THE STAIRWAY SANDSTONE

- A SEDIMENTOLOGICAL STUDY

by

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Canberra

February, 1966

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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

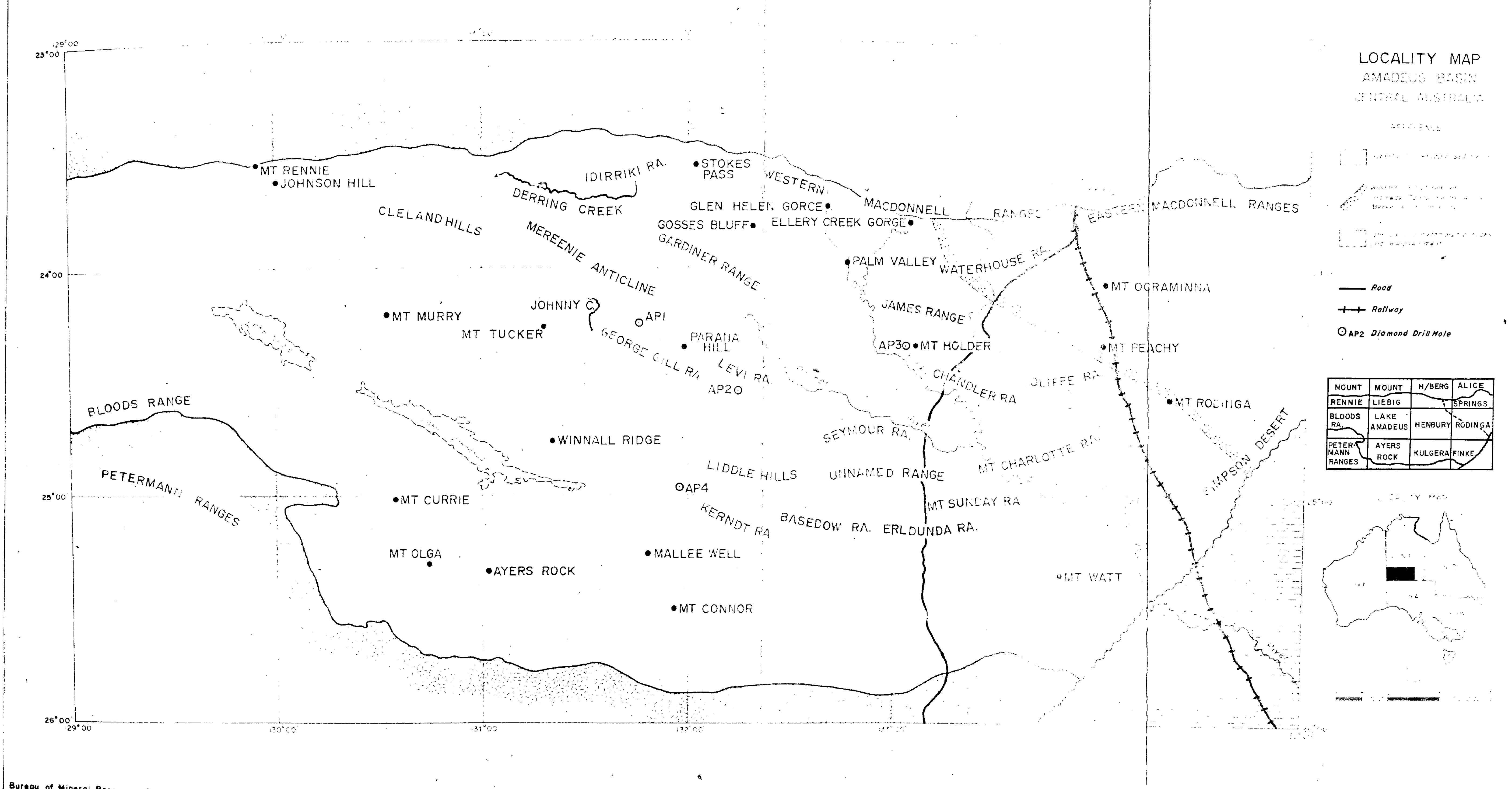

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fig.1). Sub-surface core samples were obtained from four diamond drill holes AP1, AP2, AP3 and AP4 (see fig.1). They are numbered by using the drill hole number as a prefix. The second set of numbers is the number of the sedimentation unit (see Chapter 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

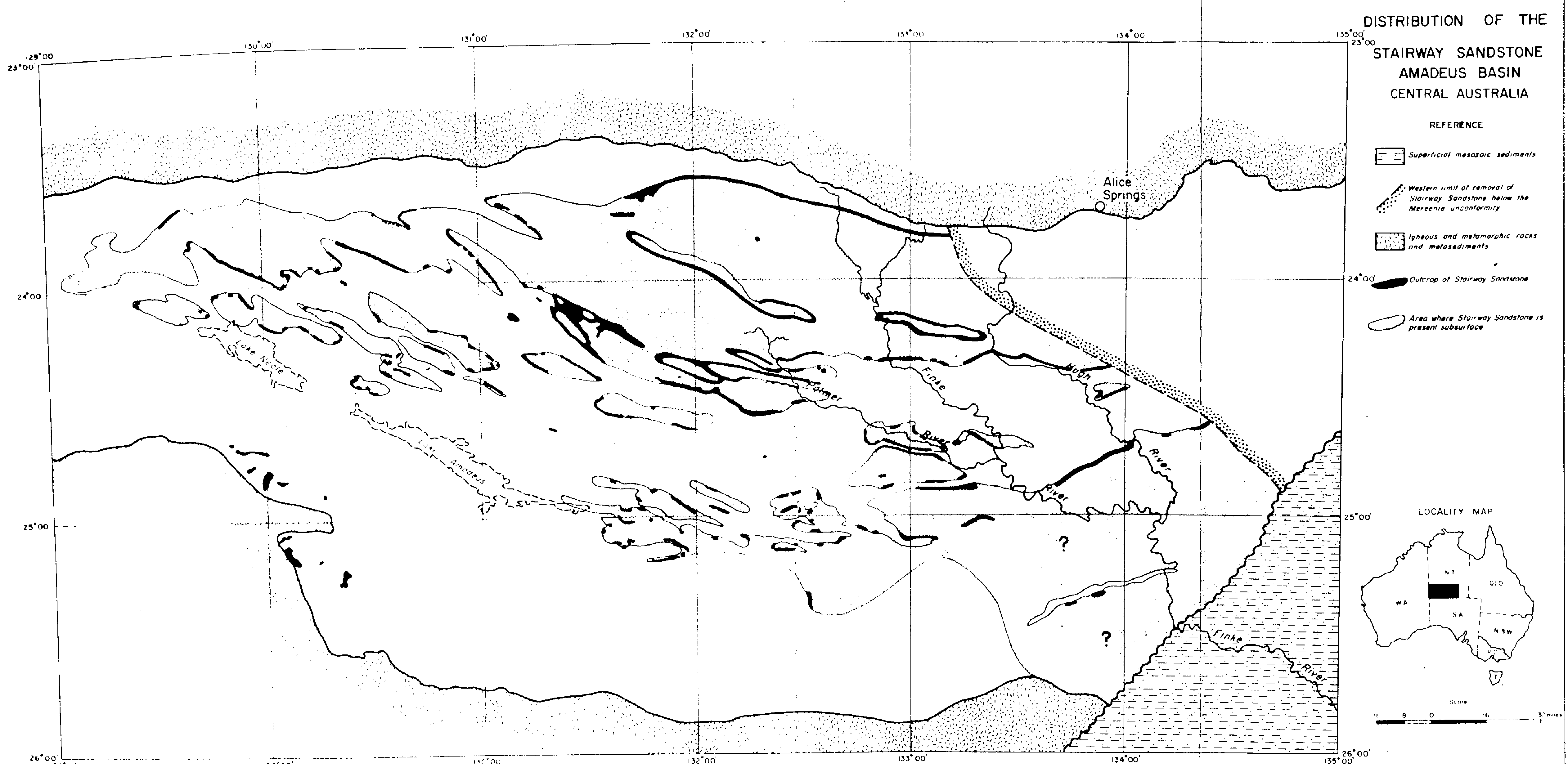
These four formations are marine sediments probably deposited under fairly shallow conditions, and are described by Cook, (1966).

<u>Previous Investigations of the Stairway Sandstone</u>

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); Ranneft, (1963) and Haites, (1963). It is also described in various unpublished company

PLATE 2



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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

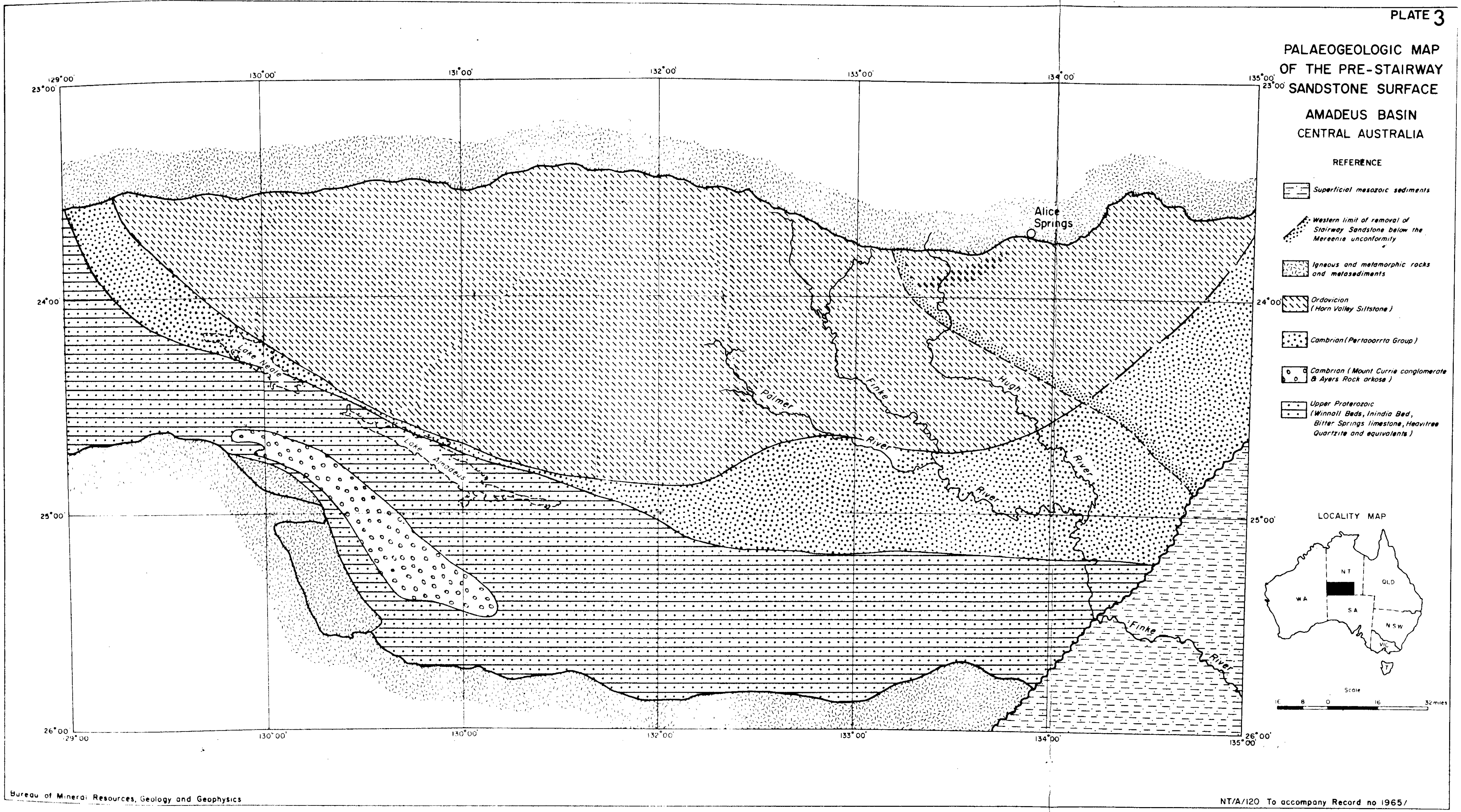
PLATE 3
PALAEOGEOLOGIC MAP
OF THE PRE-STAIRWAY
SANDSTONE SURFACE
AMADEUS BASIN
CENTRAL AUSTRALIA
REFERENCE
Superficial mesozoic sediments
Western limit of removal of Stairway Sandstone below the Mereenie unconformity
Igneous and metamorphic rocks and metasediments
Ordovician (Horn Valley Siltstone)
Cambrian (Pertaoorrta Group)
Cambrian (Mount Currie conglomerate & Ayers Rock arkose)
Upper Proterozoic (Winnall Beds, Inindia Bed, Bitter Springs limestone, Heavitree Quartzite and equivalents)
LOCALITY MAP
NT
QLD
WA
SA
NSW
VIC
Scale
16 8 0 16 32 miles
Alice Springs
Lake Neale
Lake Amadeus
Palmer River
Finke River
Hugh River
129°00'
130°00'
131°00'
132°00'
133°00'
134°00'
135°00'
23°00'
24°00'
25°00'
26°00'
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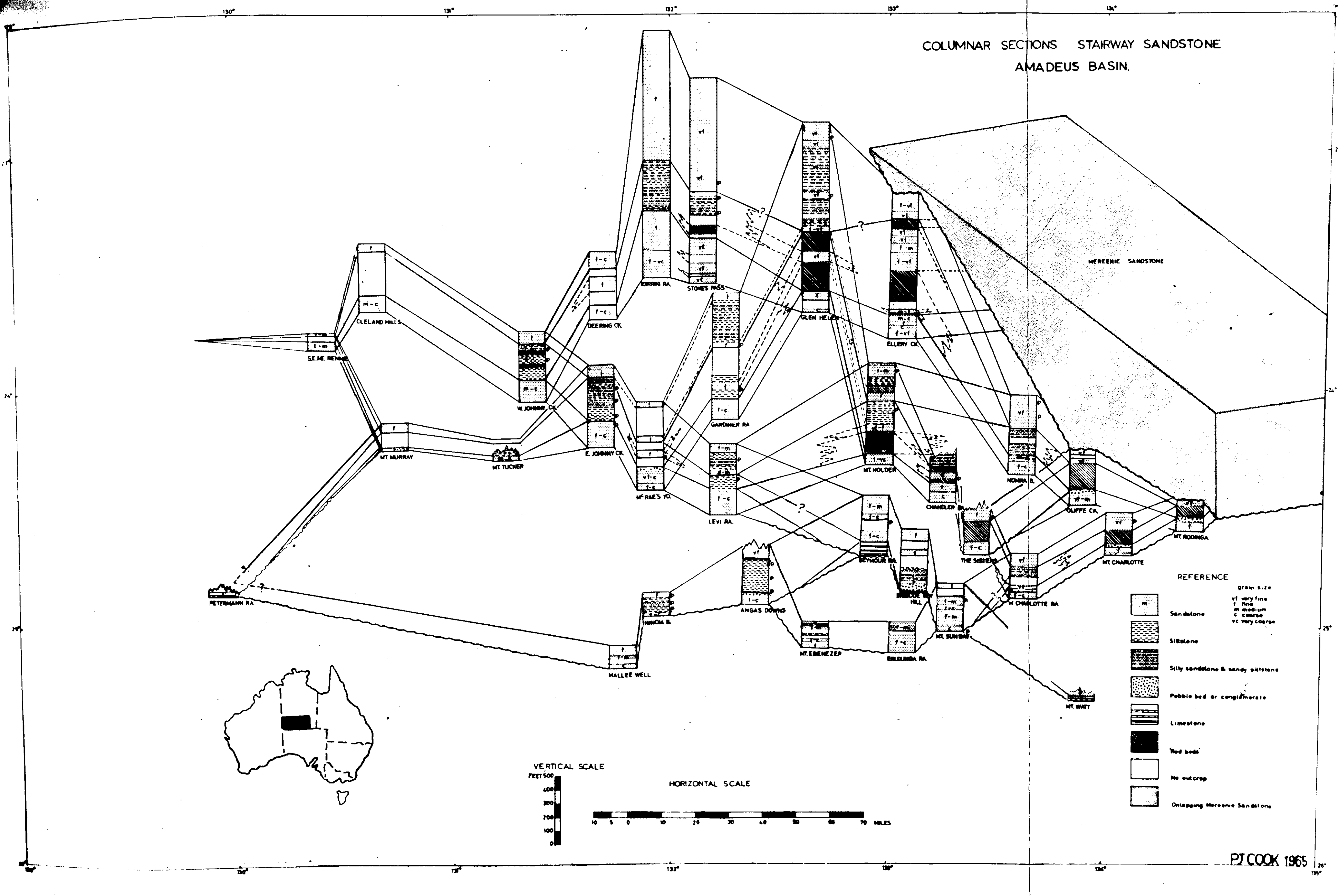
stretched well beyond the present limits of the basin.

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, brachiopods, 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.
MEREENIE SANDSTONE
CLELAND HILLS
S.E. MT. RENNIE
W. JOHNNY CK.
DEERING CK.
DIRRIG RA.
STONES PASS
GLEN HELEN
ELLERY CK.
MT. MURRAY
MT. TUCKER
E. JOHNNY CK.
GARDINER RA.
Mc RAE'S YD.
LEVI RA.
MT. HOLDER
NOMNA B.
CHANDLER RA.
OLIFFE CK.
THE SISTERS
MT. RODINGA
MT. CHARLOTTE
W. CHARLOTTE RA.
SEYMOUR RA.
ANGAS DOWNS
HINDIA B.
PETERMANN RA.
MALLEE WELL
MT. EBENEZER
ERLDUNDA RA.
MT. SUNDAY
MT. WATT
REFERENCE
grain size
vf very fine
f fine
m medium
c coarse
vc very coarse
Sandstone
Siltstone
Silty sandstone & sandy siltstone
Pebble bed or conglomerate
Limestone
Red beds
No outcrop
Onlapping Mereenie Sandstone
VERTICAL SCALE
FEET 500
400
300
200
100
0
HORIZONTAL SCALE
10 5 0 10 20 30 40 50 60 70 MILES
P.J. COOK 1965

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 expowed 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

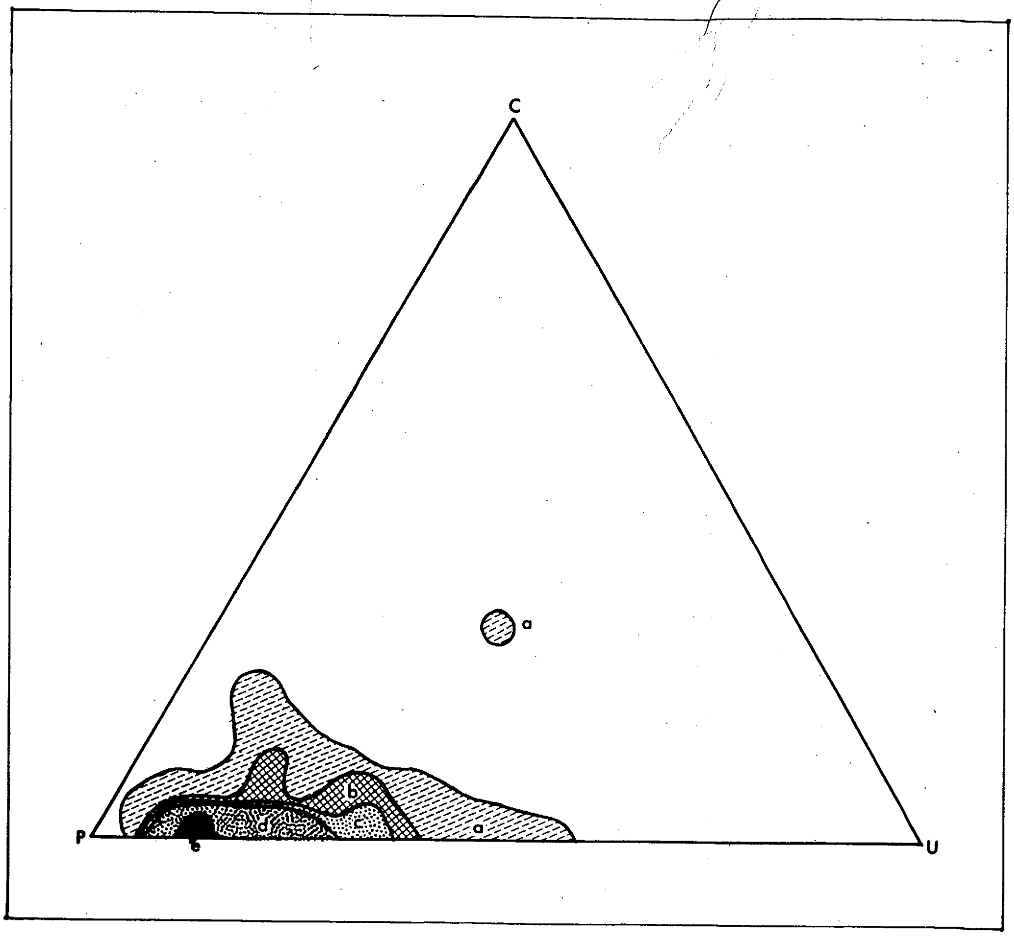


Fig.5

QUARTZ TYPES 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

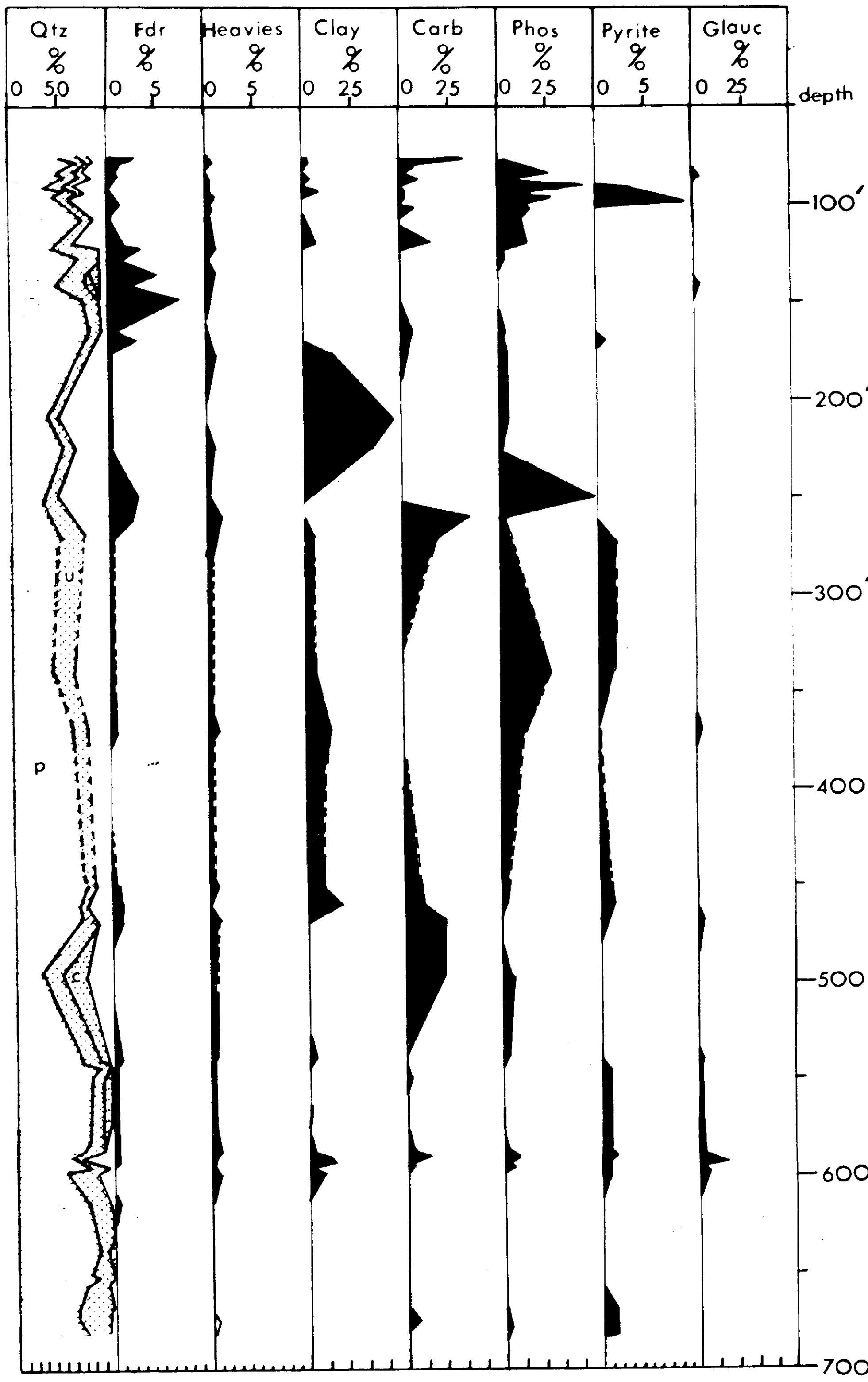
grain is somewhat arbitrary. Blatt, (1963,1964), Blatt and Christie (1963) and Greensmith (1963), have also noted this apparent instability of composite quartz. If composite grains were to be included with rock fragments then 10 - 20% of the specimens would fall into the lithic sub-labile arenite field 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) <u>Orthoquartzite</u> (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).

MINERALOGICAL VARIATION OF ORTHOQUARTZITES IN AP1



The lower orthoquartzites have a modal grain size of about 1ϕ to 2ϕ, and are quite commonly bimodal, with a secondary mode of 3ϕ to 4ϕ. 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 3ϕ to 4ϕ. 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 1ϕ to 4ϕ 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 3Ø to 5Ø; 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 (4Ø to 8Ø), 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

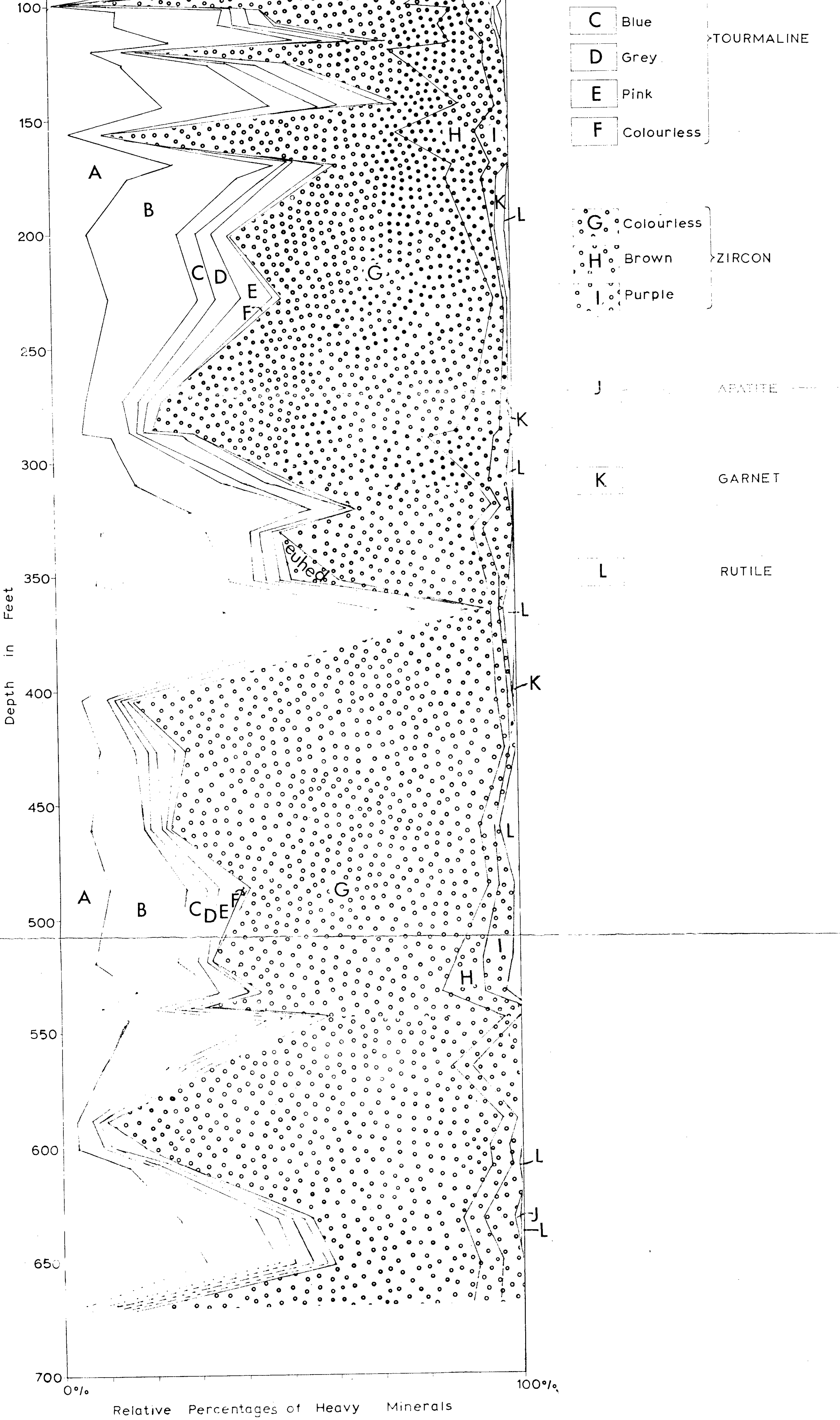
The methodology of the heavy mineral studies is given in the appendix. Heavy mineral counts were made at regular intervals throughout the Stairway Sandstone of AP1. In addition to the mineralogy it was also noted whether grains were rounded, angular or euhedral. The percentage of each heavy mineral was 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.



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
100
150
200
250
300
350
400
450
500
550
600
650
700
0%
100%
Relative Percentages of Heavy Minerals
A
B
C
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E
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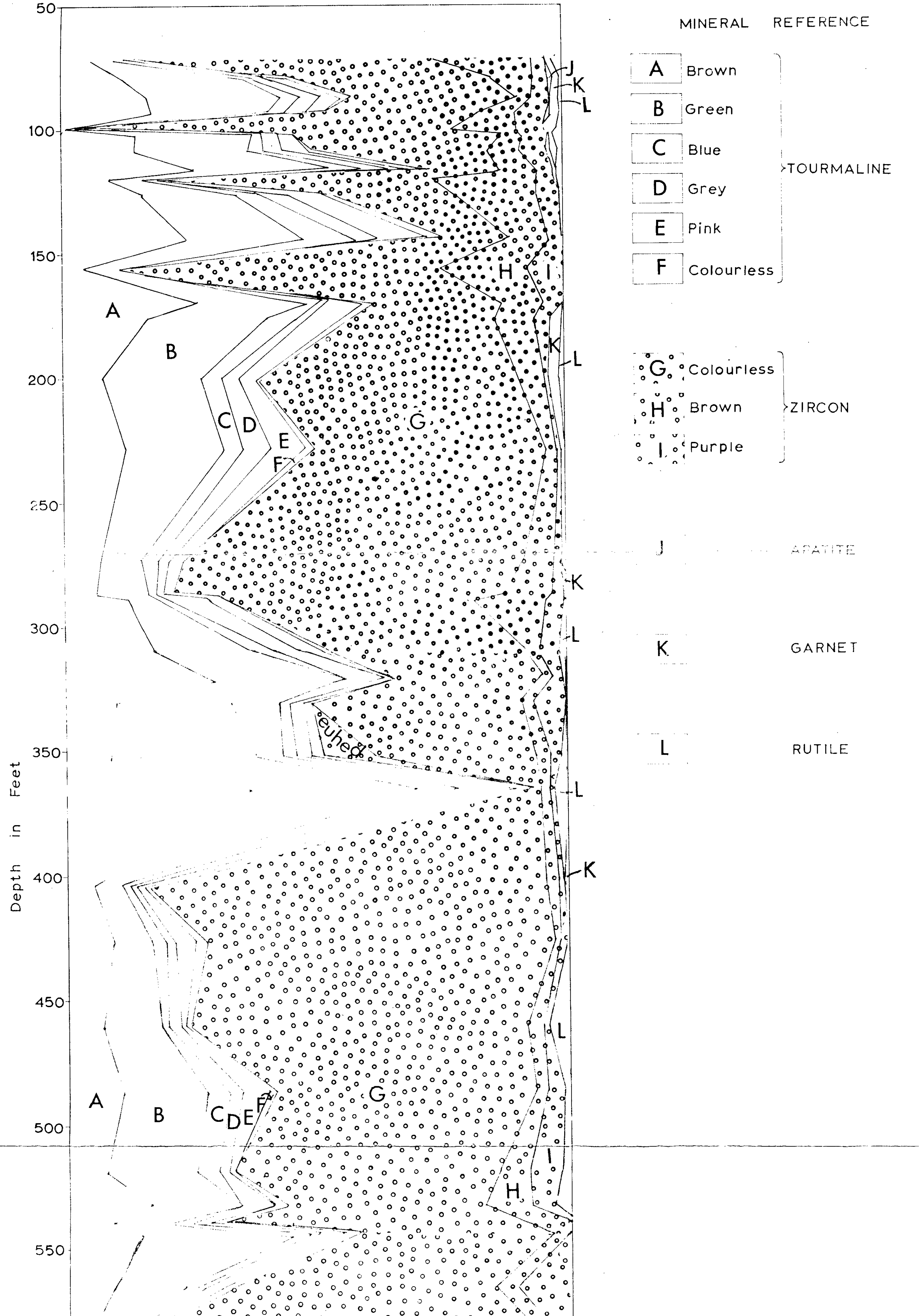
VARIATION OF HEAVY MINERAL ASSEMBLAGE WITH DEPTH

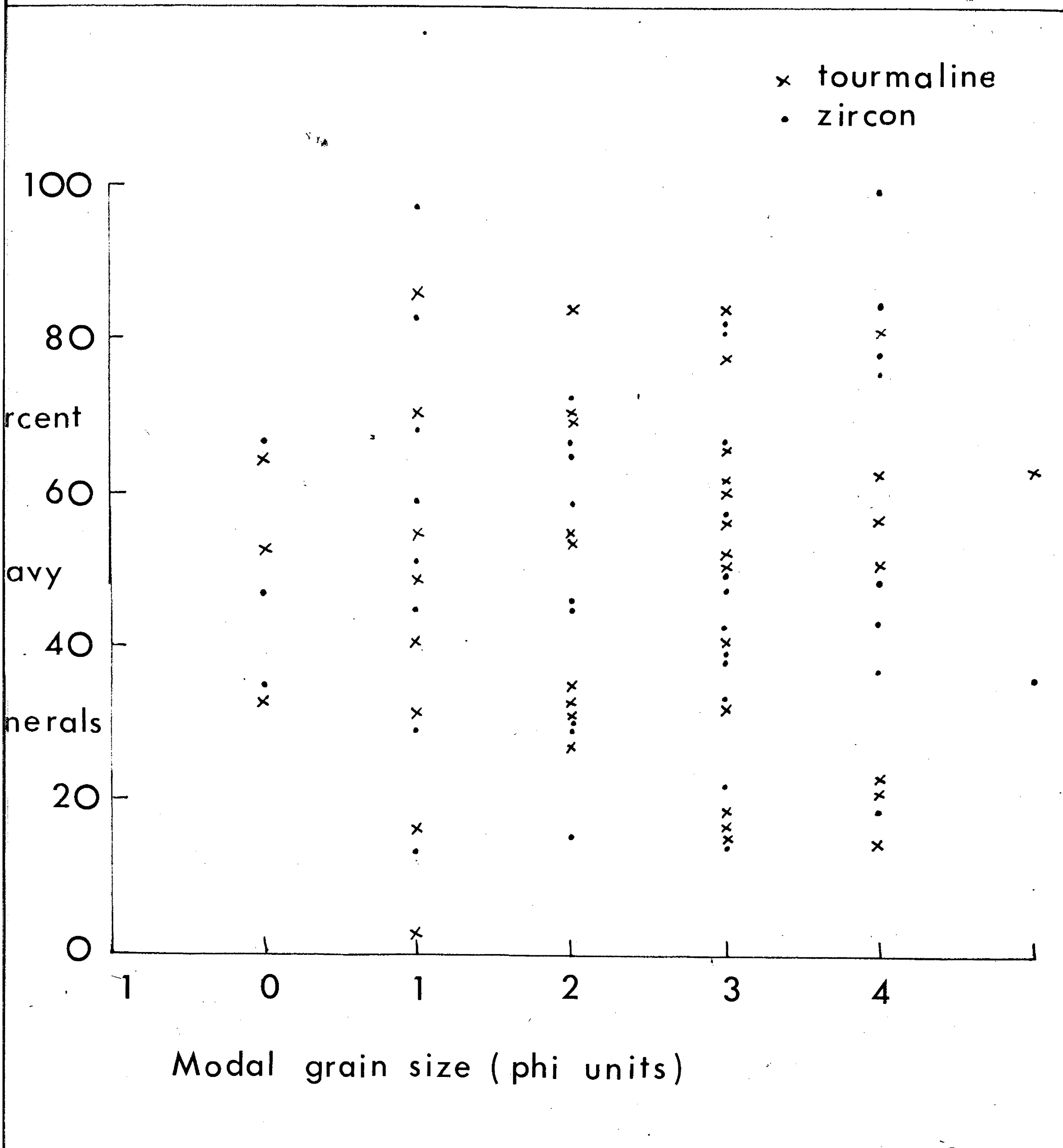


The vertical variation in the ratio of tourmaline to zircon is marked by extreme variations commonly occurring within a very small vertical distance (Fig.7). It was also observed that the diameter of the tourmaline is commonly twice or three times that of the zircon (Fig.51, appendix) - a reflection 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 ph 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

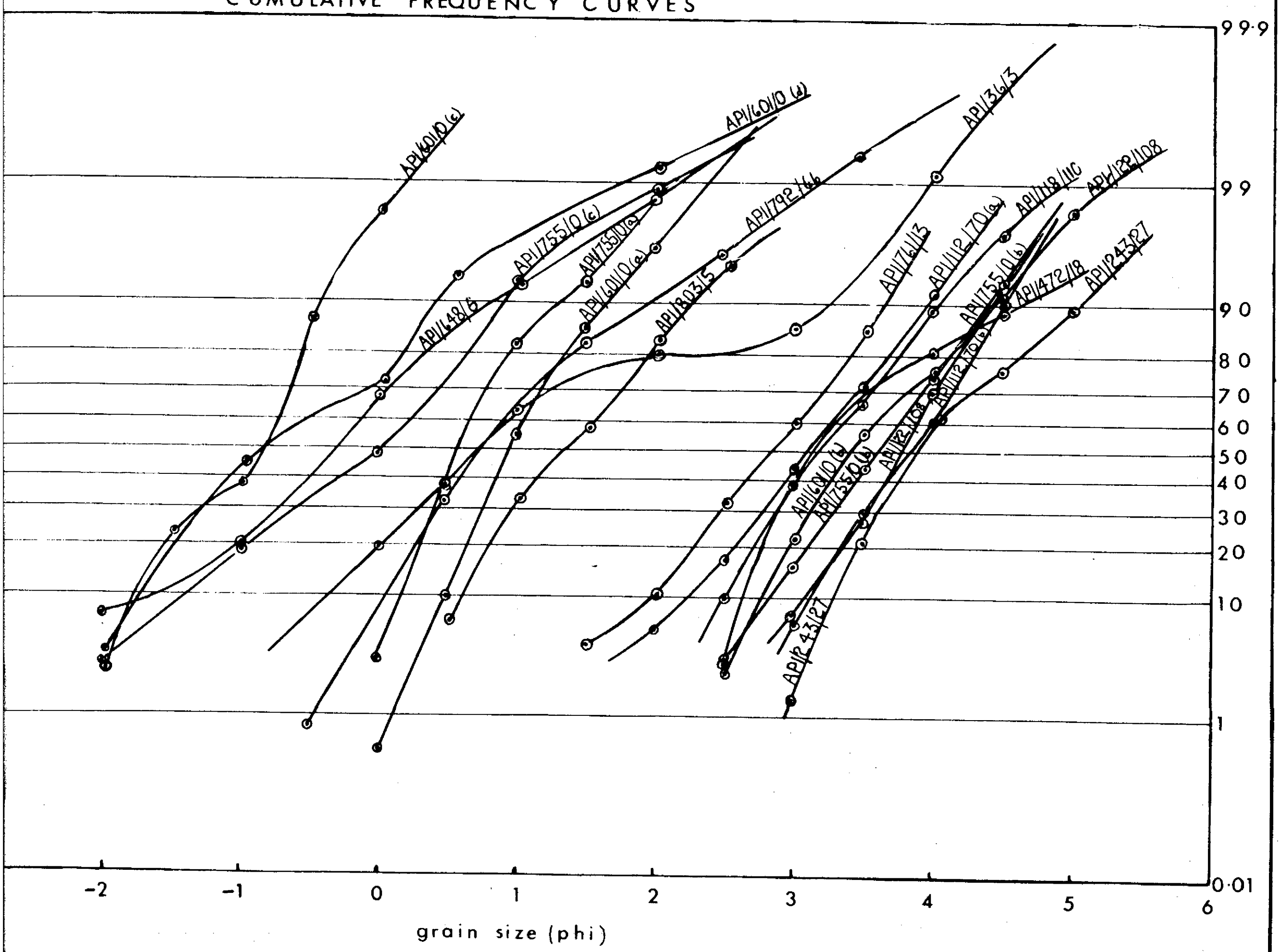
Eighteen detailed textural analyses of 12 thin sections from AP1 were carried out using Packham's (1955) method. The various percentiles ($\emptyset_{95}$, $\emptyset_{84}$, etc.) were obtained and the values for mean diameter (Mz), standard deviation ($d_{\bullet}$), skewness (sk_1) and kurtosis (K_g) 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

Fig 9

CUMULATIVE FREQUENCY CURVES



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

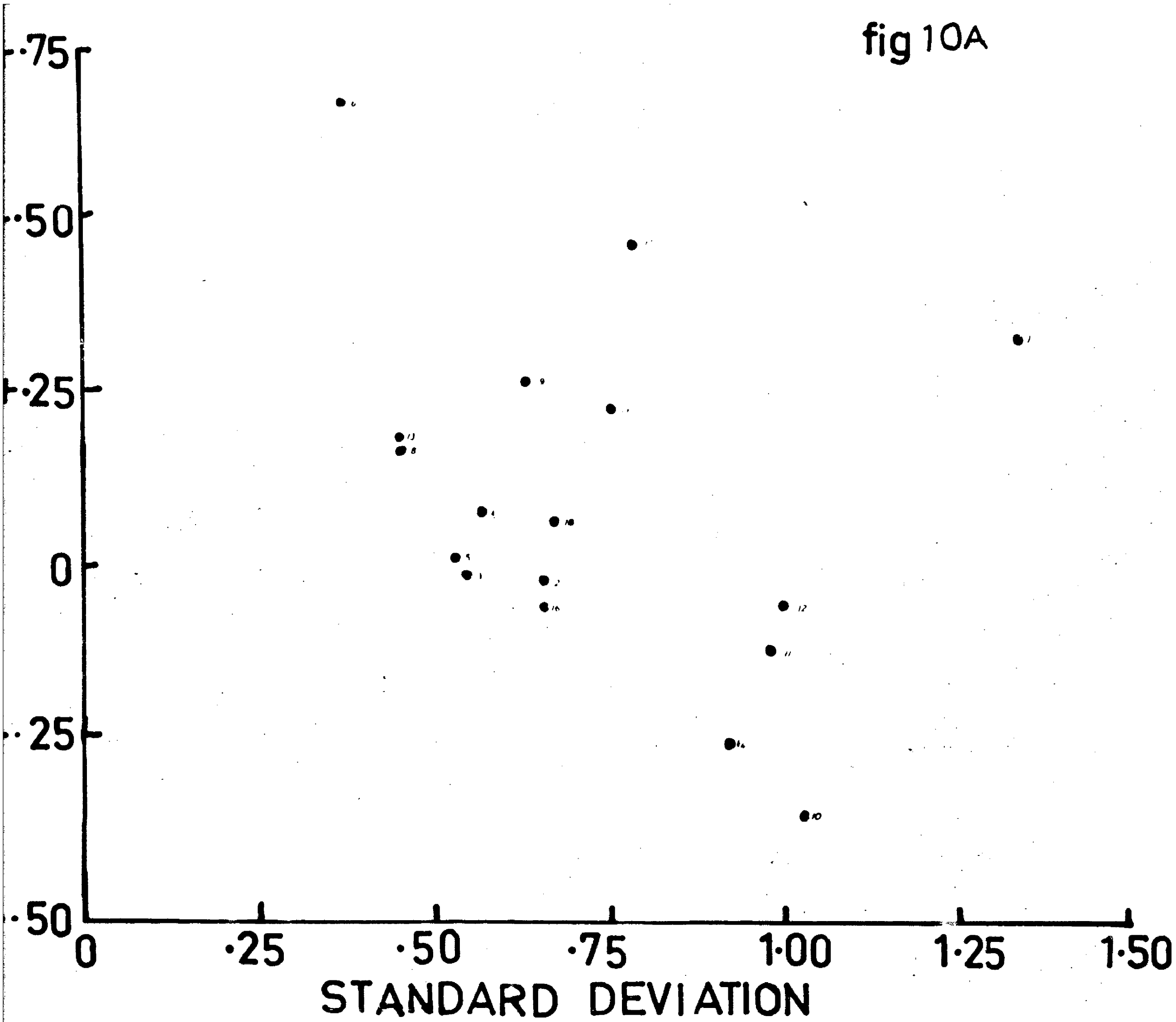


fig 10A
·75
·50
·25
0
·25
·50
0
·25
·50
·75
1·00
1·25
1·50
STANDARD DEVIATION

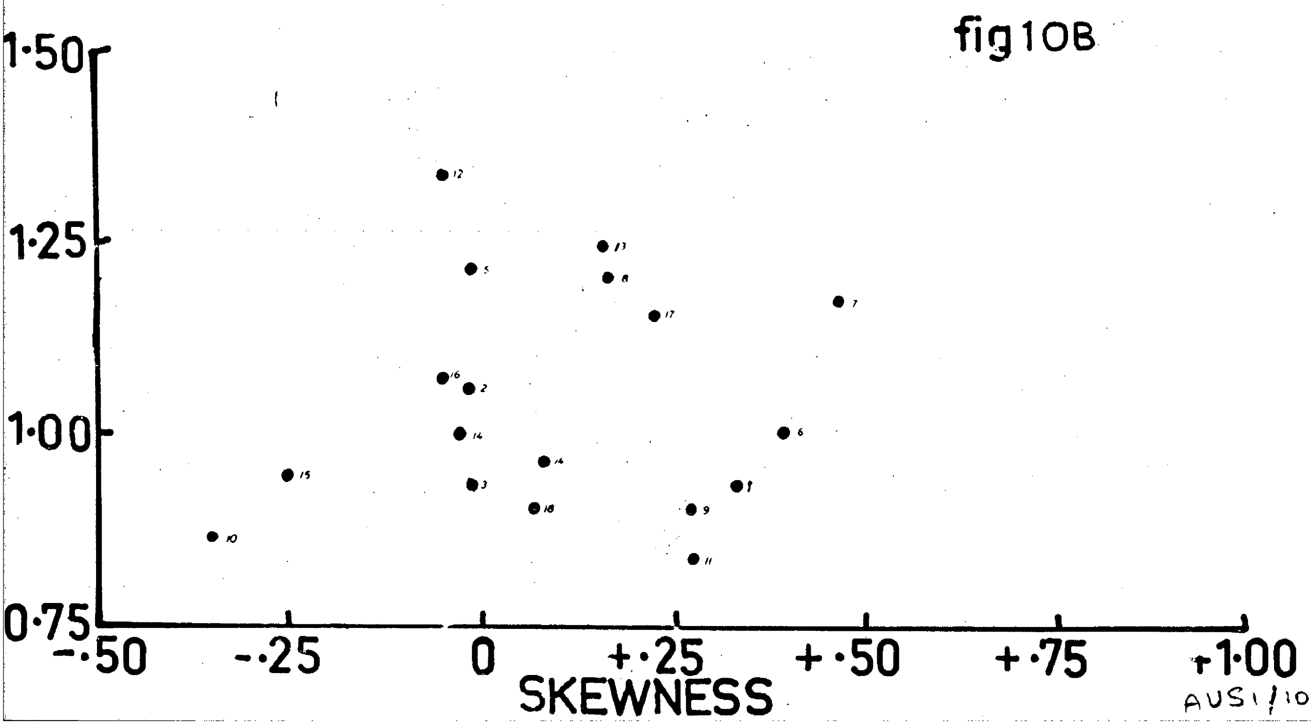


fig 10B
1·50
1·25
1·00
0·75
−·50
−·25
0
+·25
+·50
+·75
+1·00
SKEWNESS

AUS1/101

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.

<u>Determination of environment from the textural parameters</u>

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)* but in neither case can any environmental significance be ascertained. There appears to be no obvious grouping of

* 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 11A

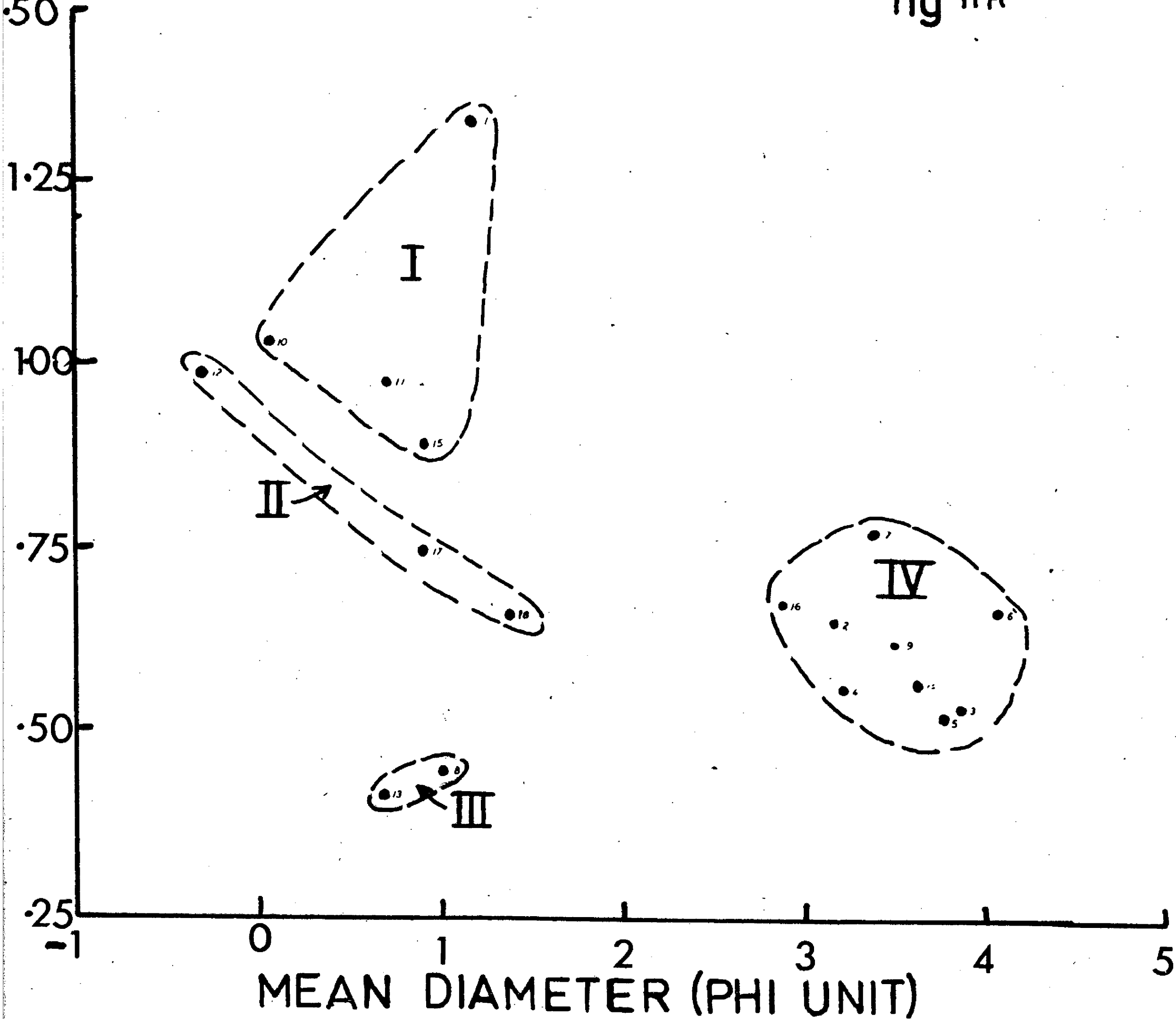
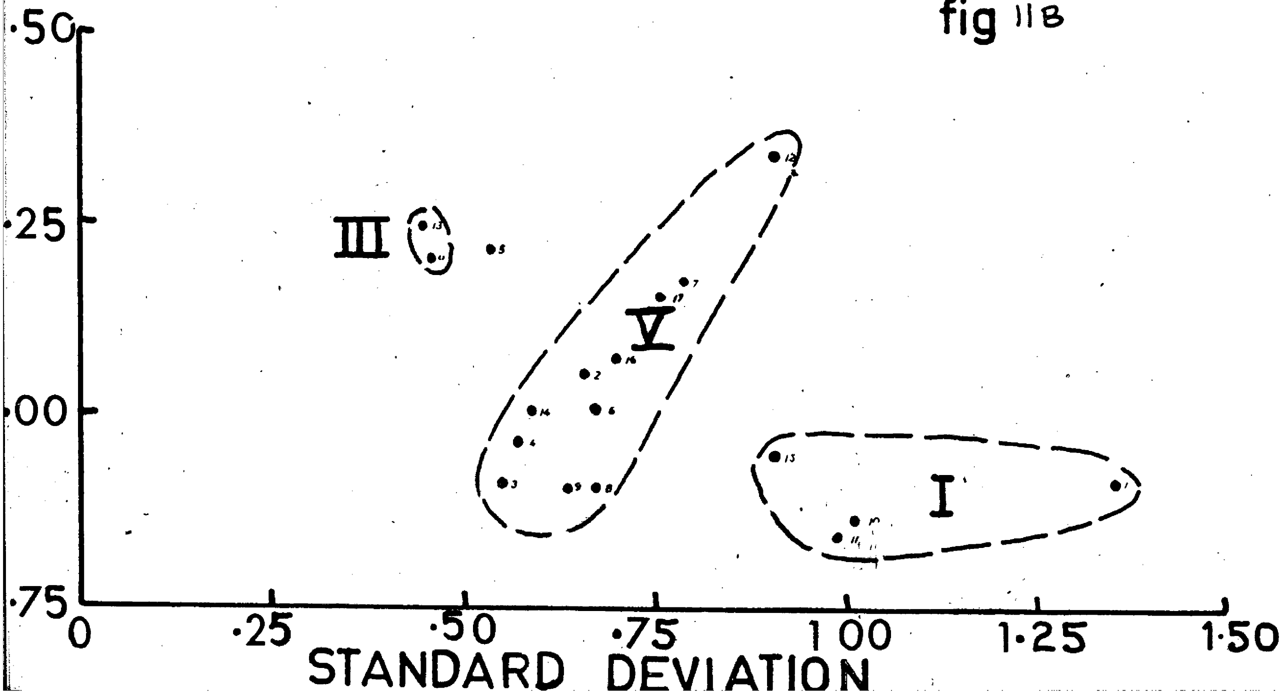


fig 11B



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:-

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

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:-

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

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:-

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

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 the 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.

<u>Summary</u>

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.

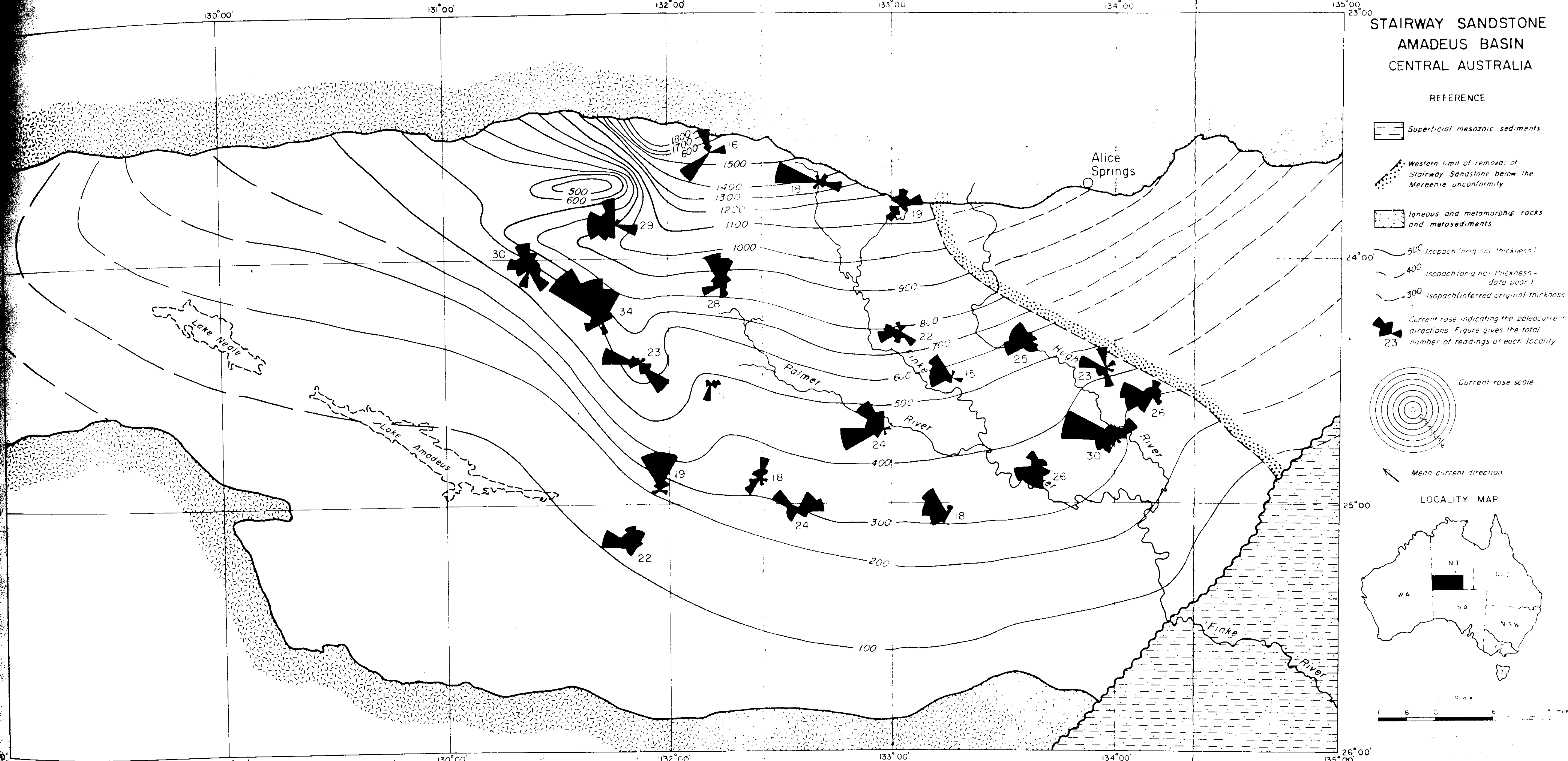
The fine sands of the upper Stairway Sandstone are moderately well sorted, near symmetrical mesokurtic sands. There is no suggestion of any mixing of environments. The most likely environment for the fine sediments is shallow water marine lagoonal or shelf.

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



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.

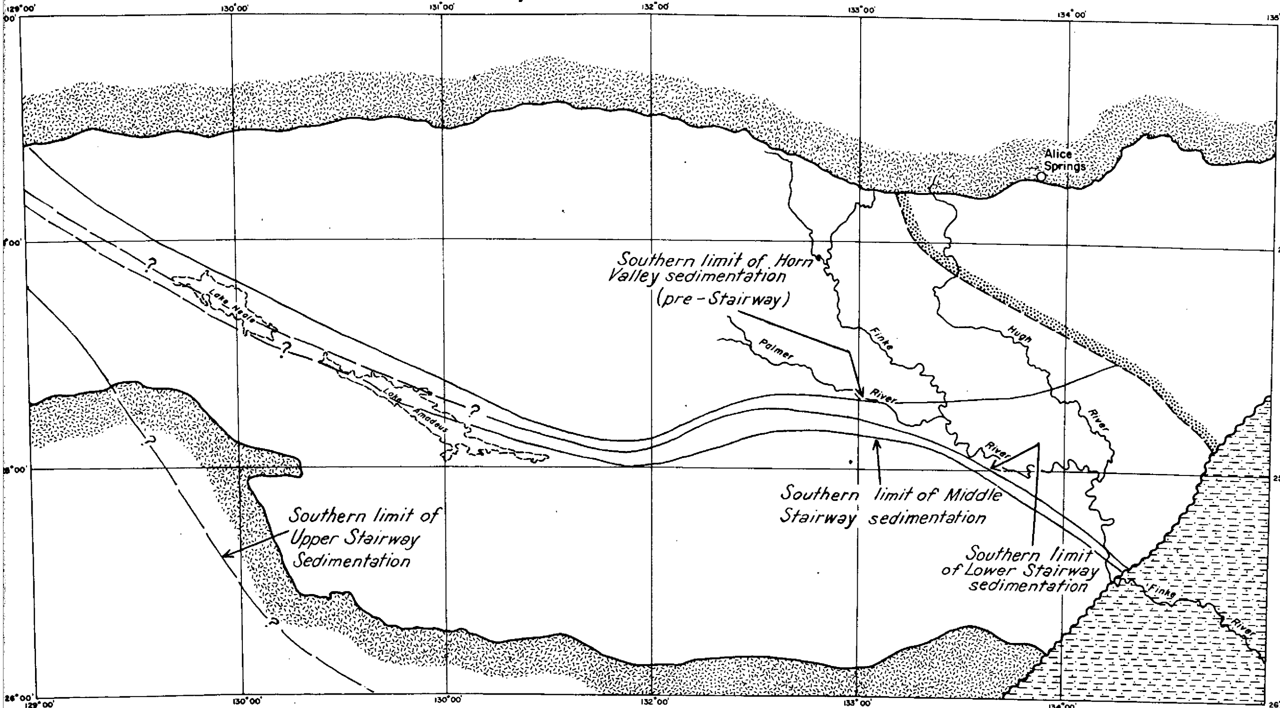
It is impossible to derive the precise form of the Stairway Sandstone palaeoslope directly, but it is a reasonable assumption that the isopachs reflect approximately the palaeoslope. It therefore follows that the deepest Stairway Sandstone seas lie in the northern part of the basin. However, it is not 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

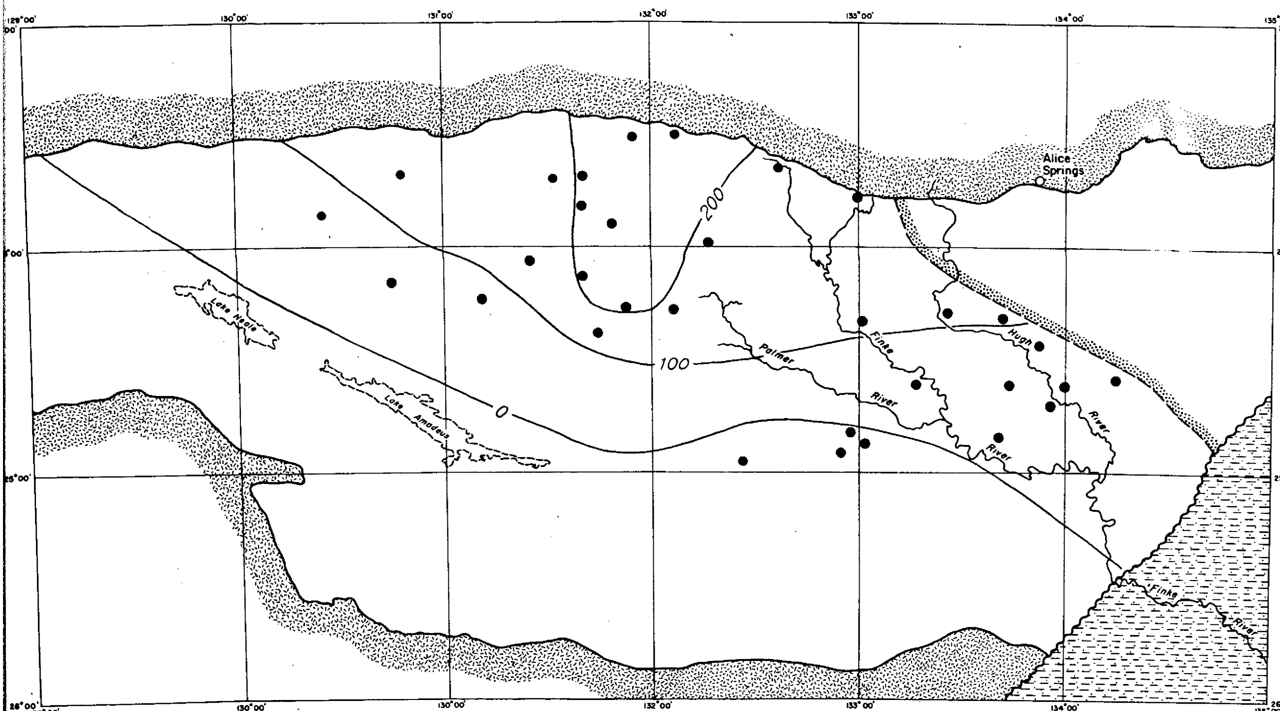
Fig. 13

A

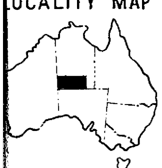


Isopachous map— Lower Stairway Sandstone

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

100 Isopach- thickness in feet

• Locality with measured thickness

To accompany Records 1966/1

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.

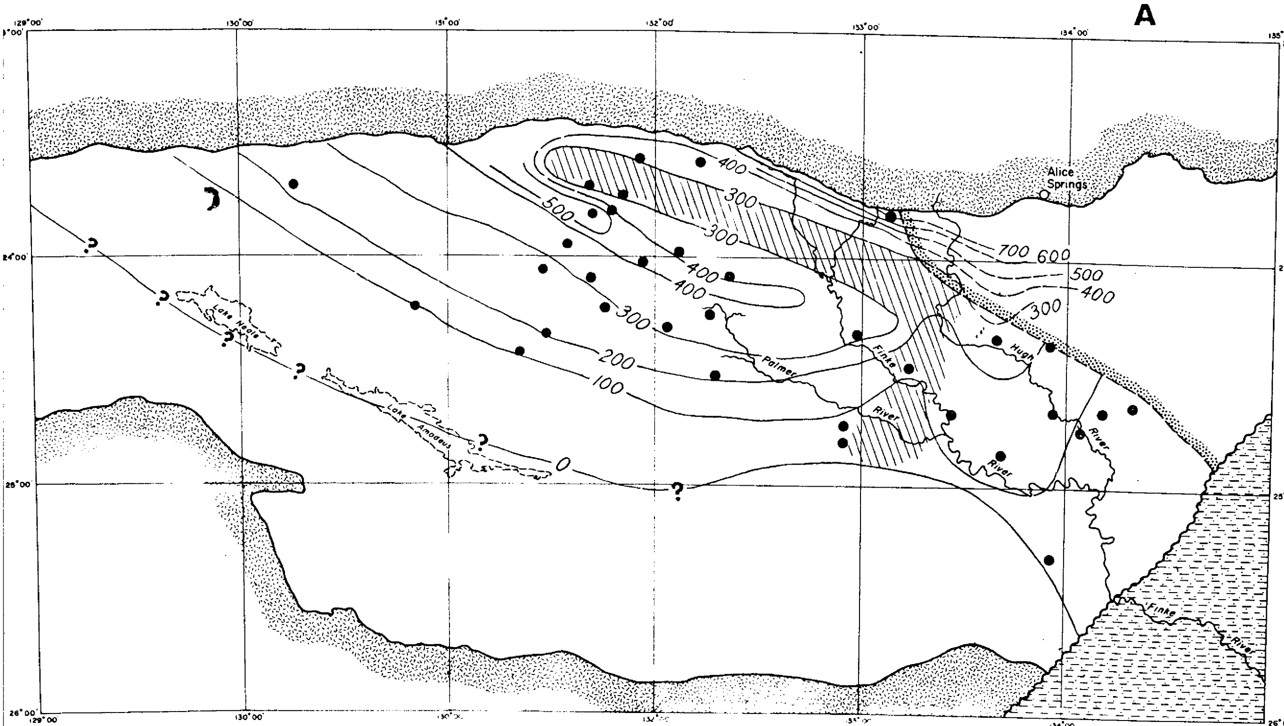
It is apparent from the lower Stairway isopachous map (Fig.13B) that following the deposition of the Horn Valley Siltstone, a large shallow embayment formed in the south-east part of the basin. The extremely uniform thicknesses of the lower Stairway suggests that the palaeoslope was probably extremely 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

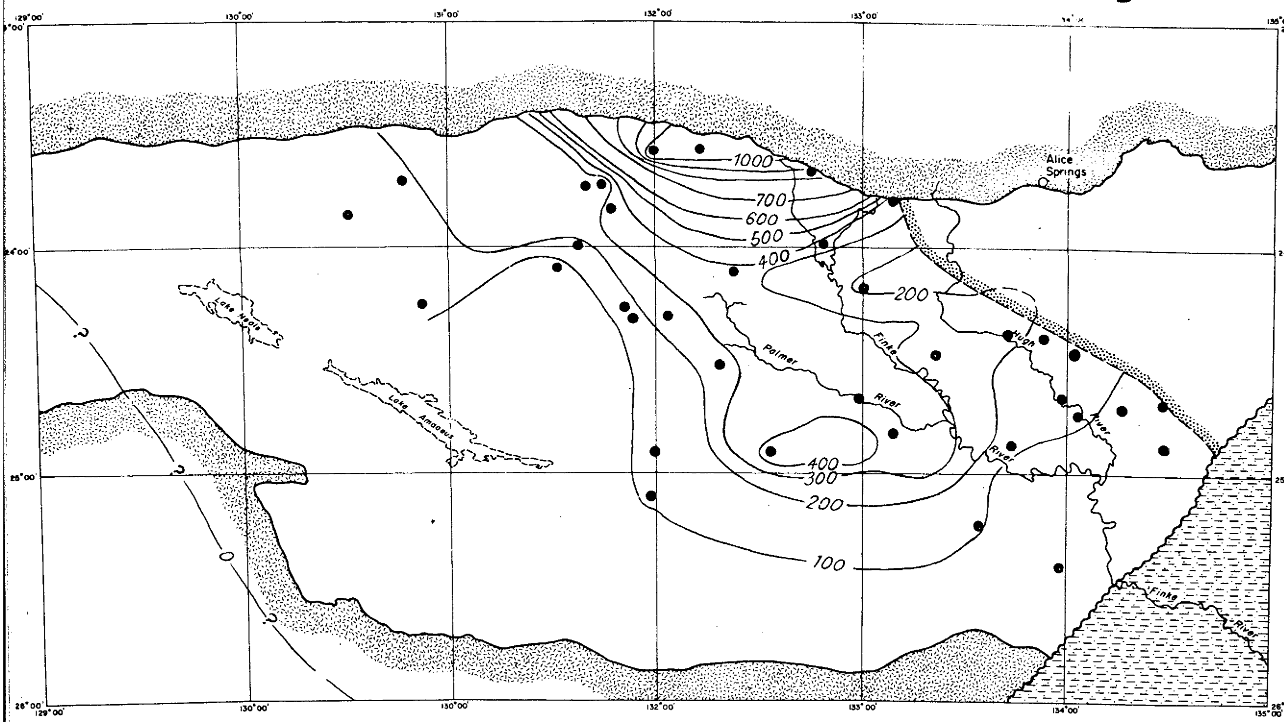
Fig. 14

A



Isopachous map — Upper Stairway Sandstone

B



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

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.

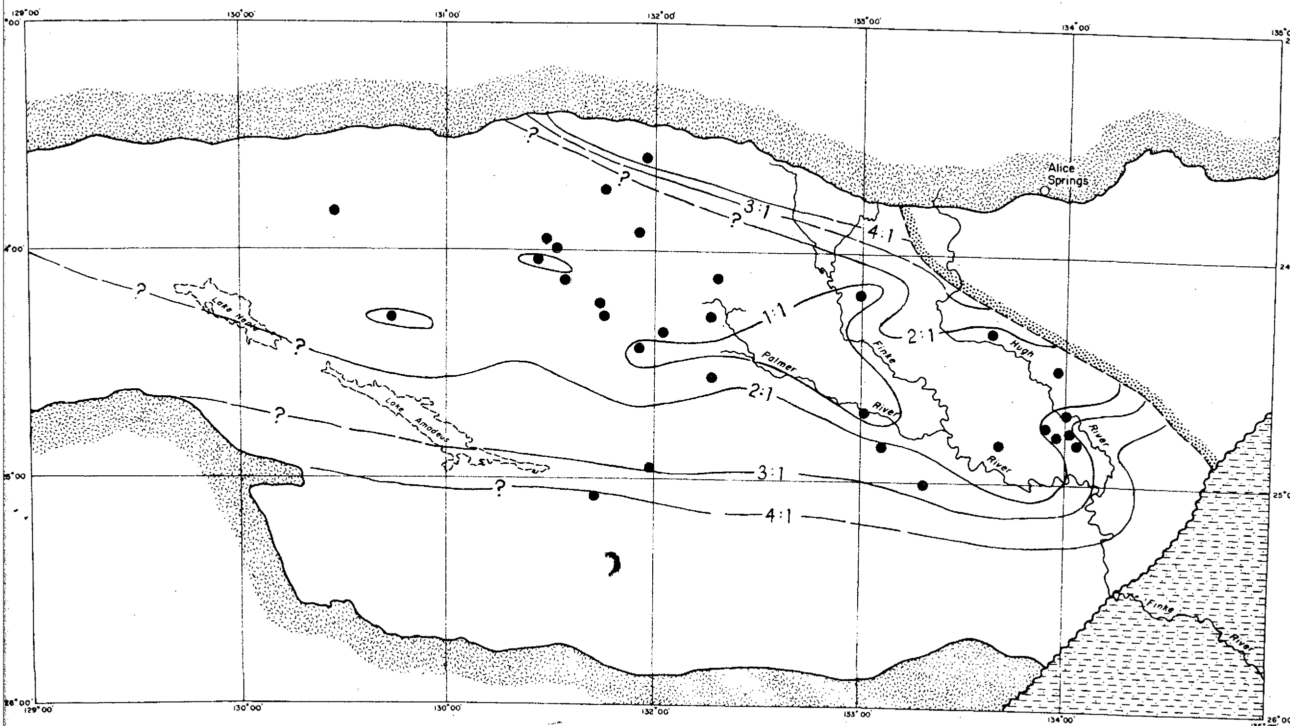
The upper Stairway isopachous map (Fig.14B) shows little relationshop to that of the Middle Stairway. The sub-basin in the southern part of the Amadeus Basin has been delineated from only a few known thicknesses and in addition the stratigraphy in parts of the southern margin of the basin (the Mount 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

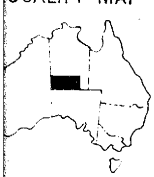
The paucity of outcrop prevents anything more than a very approximate lithofacies map being drawn up for the whole of the Stairway Sandstone (Fig.15). To some extent this gives a false impression of Stairway Sandstone sedimentation for the map suggests that the present northern margin of the Amadeus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

LITHOFACIES MAP – STAIRWAY SANDSTONE
Sand shale ratio

Fig. 15



LOCALITY MAP



SCALE

16 8 0 16 32 48

MILES

Reference

Superficial mesozoic sediments

Wester... ...mit of removal of Stairway Sandstone below the Mereenie unconformity

Igneous and metamorphic rocks and metasediments

2:1 *Isopleth - showing the sand : shale ratio*

● *Locality with measured thickness*

To accompany Records 1966/1

AUS 1/106

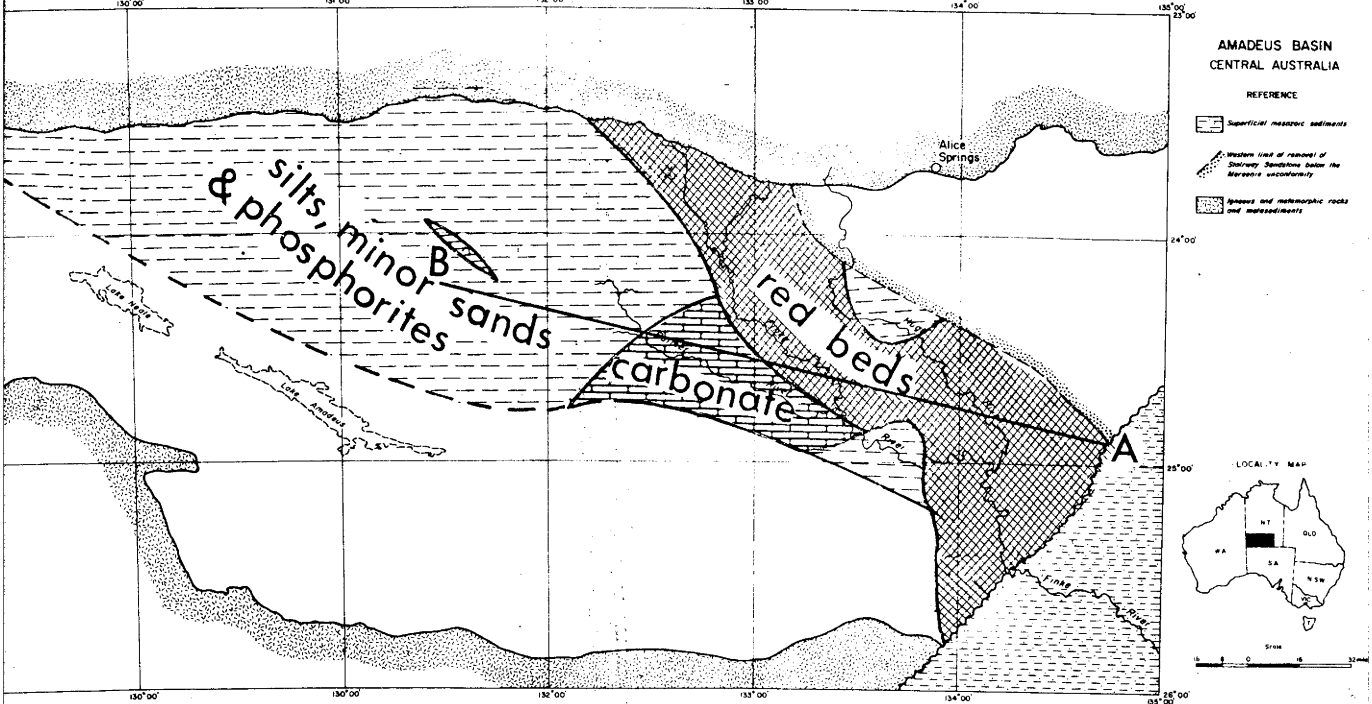
Ordovician margin. This has been shown not to be the case (see Figs.13-14). The high sand:shale[*] ratios in the northern part of the basin are entirely due to the considerable thickening of the upper Stairway Sandstone to the north. The high sand:shale ratios on the southern margin are mainly a reflection 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.

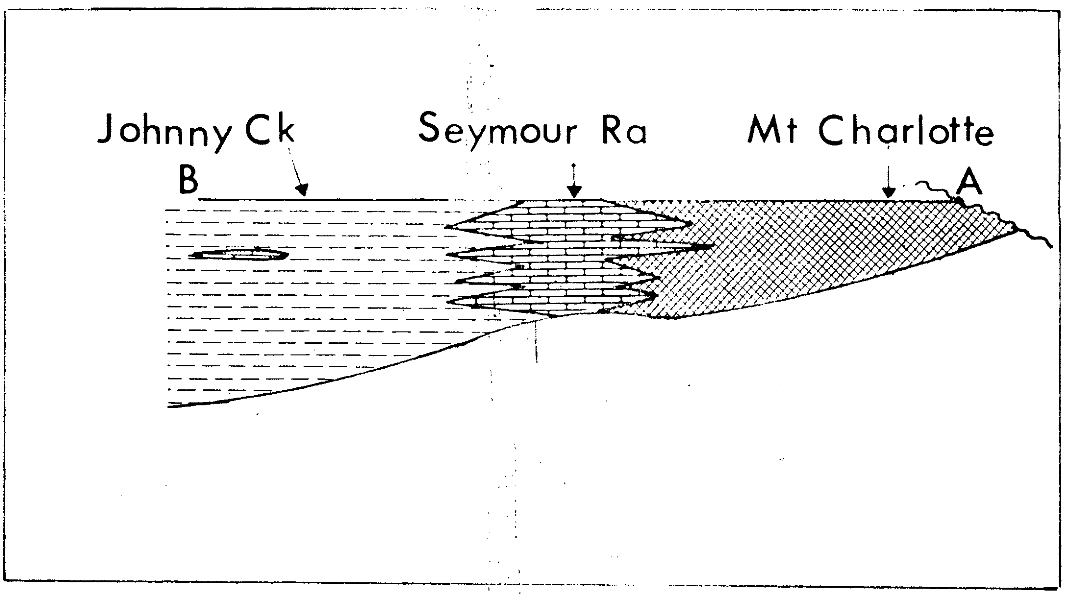
A very much more valuable picture would be obtained by drawing up lithofacies maps (both sand:shale and clastic to non-clastic) for the lower, middle and upper Stairway Sandstone, but this is at present impossible because of the lack of data. Superficial examination of the lithofacies picture in these 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).

* 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

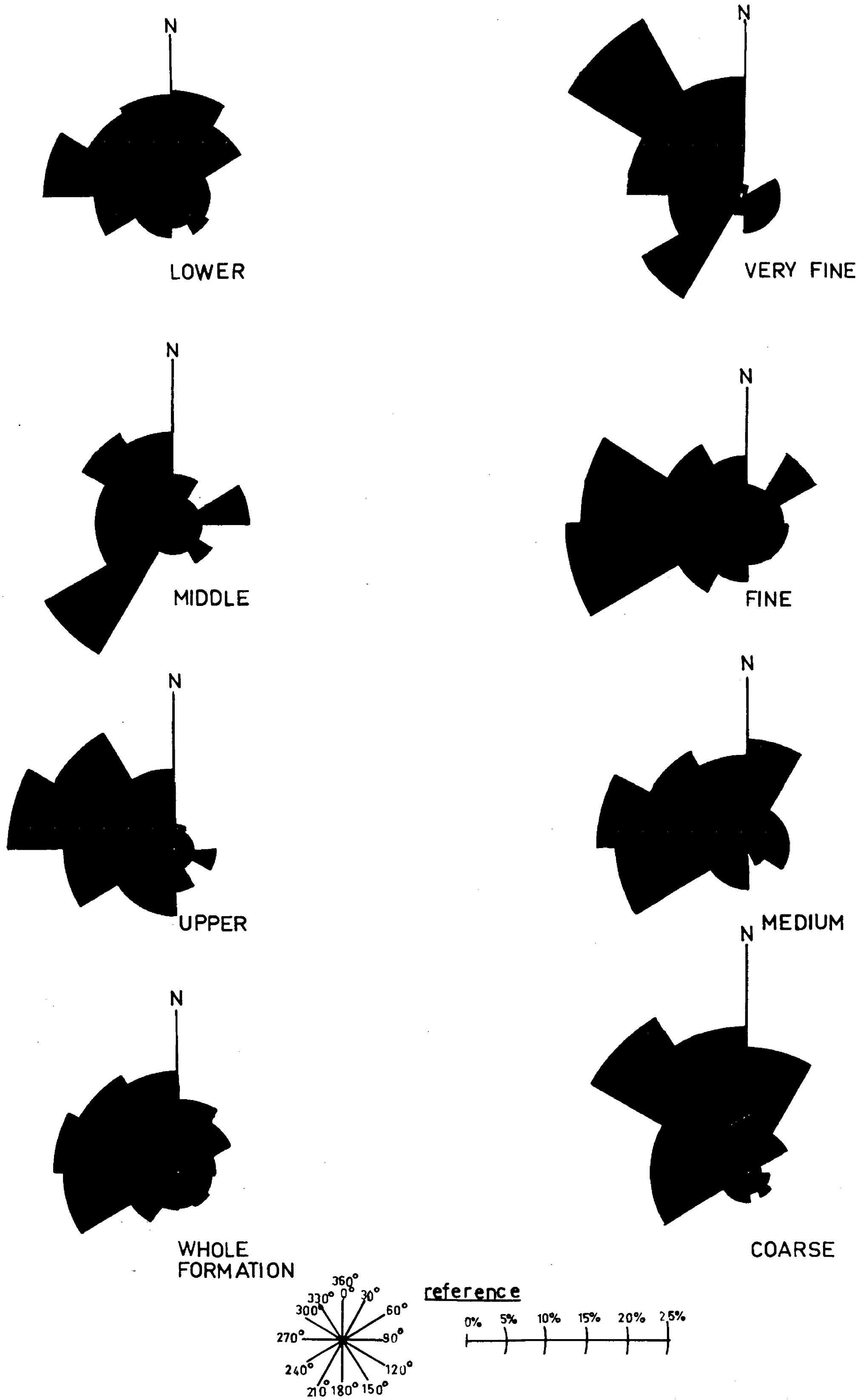
With the exception of the coarse sands in the lower Stairway Sandstone, cross-beds are both fairly rare and poorly developed. Therefore it is only possible to draw up a palaeocurrent map for the Stairway Sandstone as a whole.

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



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.

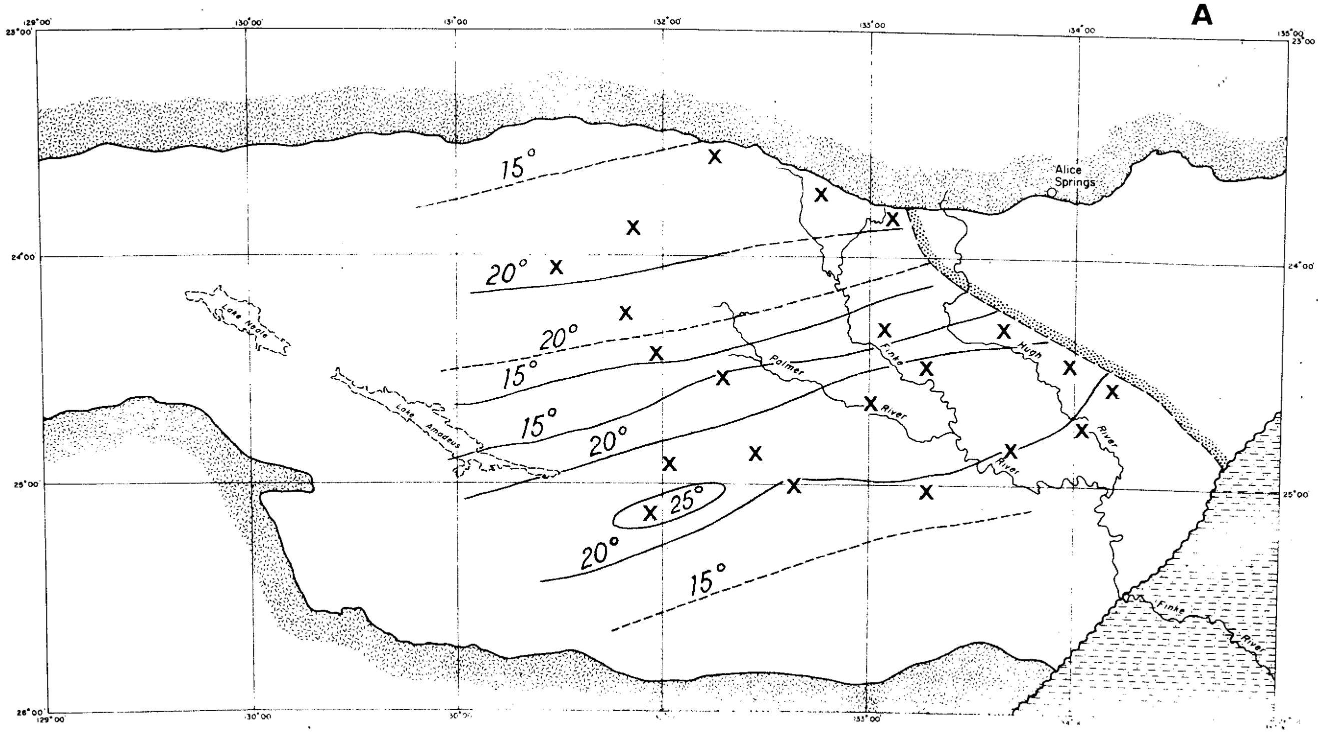
The question of whether there is any variation of angle of inclination with grain size was not investigated. When an iso-angle* map is drawn up (Fig.18A) an interesting though puzzling pattern emerges in which there are three low angle zones (less than 20°) and two intervening high angle zones (greater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

* 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

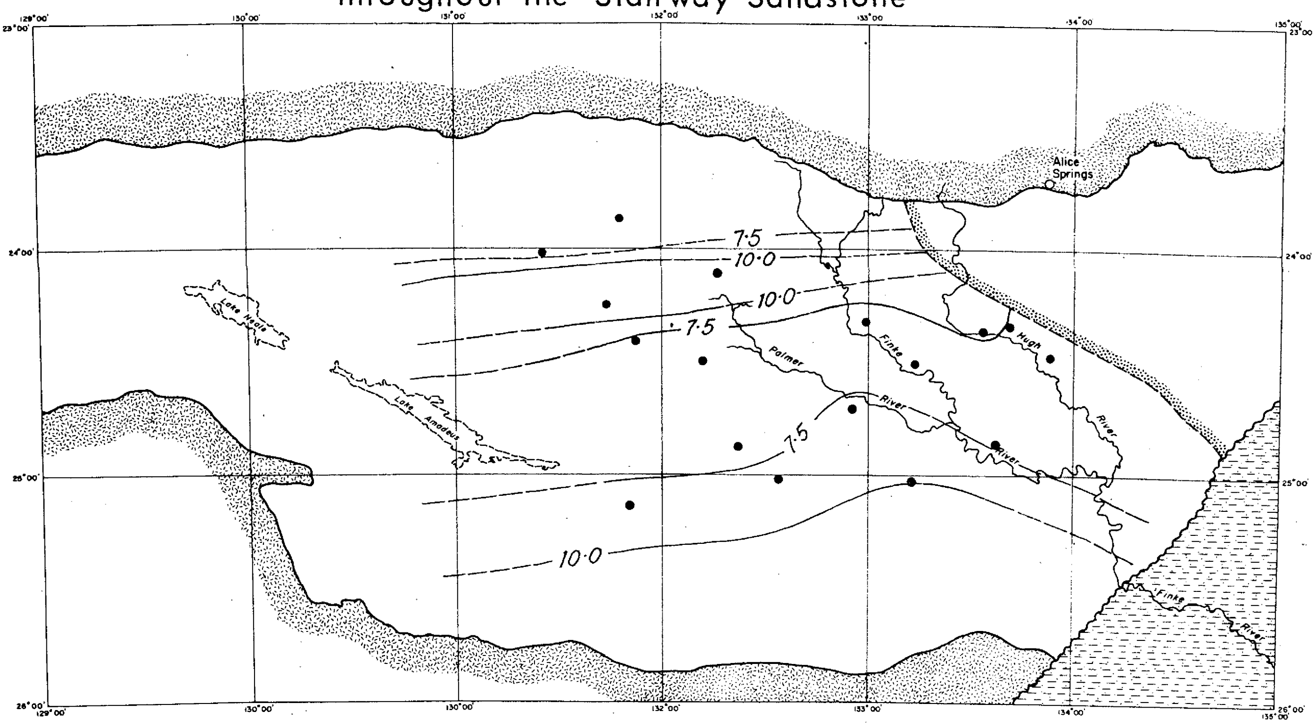
Fig.18

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

Western limit of removal of Stairway Sandstone below the Mereenie unconformity

Igneous and metamorphic rocks and metasediments

15° *Iso-dip – dip of cross-bed in degrees*

X *Locality with measured cross-bed dip*

7·5 *Iso set – thickness of cross-bed set in inches*

• *Locality with measured thickness*

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* 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

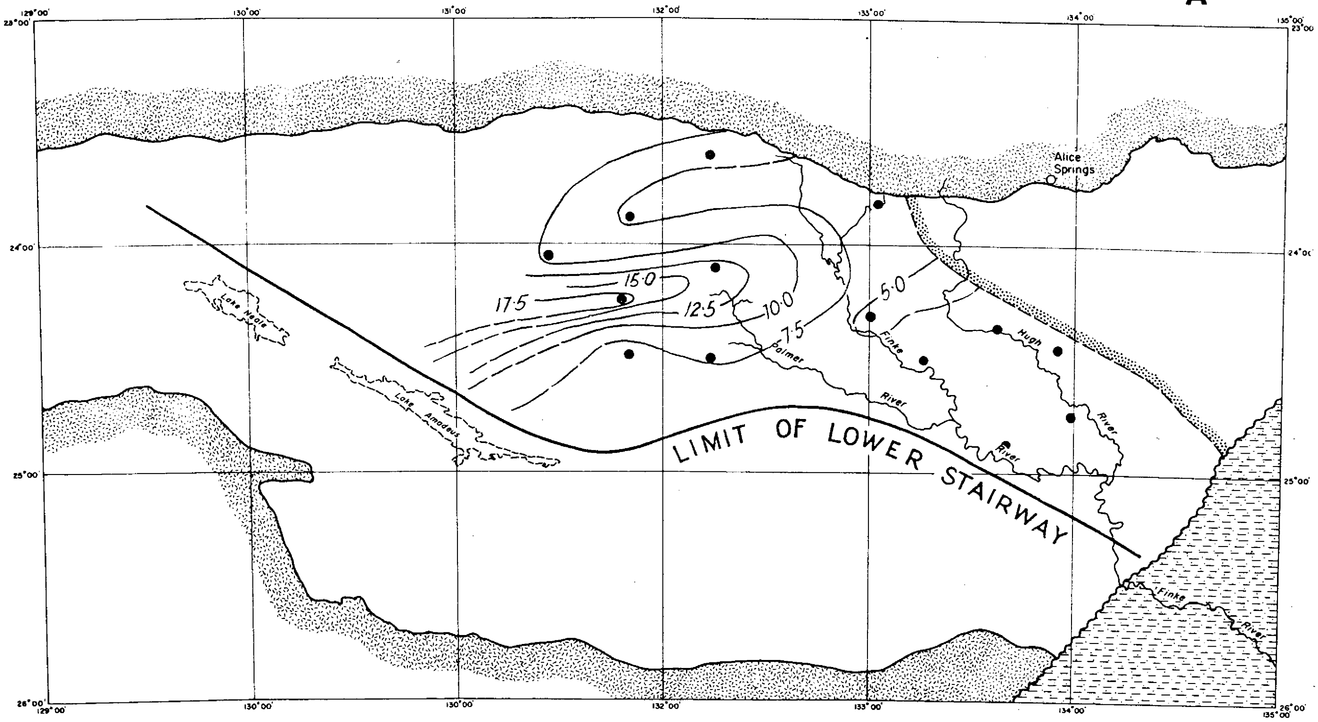
* Isosets are lines joining points with the same thickness of cross-bed set

ISO SET MAPS—STAIRWAY SANDSTONE

Fig. 19

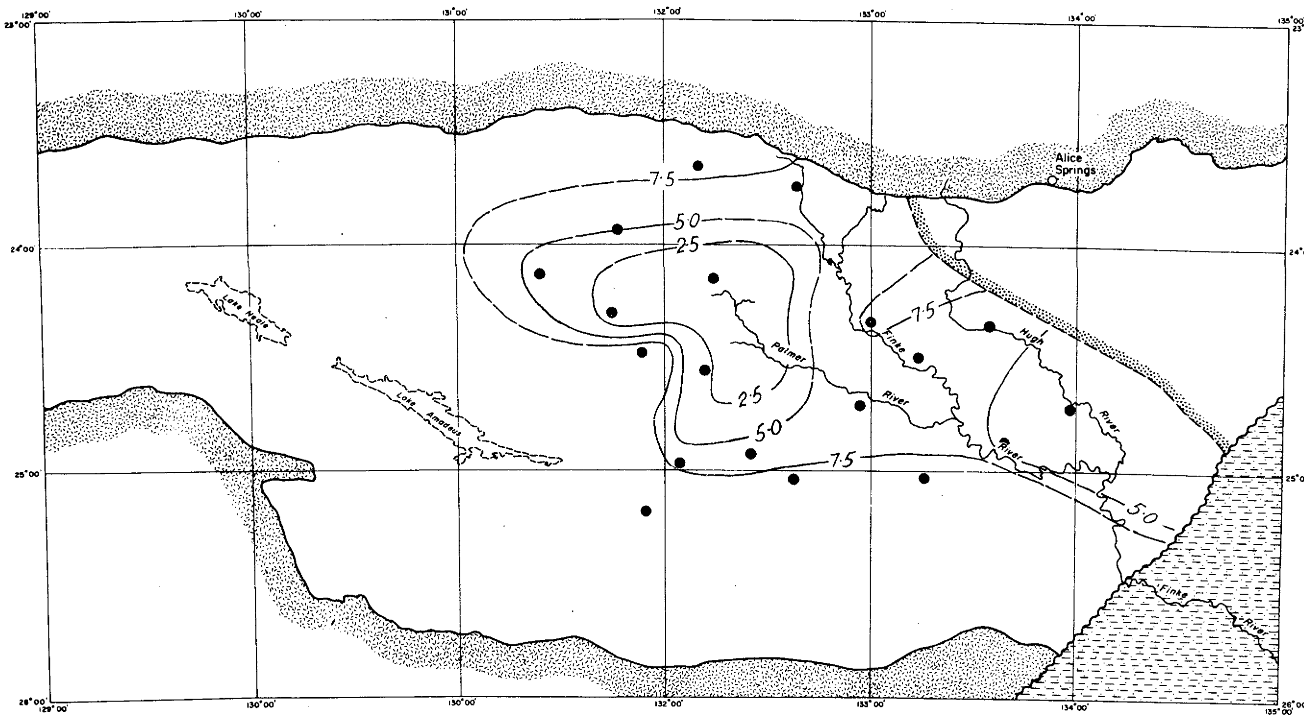
Cross—beds in the lower unit

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
- 5·0 Isoset - thickness of cross-bed set in inchess
- ● Locality with measured thickness

To accompany Records 1966/1

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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.

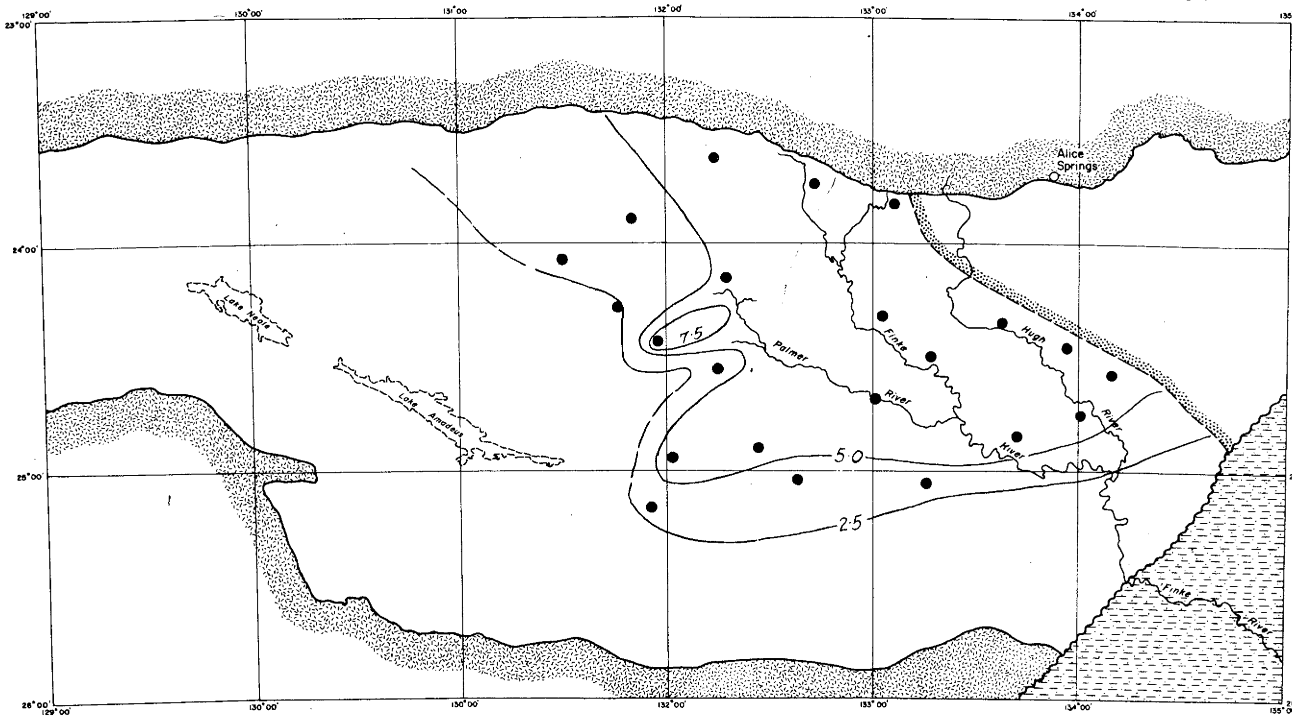
When isosets are plotted for particular grain sizes there is somewhat less regional variation (Fig.20) suggesting that set thicknesses are in part dependent on grain size (or on the current velocity, which in turn influences the grain size). There are however a variety of other factors such as the duration 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

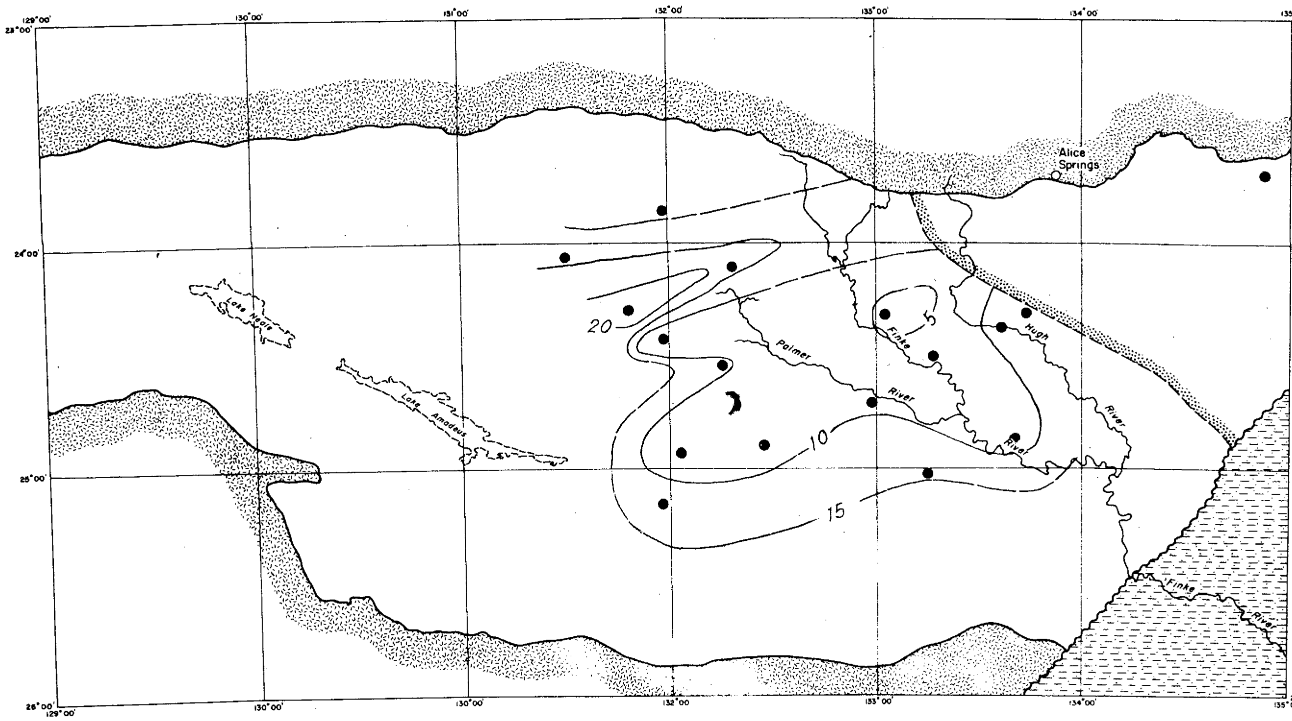
Cross beds in fine and very fine grained sandstone

A



Cross beds in coarse and very coarse grained 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

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).

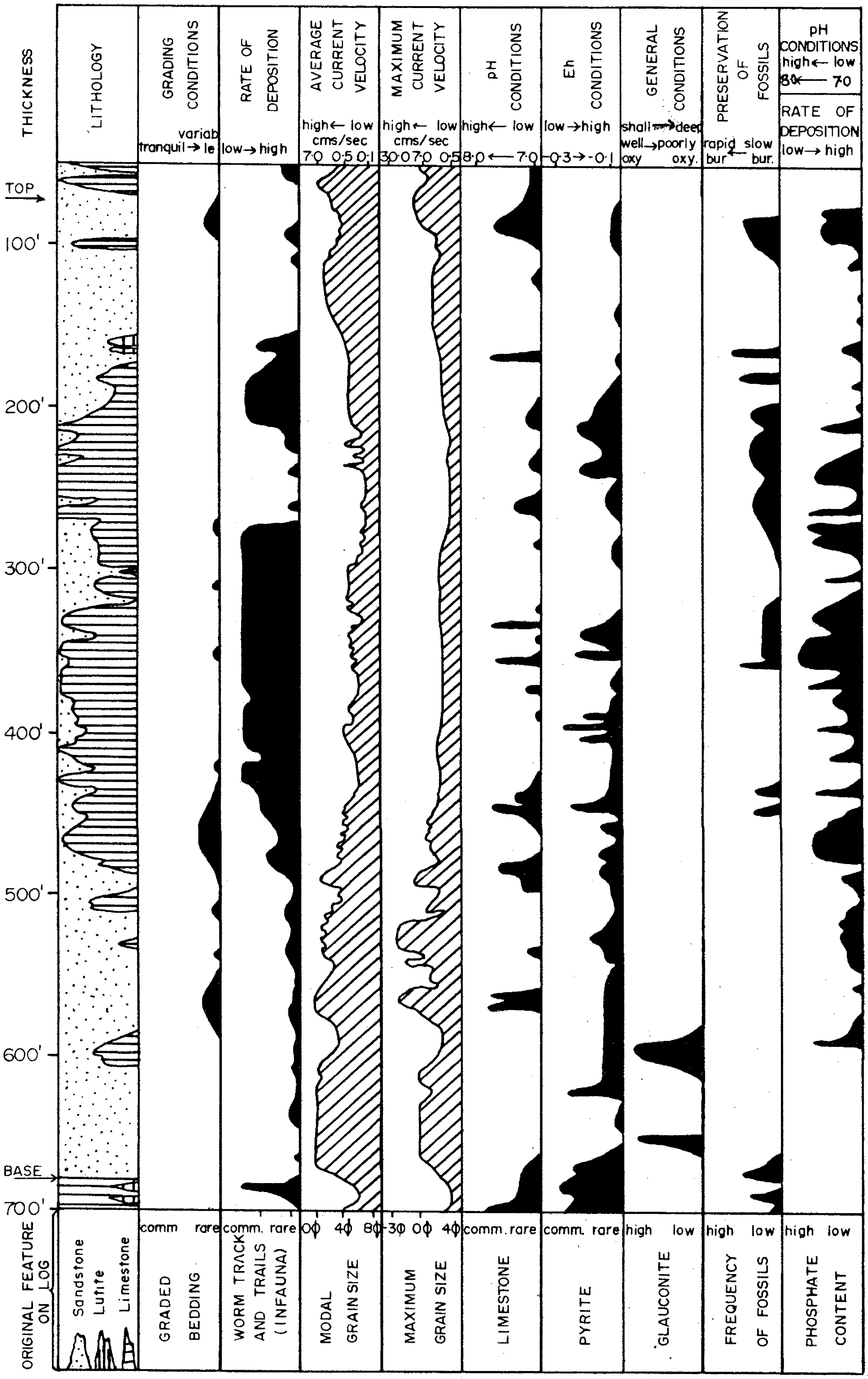
Physical Conditions

(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 interpretion 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



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.

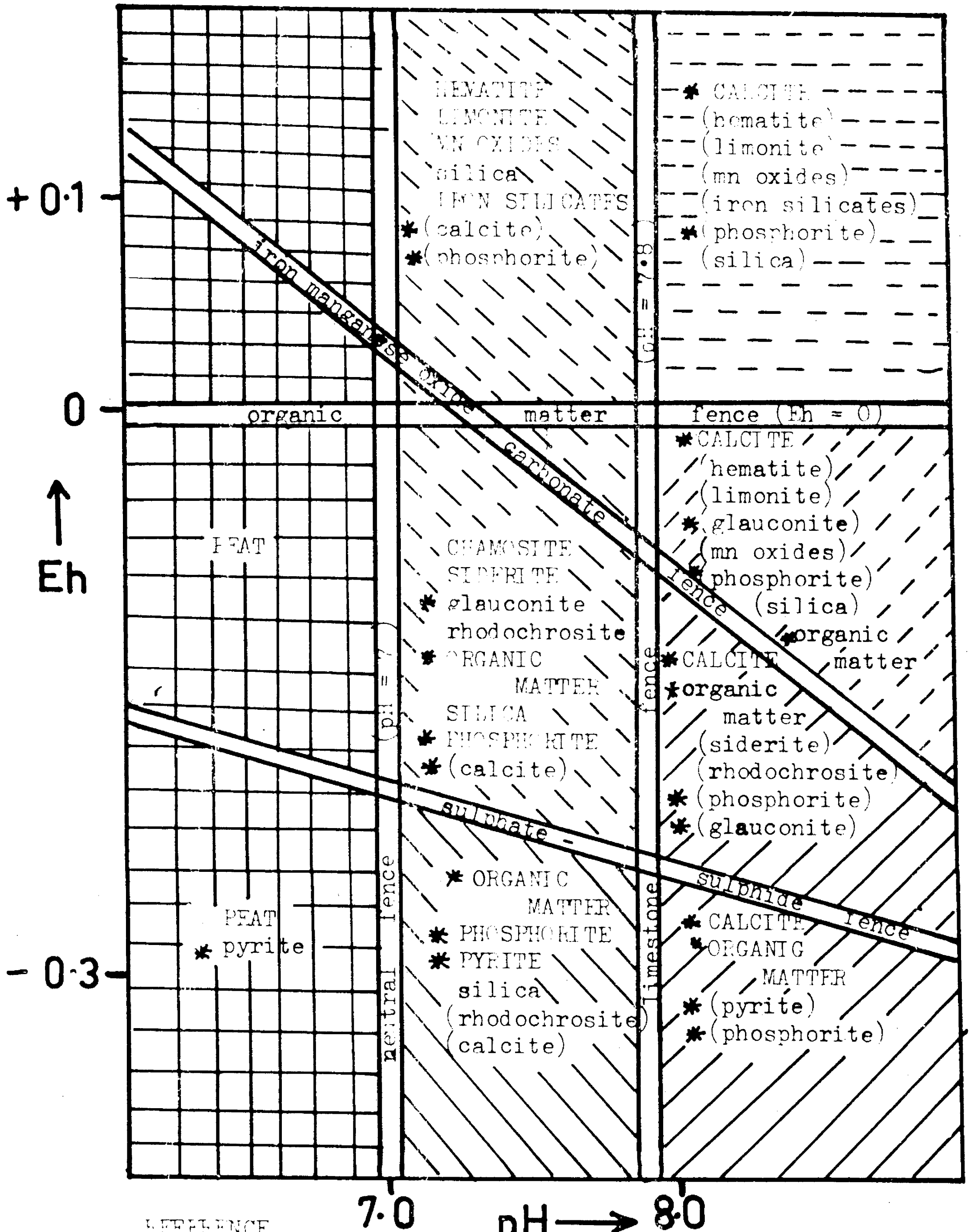
Kazakov (1937) has suggested that phosphorites form between depths of 50 and 200 metres but McKelvey, et al. (1959) have suggested the depth range is 200-1000 metres. It is probable that much of the Stairway Sandstone was deposited in depths similar to those suggested by Kazakov (1937) rather than those 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°N to 30°S. Within this zone the water temperatures in shallow marine seas range from fairly warm to very warm (about 75°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}.

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 p^H 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.

Summary

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

Lower Stairway Conditions

(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.

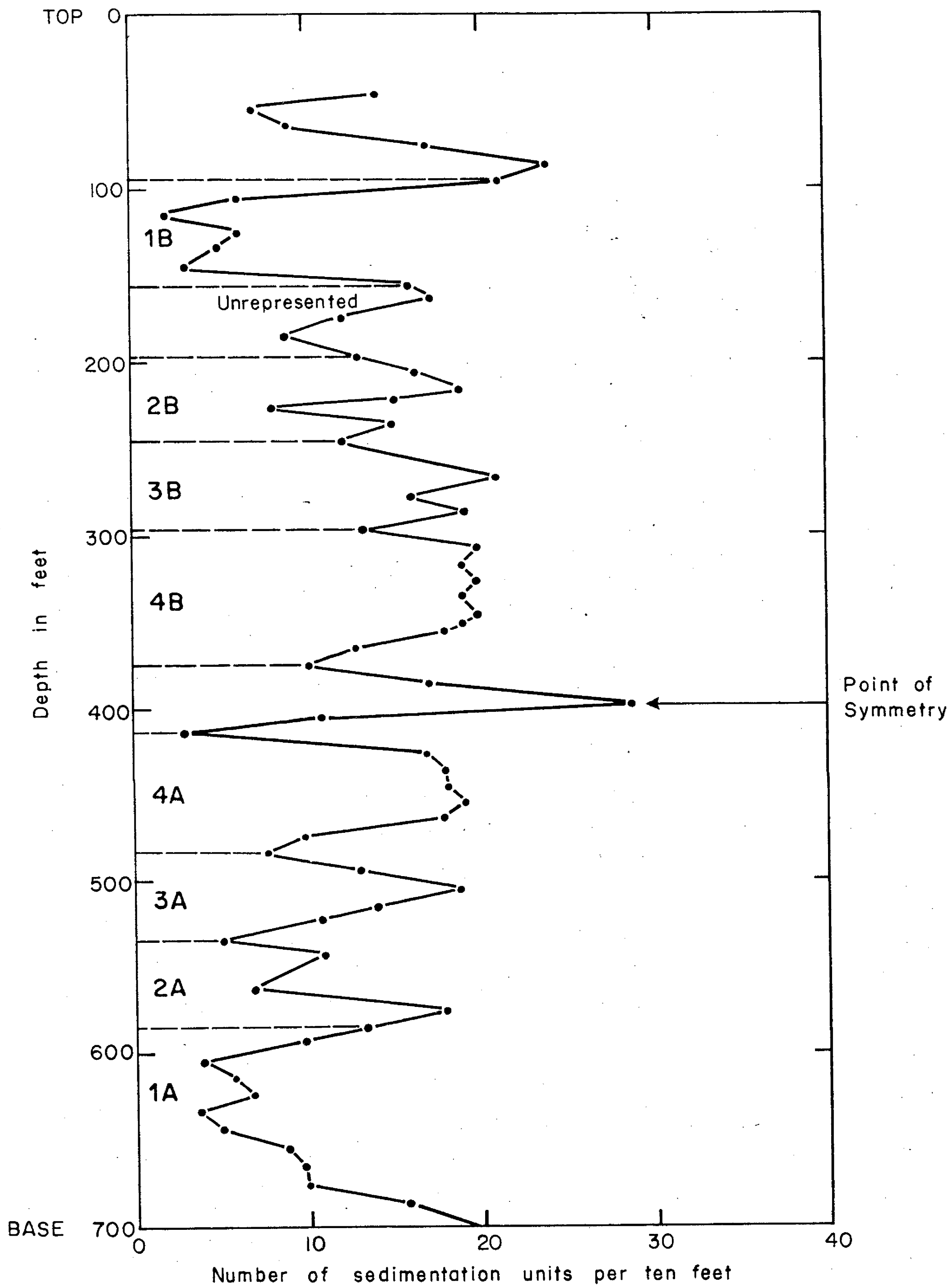
(d) Sandy clays low in silts are common in lagoons but rare in the shallow shelf environment.

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

Vertical variation in the number of sedimentation units



sedimentary picture in the Stairway Sandstone before reconstructing the specific environment.

Transgression or Regression?

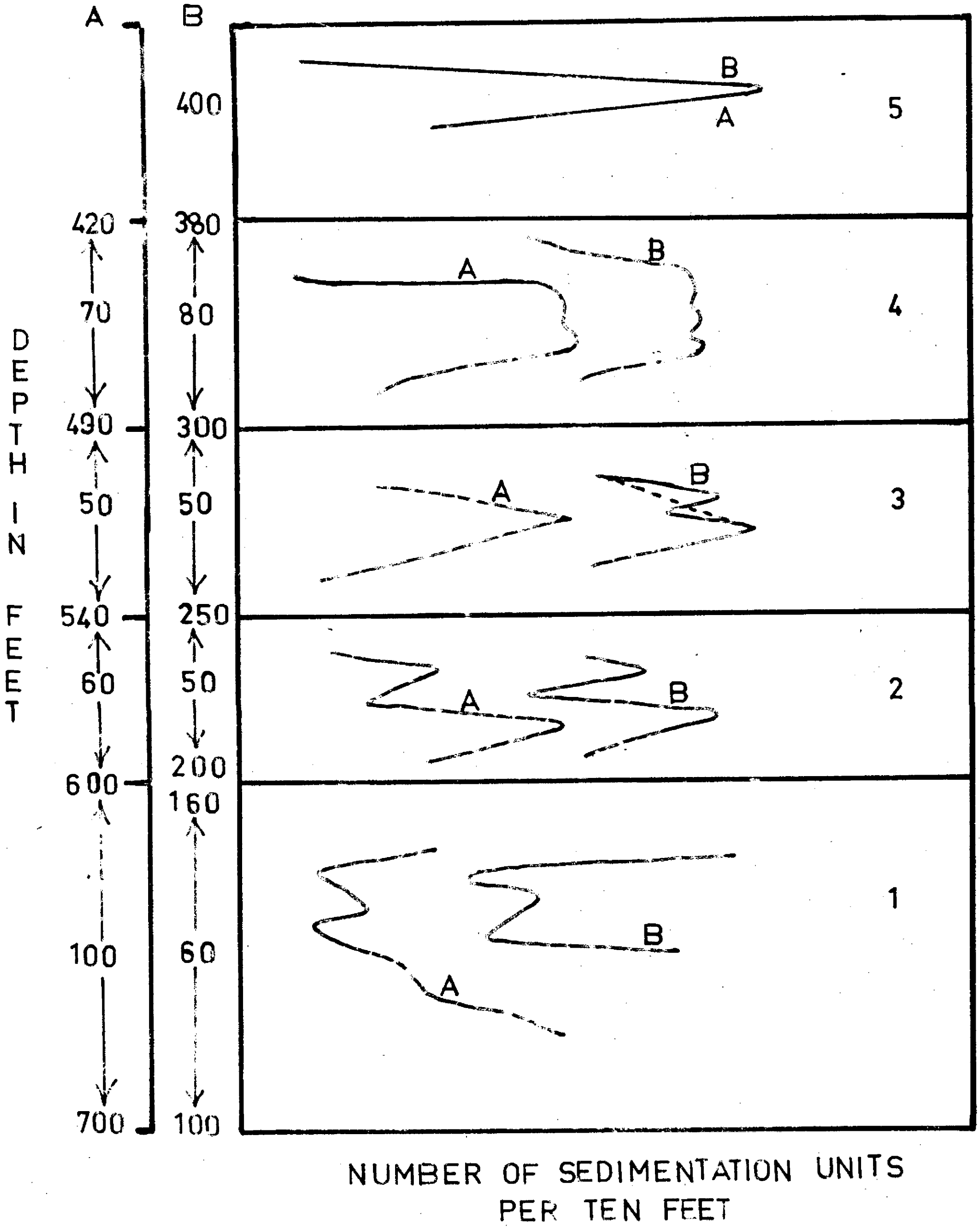
Evidence of some kind of repeated sequence is immediately apparent in the Stairway Sandstone, with the upper body of sand bearing a strong resemblance to the lower sand.

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 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.

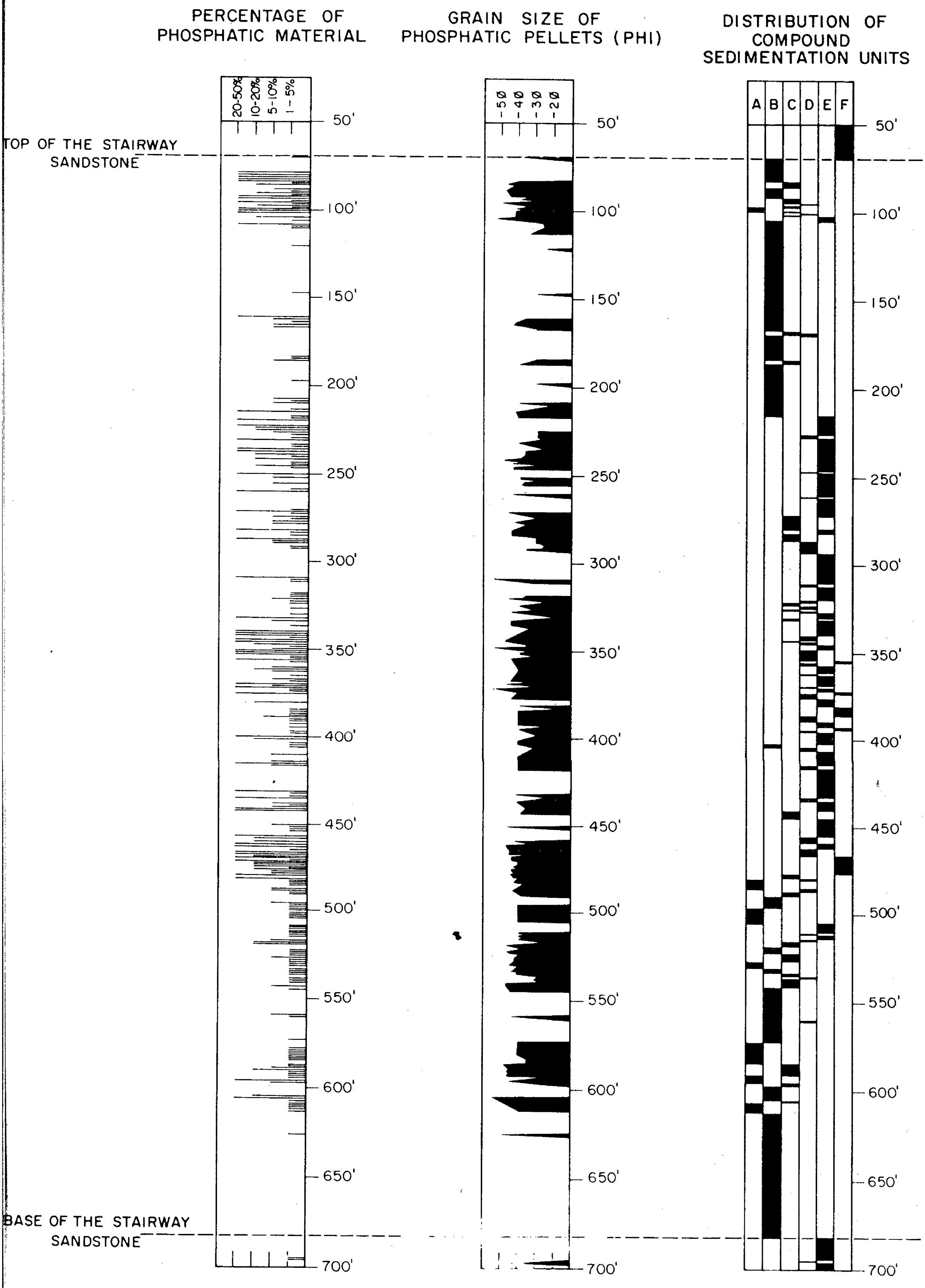
<u>The Sedimentation Unit</u>

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

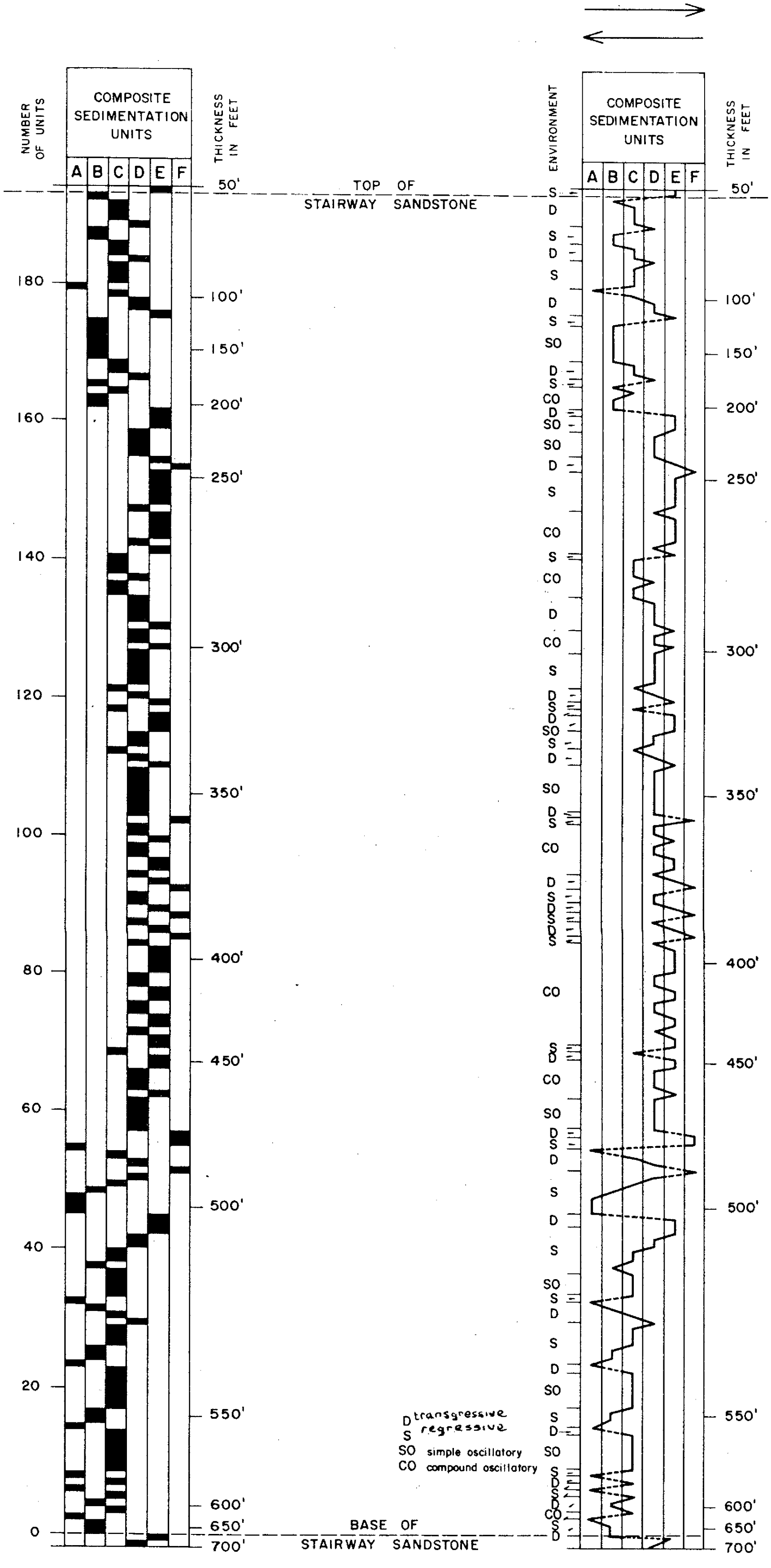


all the other sedimentological data it is possible to set up six basic types of composite sedimentation units (A - F). The average sedimentological characteristics of each of these six units are summarized in Table 10 (Appendix) and in Fig.27. The order of the sedimentation units is established mainly 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 1Ø whereas the average modal grain size of unit B in the upper Stairway is 3Ø to 4Ø. 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

VERTICAL DISTRIBUTION OF COMPOSITE SEDIMENTATION UNITS AND THE ENVIRONMENT OF DEPOSITION



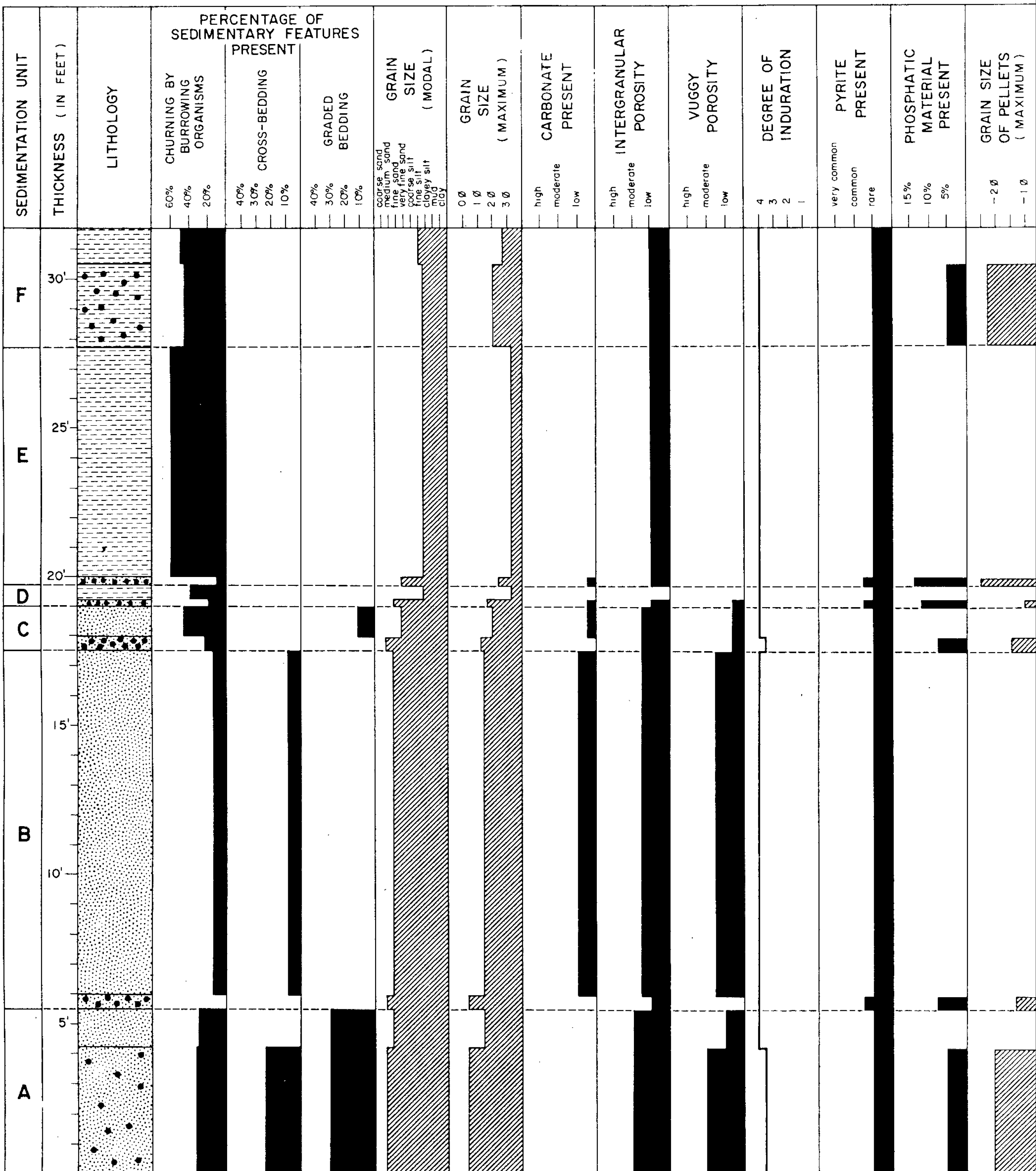
is shown in Fig.26. Each sedimentation unit is represented by unit thickness, i.e. the vertical scale is not a linear foot scale (although footages are shown), because the thickness of the composite sedimentation unit is inherent in the type of unit. The actual form of the cyclicity is now apparent and 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



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

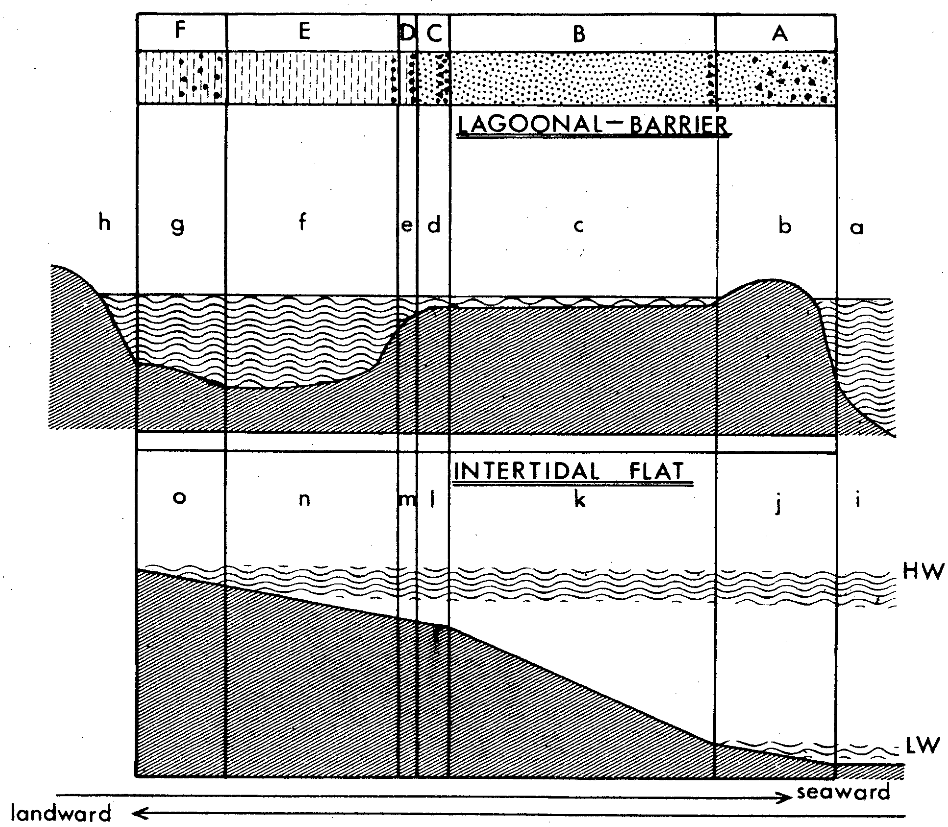
E = Central bay (mixed sediments)

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 fig28

COMPARISON OF THE COMPOUND SEDIMENTATION UNIT WITH MODERN ENVIRONMENTS



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 environment 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 normal 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).

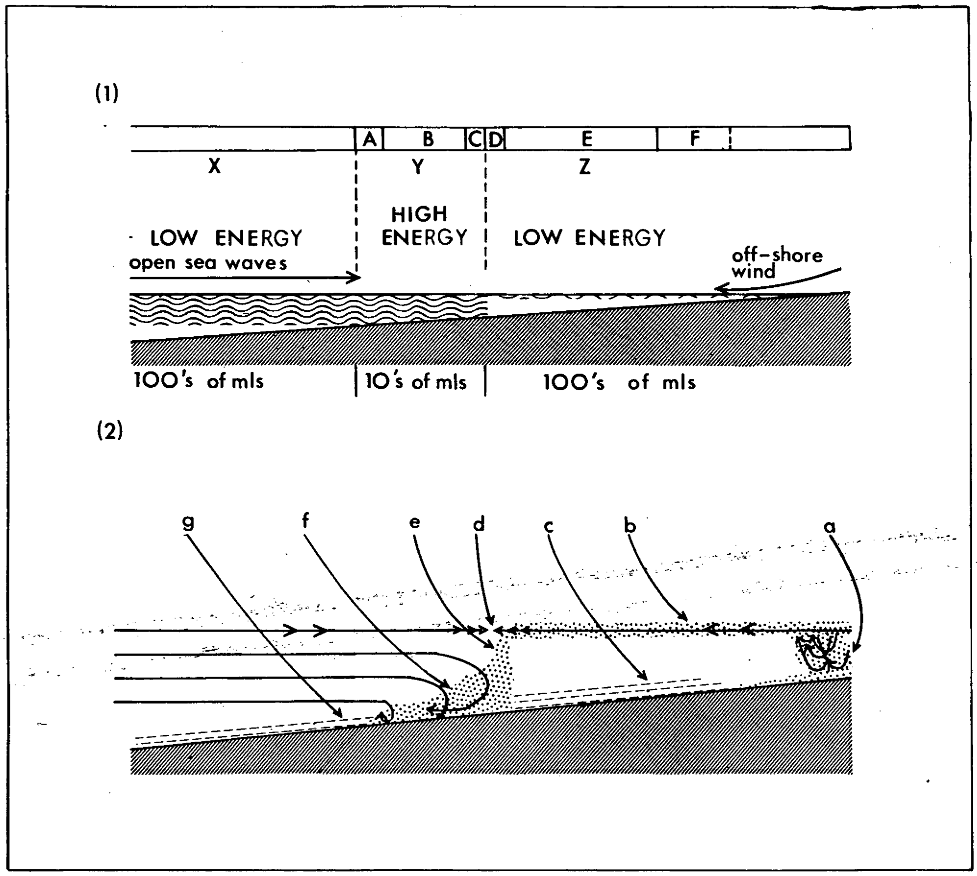
C = *Arenicola* sand flats. (Extensive reworking by waves and *Arenicola*; slow sedimentation).

D = Inner sand flats. (Limited reworking by waves; extensive reworking by *Corophium*; 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.



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, 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 ½ 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

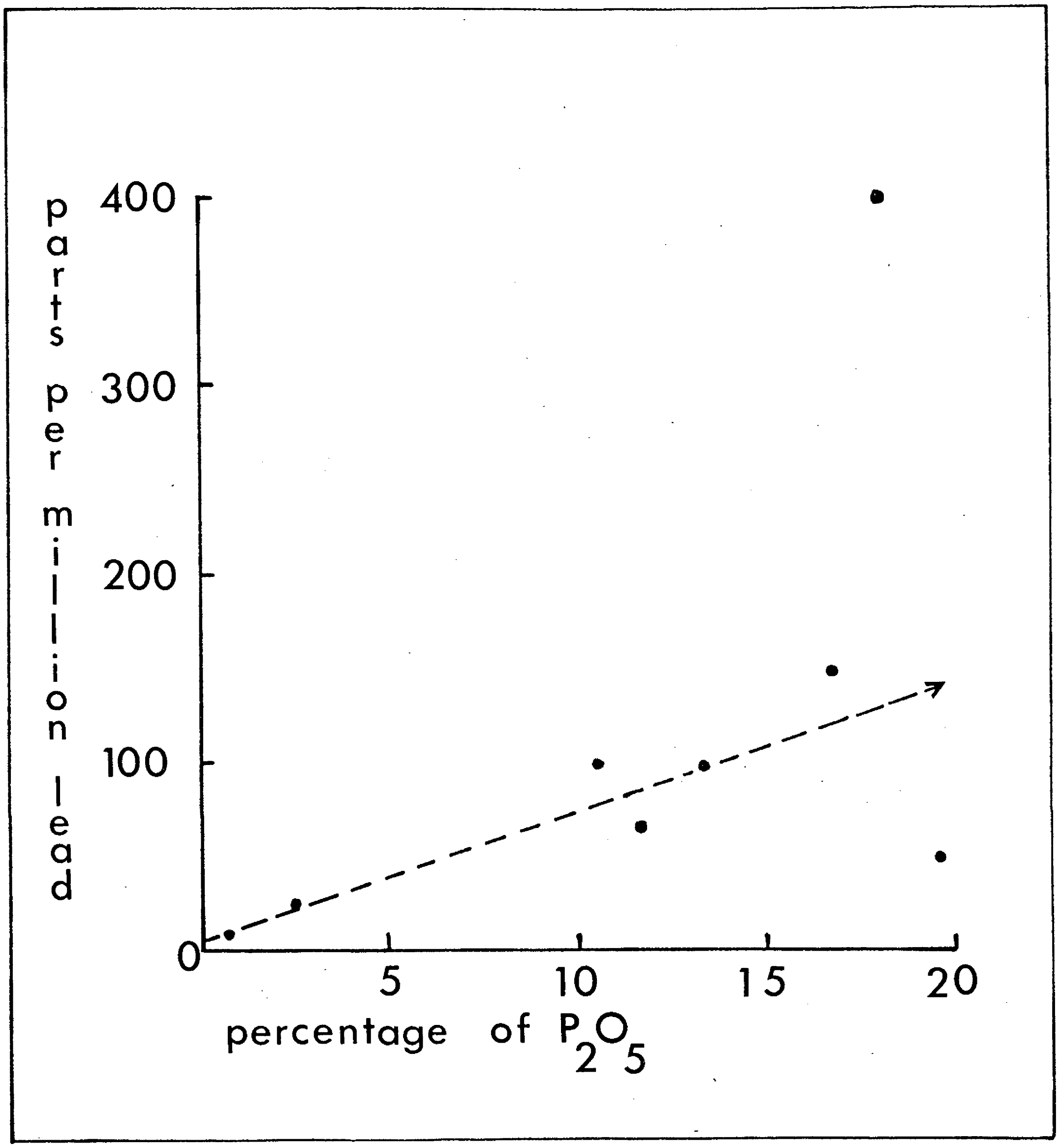
The results of P_2O_5 and trace element analyses on samples from the Stairway Sandstone are recorded by Ranford, Cook and Wells (1966), Wells, Stewart and Skwarko (1966) and Barrie, (1964).

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).

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. <u>Phosphatized Fossils (Fig.70, appendix)</u>

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) Transported or in situ?

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 s ediment 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 -7ϕ), and the accompanying coarse grained sand with a diameter of only 0ϕ to 1ϕ. 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 0ϕ 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.

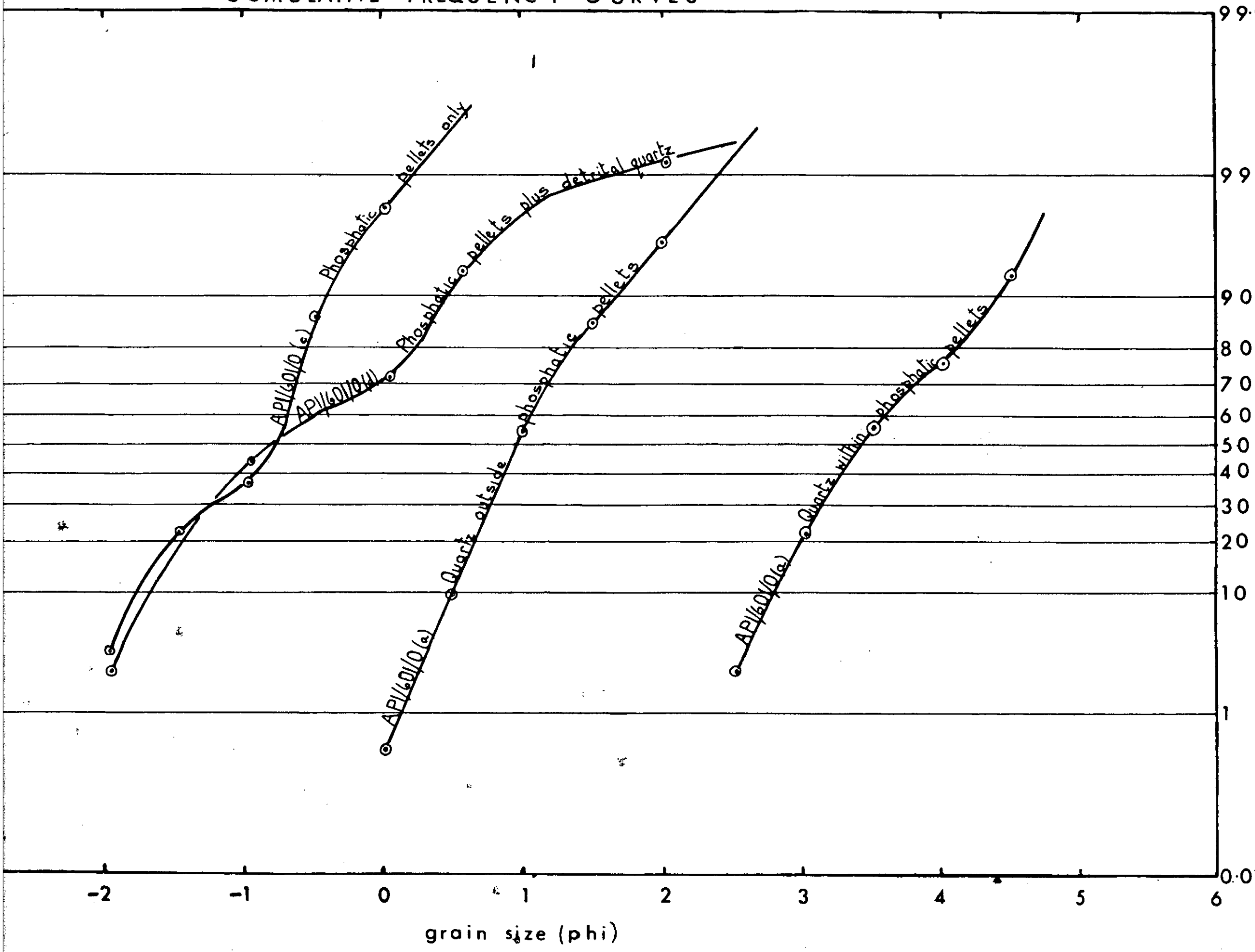
In order to establish whether the phosphatic sediments have been modified by transporting or by winnowing, the textural features of the phosphatic pellets and their associated sediments must be examined in detail.

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

Fig 31A

CUMULATIVE FREQUENCY CURVES



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 3.3ϕ for the detrital quartz within the phosphatic pellet and about 1ϕ for the detrital quartz in the surrounding sediment. This difference of about 2.3ϕ 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.

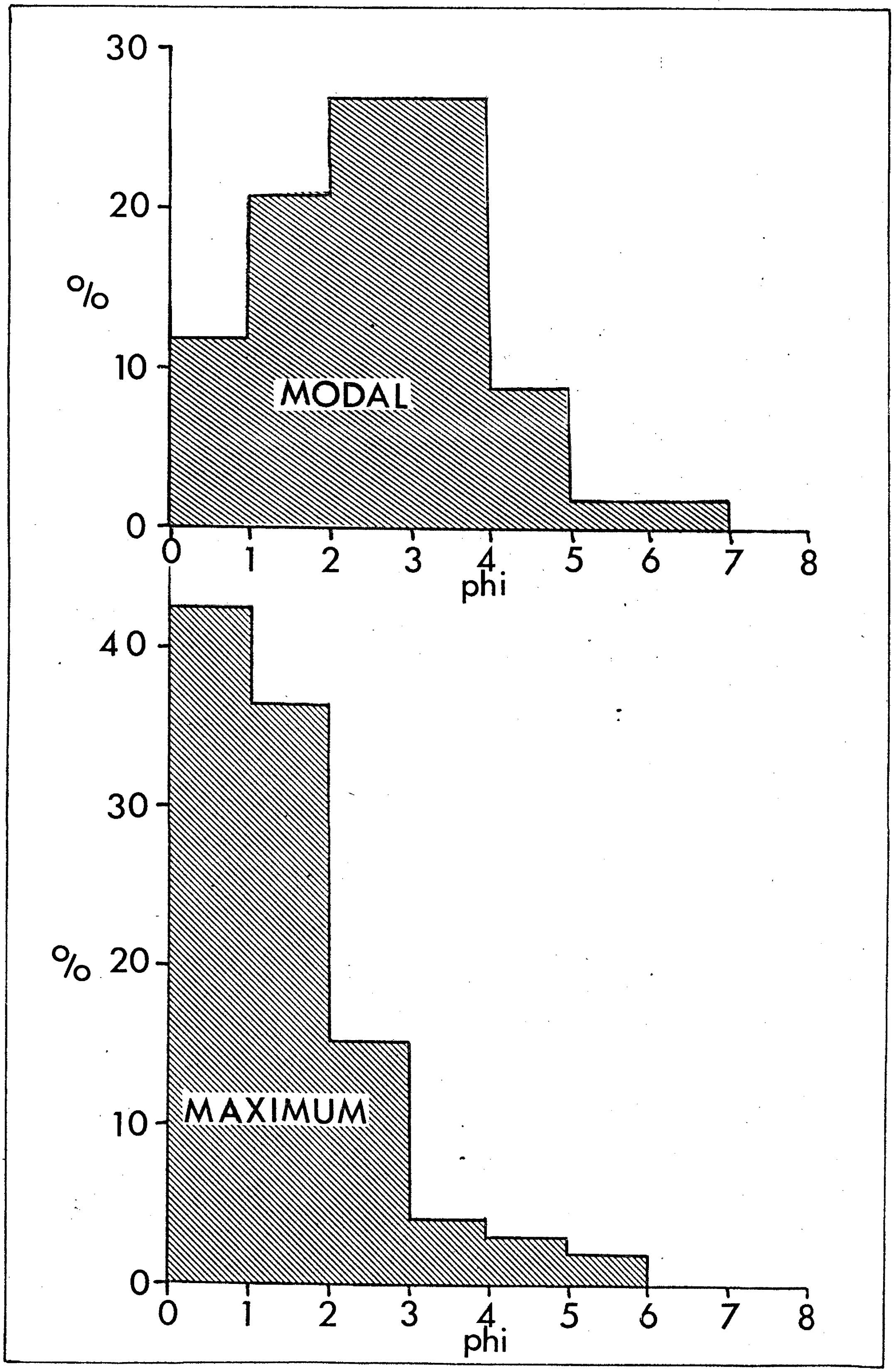
If the equations of Sahu (1964) are applied to AP1/601/0 (see Chapter 4, pages 34-36, and Table 5, appendix) in order to find the environment of deposition, the value of the discriminant function indicates a beach environment for the coarse sand outside the phosphate pellets, and a shallow water marine 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 ofphosphate 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



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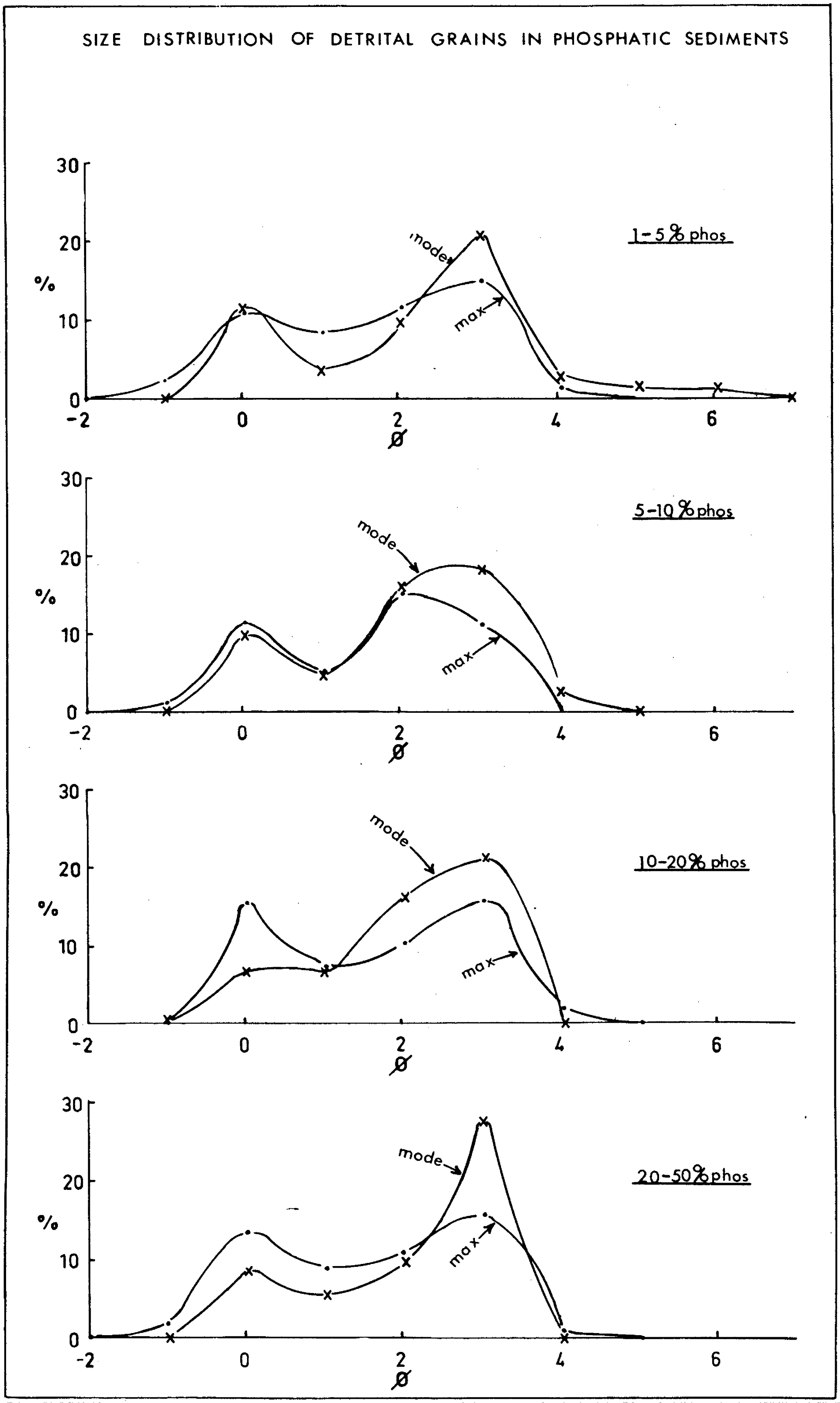
of from 2 to 4 phi units (mean of 2.85 phi units) but increases of maximum grain size of only from 0 to 2 phi units (mean of 1.12 phi units). These results may be adequately explained by winnowing which would remove the finer material producing a very marked increase in the modal grain size, whilst little 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%	1.25Ø


SIZE DISTRIBUTION OF DETRITAL GRAINS IN PHOSPHATIC SEDIMENTS
1-5 % phos
5-10 % phos
10-20 % phos
20-50 % phos
mode
max
%
Ø
30
20
10
0
-2
0
2
4
6

Percentage of phosphatic material	Median diameter
5-10%	1.10Ø
10-20%	1.20Ø
20-50%	1.10Ø

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%	2.0Ø
5-10%	1.7Ø
10-20%	1.8Ø
20-50%	2.0Ø

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 3ø to 4ø 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 3ø to 4ø 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 theprocesses 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.

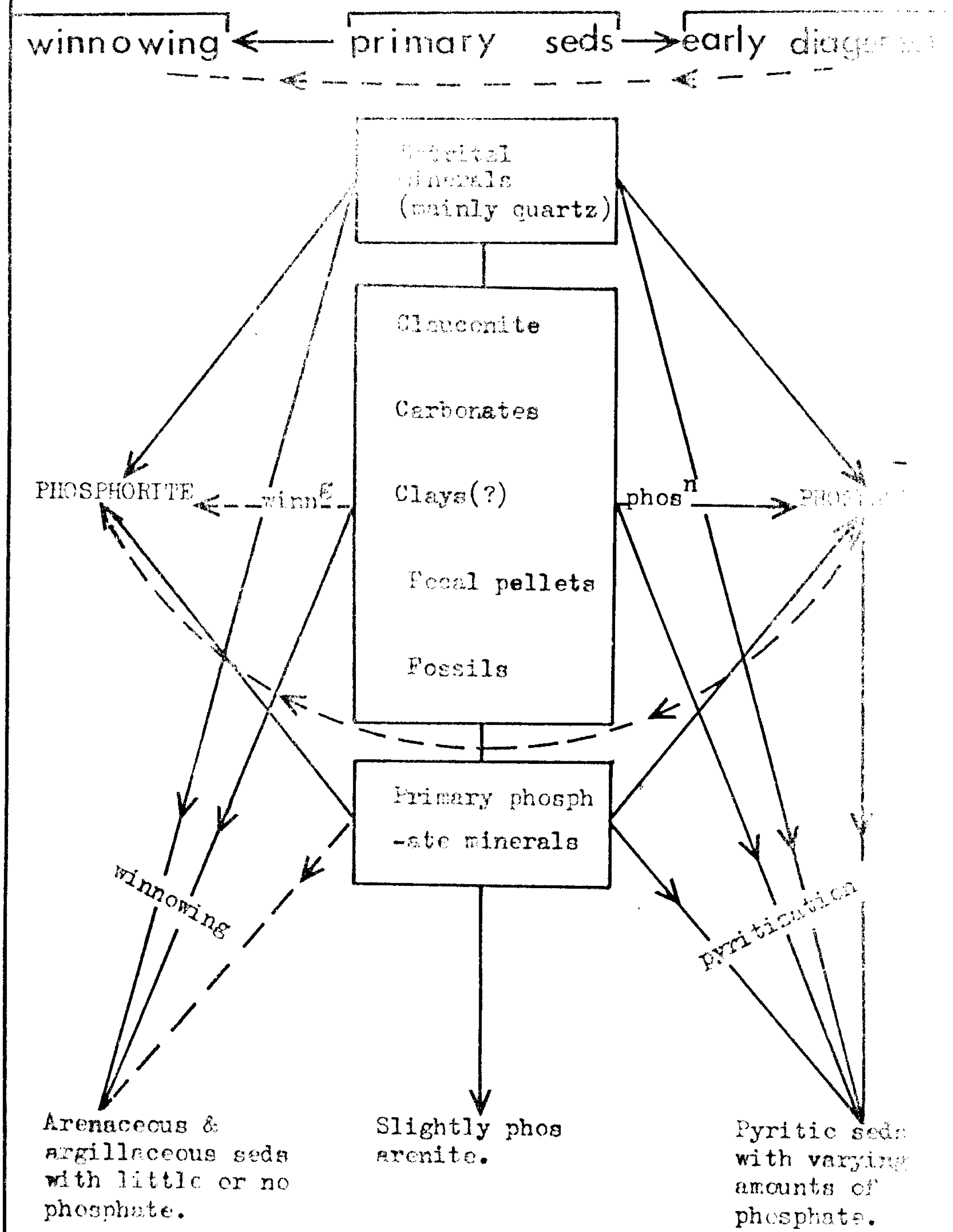
(iii) The Environment of Deposition

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 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, for the phosphatic

Stairway Sandstone sediments.



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 maybe 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 = 732 percent/ft of apatite

= 315 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 = 367 percent/ft

(d) The total weight of P_2O_5 present in a 1 sq.ft. column right through the Stairway Sandstone near AP1

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

$$= 600 \text{ lb. of } P_2O_5$$ (per cylinder of 1 sq.ft. 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:

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

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

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

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

(vii) Stairway Sandstone times are thought to have lasted for approximately 20 million years. Therefore the average quantity of phosphorus deposited per annum was:

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

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

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 s cope 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°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

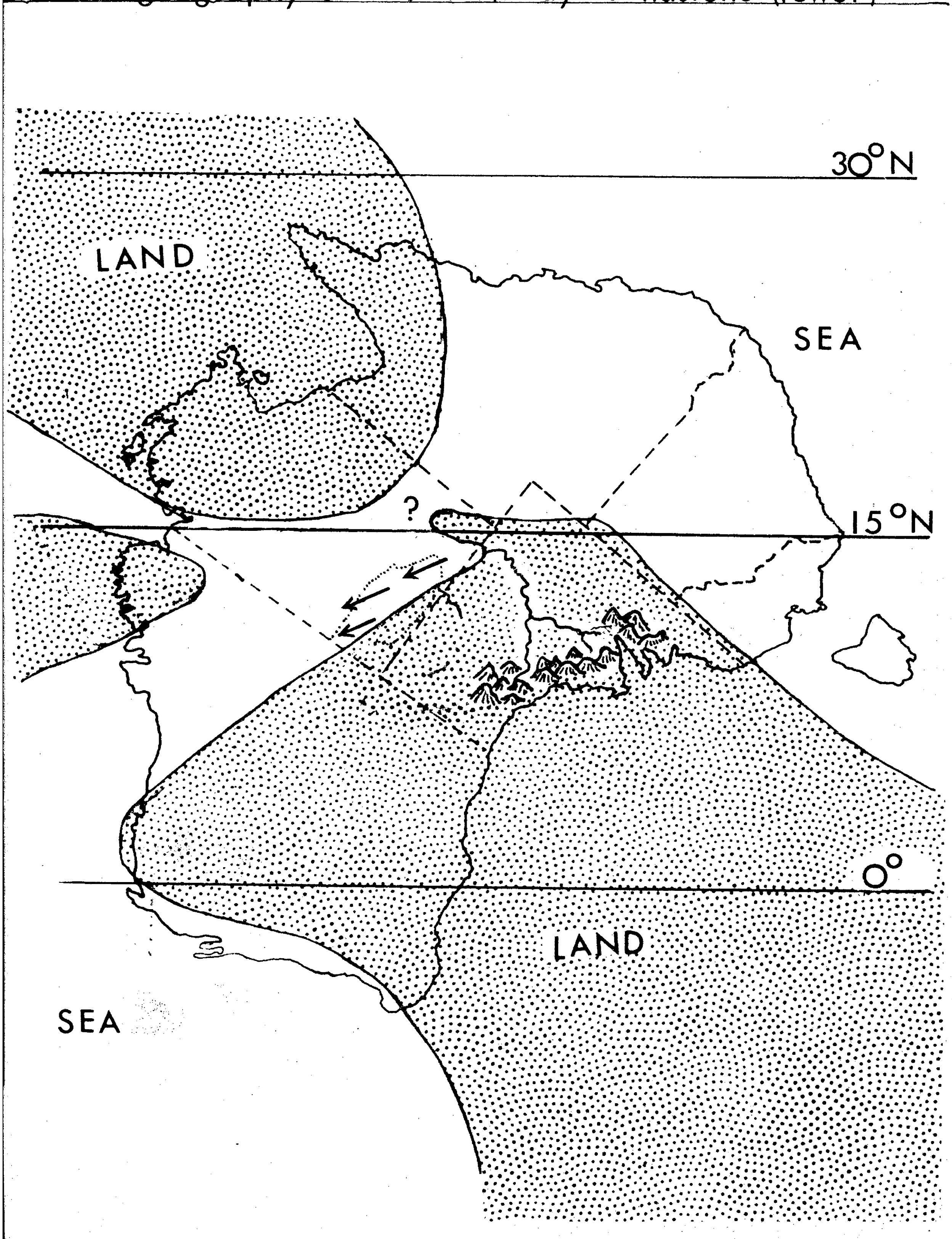
The petrology of the Stairway Sandstone is perhaps best explained by a desert hinterland from which little or no material is derived but through this area flow a few rivers, bringing down detritus from the more tropical areas to the Ordovician south.

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

Palaeogeography of the Stairway Sandstone (lower)



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.

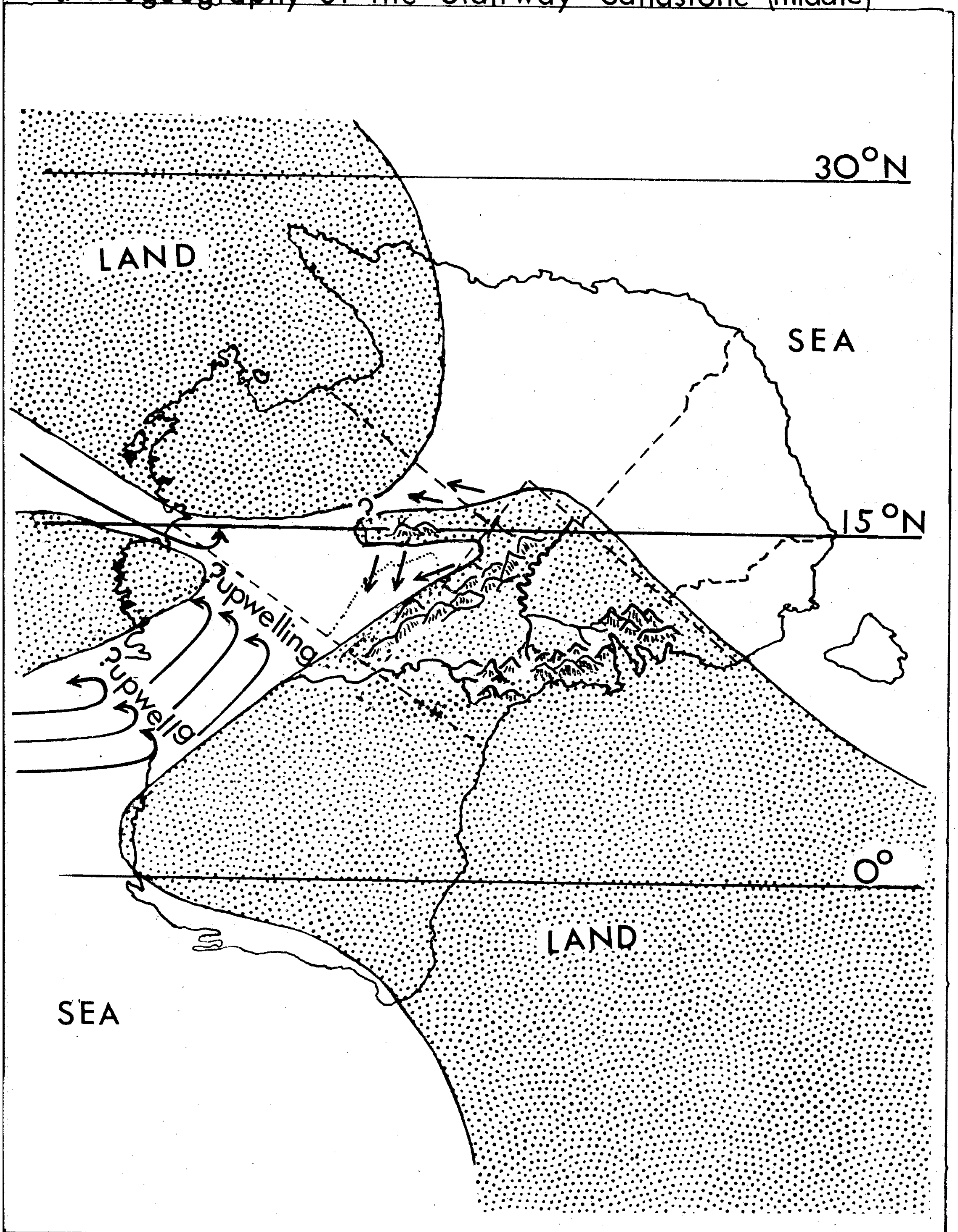
In upper Stairway times abundant common quartz again suggests a predominantly quartz arenite source area. The presence of chert suggests that the provenance may have been calcareous in part. The absence of euhedral grains of heavy minerals support a wholly sedimentary source.

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

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°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)

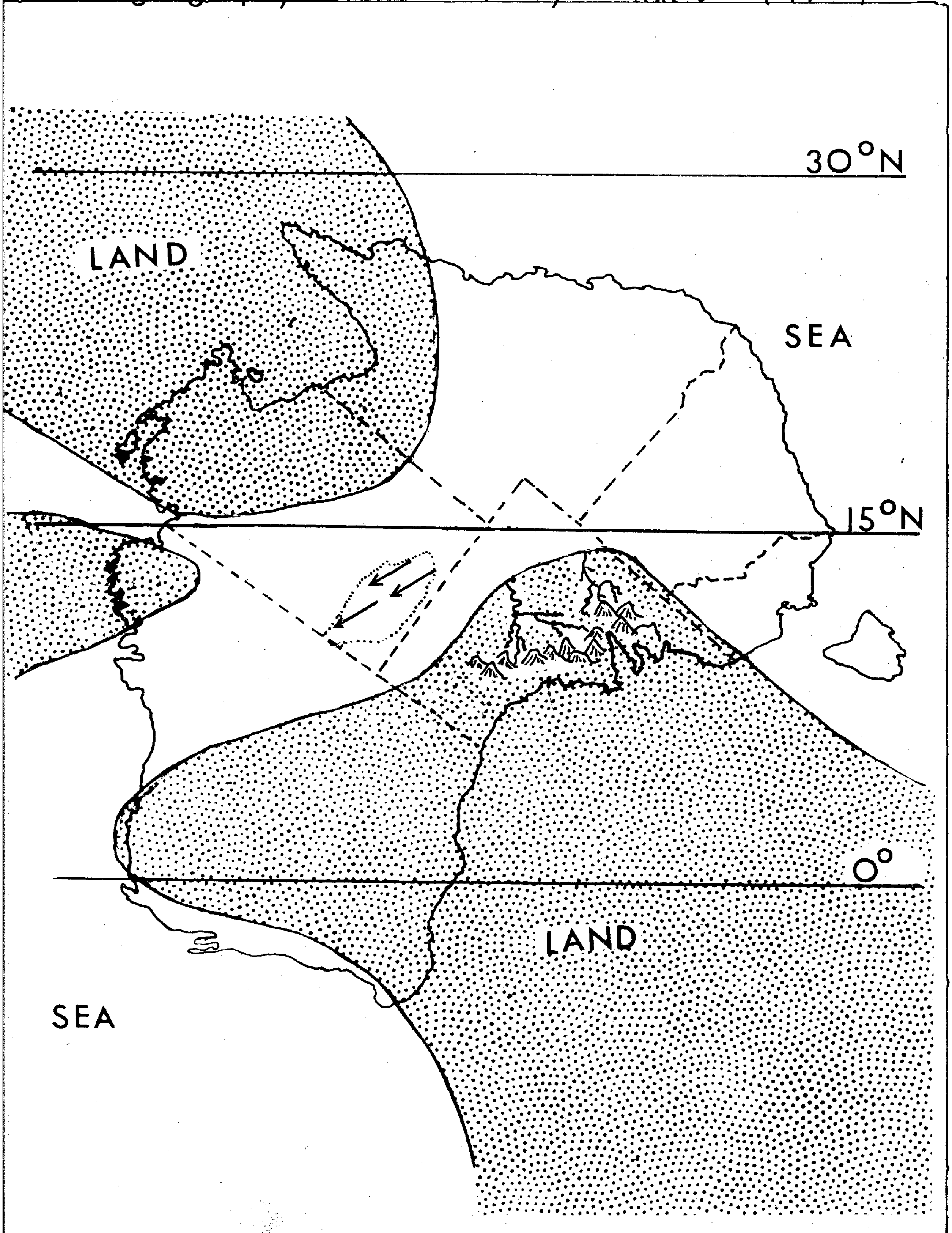


barrier or more likely, due to a local downwarping in the south-east. It would seem that during lower Stairway times the southern margins of the basin were formed by fairly high cliffs of Cambrian and Upper Proterozoic sediments (there is evidence of cliffs up to 100 feet high in the Mount Sunday range 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)



desert belt. The hinterland was probably a wide peneplained desert area. The east ridge was probably now more prominent and the Amadeus Basin almost 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 palaeogeography 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 s econdary 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 count).

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 x 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.

ACKNOWLEDGEMENTS

The author wishes to thank the Geological Branch of the Bureau of Mineral Resources for making this study of the Stairway Sandstone possible, and Mr.J.N.Casey for first suggesting the investigation. Professor D.A.Brown kindly made facilities of the Department of Geology, Australian National University, available to the author.

Dr.K.A.W.Crook offered valuable assistance and advice at all stages of the work and read the manuscript of this thesis. Dr.R.A.H.Nichols and Dr.R.P.Sheldon also kindly read the manuscript. Mr.L.C.Ranford and Mr.A.T.Wells were party leaders during the author's work on the Stairway Sandstone and helped in many ways during both field and laboratory work. Members of the Bureau of Mineral Resources and the Australian National University (too numerous to mention individually) helped and stimulated this study through their discussions with the author.

My wife deserves special mention for cheerfully undertaking the major task of reading my illegible handwriting and typing this thesis and also for assistance in a variety of other capacities.

Field data of L.C.Ranford, A.T.Wells, D.J.Forman, A.J.Stewart and J.Barrie is used in this thesis. Miss J.G.Tomlinson supplied the palaeontological data. Chemical analyses were undertaken either by the laboratory staff of the Bureau of Mineral Resources or by the Australian Mineral Development Laboratories.

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