
vuggy    (
         (
         (rare fine (as above)
         (
         (
         (rare coarse (as above)
         (
         (
         (rare very coarse (as above)
```
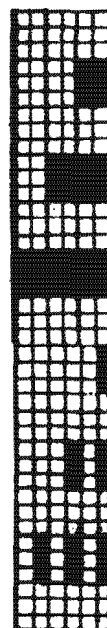
LOG REFERENCE VIII

Induration

1. <u>loose</u>: grains falling apart in dry condition

2. <u>friable</u>: grains can be detached using a finger-
                nail

3. <u>moderately hard</u>: grains can be detached with a
                         knife

4. <u>hard</u>: grains cannot be detached with a knife

5. <u>weakly metamorphic</u>: fractures pass through the
                             grains

                                              (rare
                                              (
                                  pyrite (common
                                              (
                                              (very common

pyrite and oolitic pyrite (gradation as above)

oolitic pyrite (gradations as above)

glauconite (gradations as above)

                  (present as irregular patches or in fractures
                  (
hydrocarbons (
                  (saturating the core
                  (

                  (weak patchy developments
                  (
fluorescence (
                  (strong development
                  (

SECTION OR CORE

NAME AP1   No.1   SCALE One inch to four feet (1:48)

FORMATION Stairway Sandstone   AGE Ordovician

LOCATION Johnny Creek, N.T.   MEASURED BY P.J. Cook   DATE 1964

THICKNESS IN FEET	CORE			ROCK TYPE	BEDDING PLANE PROPERTIES			CURRENT DIRECTION	LAYER PROPERTIES	LITHOLOGY						FOSSILS	COLOUR		PROPERTIES OF PHOSPHATIC MATERIAL						NUMBER OF LAYERS	UNIT NUMBER	REMARKS
	RECOVERY	CONDITION			TYPE	STRUCTURES ON THE BEDDING PLANE				TEXTURE	MAXIMUM GRAIN SIZE	CALCIUM CARBONATE	POROSITY		INDURATION	SUPPLEMENTARY DATA		FRESH	WEATHERED	APPROX % OF PHOSPHATIC PELLETS & GRAINS	TEXTURAL RANGE	ROUNDNESS	SPHERICITY	COLOUR				

Remarks column (top to bottom): MC, THS, TH, TH, TH, TH, X, M, TH, H, TH, T, TH, TX, THX, T, TC, TH, THC, TH, THC, THC, TH, THS, T, M, THS, C, TH

Base of Stokes Fmn.
Top of Stairway Sst.

TO ACCOMPANY RECORD 1966/1   AUS 1/139
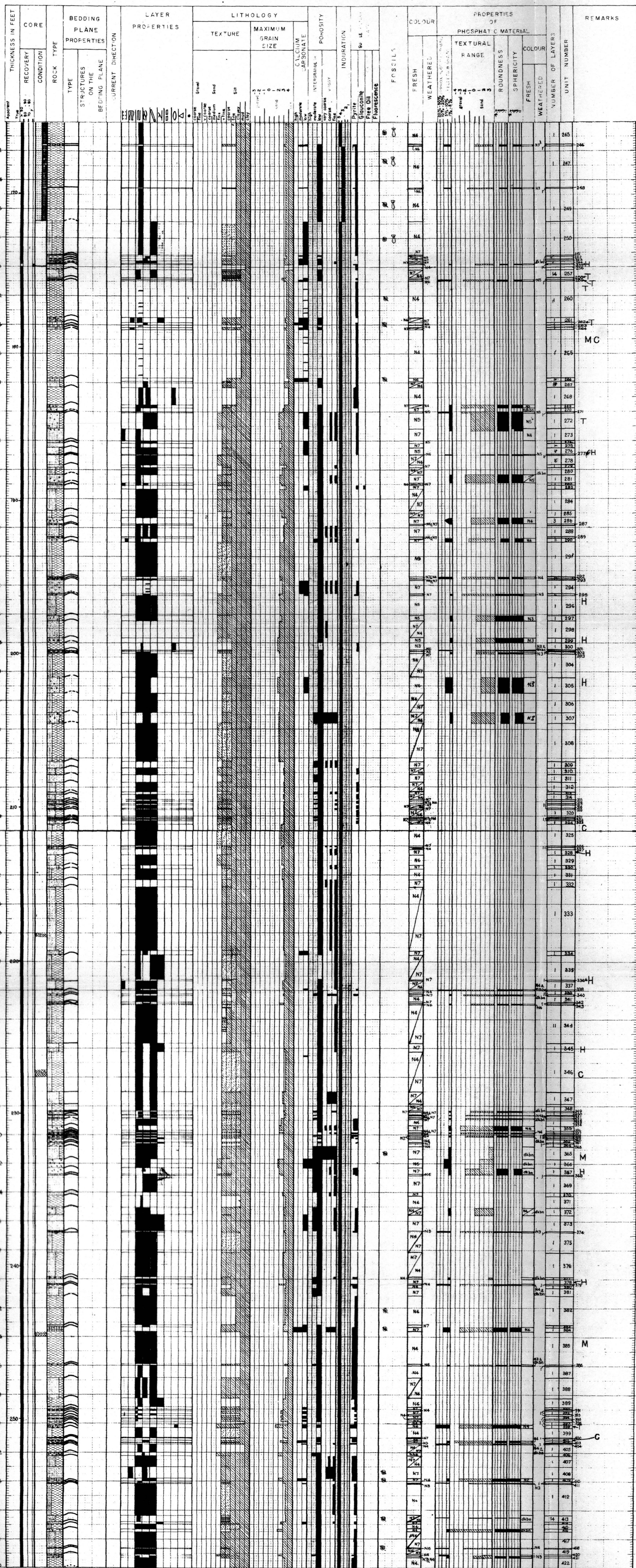
SECTION OR CORE

NAME AP1   No. 2   SCALE One inch to four feet (1:48)

FORMATION Stairway Sandstone   AGE Ordovician

LOCATION Johnny Creek, NT   MEASURED BY P.J.Cook   DATE 1964

THICKNESS IN FEET	CORE			BEDDING PLANE PROPERTIES		LAYER PROPERTIES	LITHOLOGY			CALCIUM CARBONATE	POROSITY	INDURATION	SUPPLEMENTARY DATA	FOSSILS	COLOUR		PROPERTIES OF PHOSPHATIC MATERIAL						NUMBER OF LAYERS	UNIT NUMBER	REMARKS
	RECOVERY	CONDITION	ROCK TYPE	TYPE	STRUCTURES ON THE BEDDING PLANE / CURRENT DIRECTION		TEXTURE	MAXIMUM GRAIN SIZE							FRESH	WEATHERED		TEXTURAL RANGE	ROUNDNESS	SPHERICITY	COLOUR				

TO ACCOMPANY RECORD 1966/1   AUS 1/140

SECTION OR CORE

NAME AP1   No.3   SCALE One inch to four feet (1:48)

FORMATION Stairway Sandstone   AGE Ordovician

LOCATION Johnny Creek, N.T.   MEASURED BY P.J.Cook   DATE 1964

THICKNESS IN FEET	CORE			ROCK TYPE	BEDDING PLANE PROPERTIES			LAYER PROPERTIES	LITHOLOGY					POROSITY	INDURATION		FOSSILS	COLOUR		PROPERTIES OF PHOSPHATIC MATERIAL							REMARKS
	RECOVERY	CONDITION			TYPE	STRUCTURES ON THE BEDDING PLANE	CURRENT DIRECTION		TEXTURE	MAXIMUM GRAIN SIZE		CALCIUM CARBONATE						FRESH	WEATHERED	TEXTURAL RANGE		ROUNDNESS	SPHERICITY	COLOUR		NUMBER OF LAYERS	UNIT NUMBER	

TO ACCOMPANY RECORD 1966/1

AUS 1/141

SECTION OR CORE

NAME AP1   N.4   SCALE One inch to four feet (1:48)

FORMATION Stairway Sandstone   AGE Ordovician

LOCATION Johnny Creek, NT   MEASURED BY P.J.Cook   DATE 1964

THICKNESS IN FEET	CORE		ROCK TYPE	BEDDING PLANE PROPERTIES			LAYER PROPERTIES	LITHOLOGY					SUPPLEMENTARY DATA	FOSSILS	COLOUR		PROPERTIES OF PHOSPHATIC MATERIAL					NUMBER OF LAYERS	UNIT NUMBER	REMARKS
	RECOVERY	CONDITION	TYPE	TYPE	STRUCTURES ON THE BEDDING PLANE	CURRENT DIRECTION		TEXTURE	MAXIMUM GRAIN SIZE	CALCIUM CARBONATE	POROSITY INTERGRANULAR VUGGY	INDURATION			FRESH	WEATHERED	TEXTURAL RANGE	ROUNDNESS	SPHERICITY	COLOUR FRESH	WEATHERED			

TO ACCOMPANY RECORD 1966/1

AUS 1/142

SECTION OR CORE

NAME AP1 No.5 SCALE One inch to four feet (1:48)

FORMATION Stairway Sandstone AGE Ordovician

LOCATION Johnny Creek, NT MEASURED BY P.J.Cook DATE 1964

SECTION OR CORE

NAME AP1 No. 6 SCALE One inch to four feet (1:48)

FORMATION Steirway Sandstone AGE Ordovician

LOCATION Johnny Creek, NT MEASURED BY P.J. Cook DATE 1964

SECTION OR CORE

NAME AP1 No.7 SCALE One inch to four feet. (1:48)

FORMATION Stairway Sandstone AGE Ordovician

LOCATION Johnny Creek, N.T. MEASURED BY P.J.Cook DATE 1964

THICKNESS IN FEET	CORE		ROCK TYPE	BEDDING PLANE PROPERTIES		CURRENT DIRECTION	LAYER PROPERTIES	LITHOLOGY			CALCIUM CARBONATE	POROSITY	INDURATION	SUPPLEMENTARY DATA	FOSSILS	COLOUR		PROPERTIES OF PHOSPHATIC MATERIAL					NUMBER OF LAYERS	UNIT NUMBER	REMARKS
	RECOVERY	CONDITION		TYPE	STRUCTURES ON THE BEDDING PLANE			TEXTURE	MAXIMUM GRAIN SIZE			INTERGRANULAR / VUGGY		Pyrite / Glauconite / Free Oil / Fluorescence		FRESH	WEATHERED	APPROX % OF PHOSPHATIC PELLETS & GRAINS	TEXTURAL RANGE		ROUNDNESS	SPHERICITY	COLOUR FRESH / WEATHERED		

COLUMN HEADINGS: Apparent / True · 3–80% · 80%–90% · 70%–80% · <70%

Texture: coarse / fine / v.coarse / coarse / medium / fine / v.fine / coarse / fine / clayey / mud / clay

Maximum grain size: gravel −3 −2 −1 0 1 2 3 4 · sand · silt

Calcium carbonate: high / moderate / low

Porosity: high / moderate / low / very coarse / coarse

Colour / Properties of phosphatic material: 20% 10% / 5% 0% / 1% 5% · gravel −4 −3 −2 −1 0 1 2 3 · sand · 6 5 / 7 3 / 9 7

Depth (ft)	Colour	Unit No.	Remarks
650		792	
652	N7	793	THS
	N4		TH
654	10YR4/2	794	
656		795	T
658 (590)	N6 / 10YR4/2	795	
	N7	796	
660	N7 / 10YR4/2	797	
662	N7	798	
664	N6	799	
666	N7	800	
	N4	801	
668 (560)	N7	802	30
	N6 / N6	803	THS
670	N4 & N7	804 / 805	
	N7	806	
	N5	807	
672	N7 / N4	808	
	N3	809	
674	N7	810	
	N6	811	T
676	N6	812	
	5Y6/1	813	
678	N7	814	
	N6	815	
680 (570)	N7	816	M
	5Y6/1	817	T
	N7	818	T
682 (572.5)	N3	819	Base of Stairway Sandstone / Top of Horn Valley Siltstone T
	N4 / N7	820	
684	5Y3/2	821	
	N7 / N4 / N7	822 / 823 / 824	
	N3		
686	N7	825	
688	N4	826	
690	N7 / N4	827	
692	N4	828	
694	N4 / N7	829	
	N3	830	
696	N4 / N7 / N4 / N4 / N7	831 / 832 / 833 / 834 / 835	
	N7 / N4	836	M
698	N7 / N4	837	
	N7 / N4	838 / 839	T
700	N7 / N6 / N7	840 / 841 / 842	