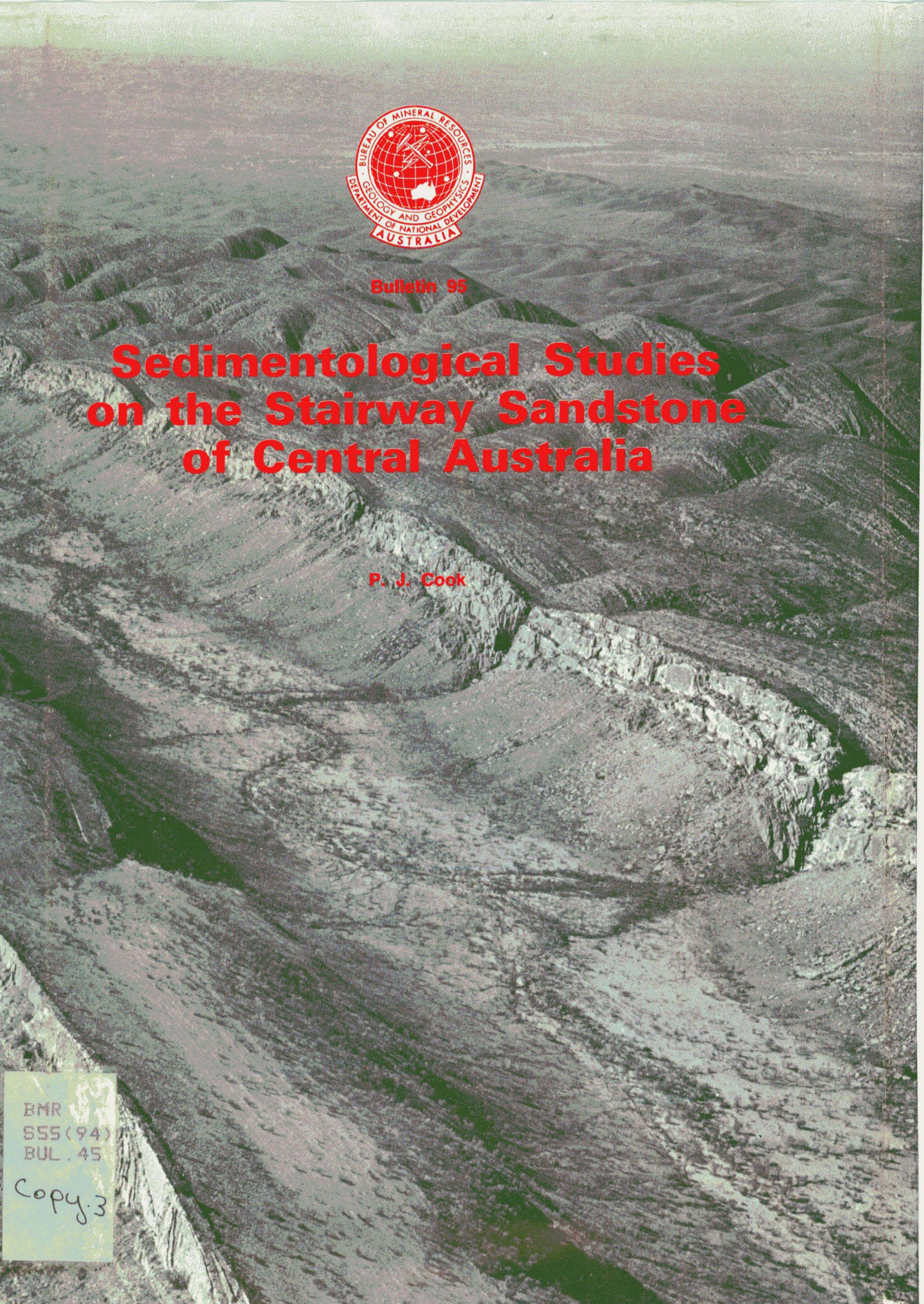

BUREAU OF MINERAL RESOURCES · GEOLOGY AND GEOPHYSICS · DEPARTMENT OF NATIONAL DEVELOPMENT · AUSTRALIA

Bulletin 95

Sedimentological Studies on the Stairway Sandstone of Central Australia

P. J. Cook

Prominent ridge of steeply dipping Stairway Sandstone (centre) in the Western MacDonnell Ranges, flanked by valleys underlain by the Horn Valley Siltstone on the left and the Stokes formation on the right.

DEPARTMENT OF NATIONAL DEVELOPMENT
BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

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Sedimentological Studies on the Stairway Sandstone of Central Australia

by

P. J. Cook

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SUMMARY

The Stairway Sandstone is an Ordovician formation in the Amadeus Basin of central Australia. It can be divided into a lower unit of coarse-grained super-mature orthoquartzite; a middle unit of illitic mudstone and phosphorite, grading into carbonate and redbeds to the southeast; and an upper unit mainly of fine-grained mature orthoquartzite. The heavy mineral assemblage consists almost exclusively of well rounded tourmaline and zircon.

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 northern margin of deposition of the Amadeus Basin to be eroded; the thickest part of the Stairway Sandstone is abruptly cut off in the vicinity of the Macdonnell Ranges. Lithofacies studies suggest that the axis of the basin trended northwest to southeast. Cross-bedding studies indicate that the palaeocurrents flowed from the southeast, 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 time are postulated from the mineralogy, textures, and sedimentary structures of the sediments. These suggest a low average rate of sedimentation, fairly uniform conditions in the lower and upper Stairway, current velocities with a range of 1 to 30 cm/sec., fairly warm conditions, normal salinities (except in the Mount Charlotte embayment), pH values of 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 of corehole AP1. It is apparent that the overall Stairway Sandstone sequence is regressive-transgressive. From the basic sedimentation units it is possible to recognize composite units which together make up a compound unit which can be related to a sedimentological model. 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 barrier-lagoon complex is regarded as the most likely model for Stairway sedimentation.

There are eight modes of occurrence of phosphatic material, of which the sandy pellet is the commonest. A little of the phosphate is possibly a primary precipitate, but most is thought to have formed by the diagenetic phosphatization of muds, immediately below the sediment-water interface. The phosphatic mud was subsequently winnowed to produce a lag deposit of phosphate pellets and coarser quartz grains. If this were the mechanism it is unnecessary to invoke excessively high phosphate concentrations in the Stairway seas.

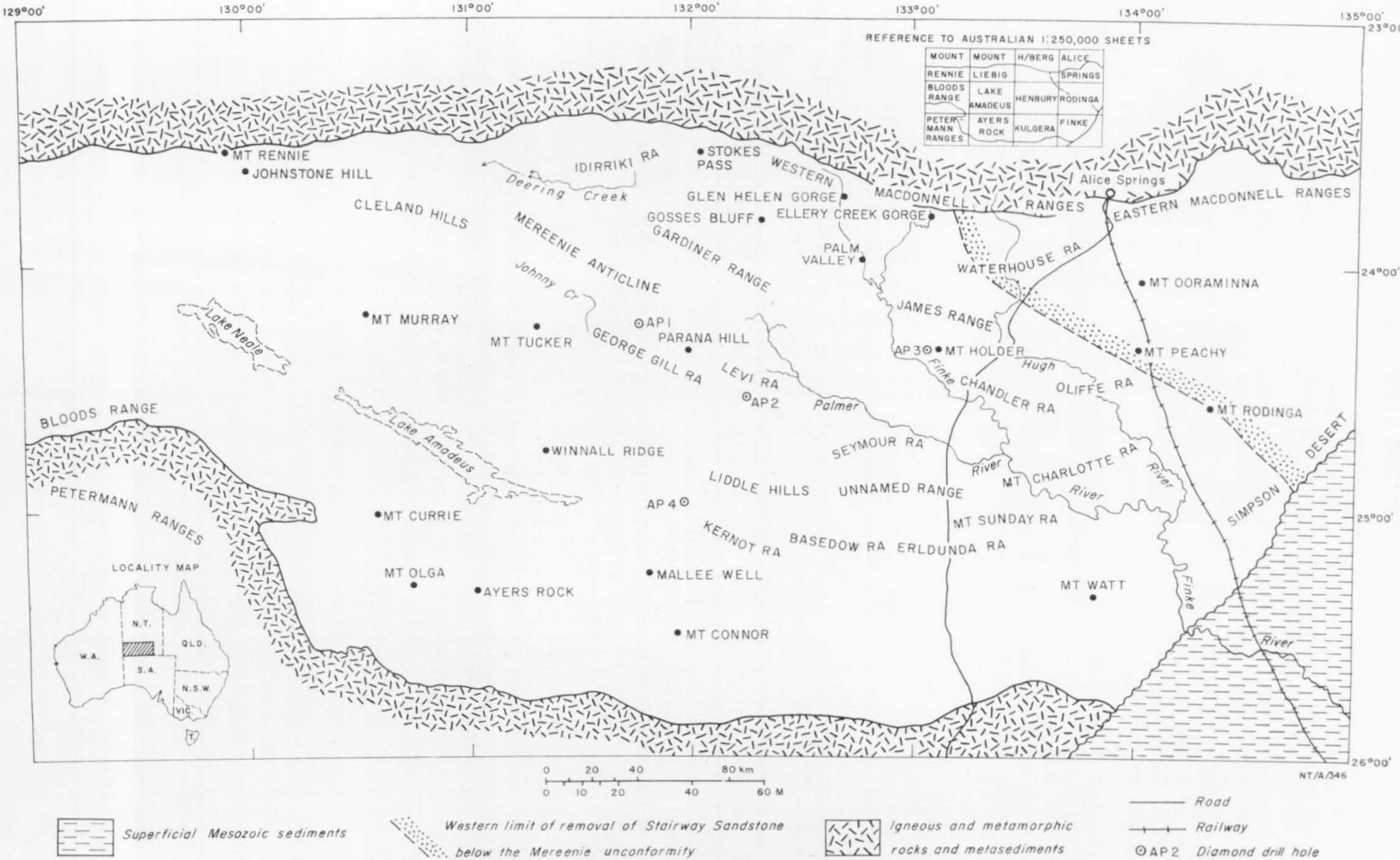

Figure 1. Locality map showing the position of features referred to in the text.

INTRODUCTION

The Stairway Sandstone was studied in the field in 1962 and 1963 during the reconnaissance geological mapping of the Amadeus Basin. In 1964 rather more detailed work was carried out: sections were measured and cross-bedding determined throughout the Amadeus Basin, and the phosphorites were examined in some detail because of their possible economic significance. In 1965 and 1966 surface and subsurface material was studied in detail to determine the provenance, environment of deposition, and palaeography of the formation. This work was done partly in the laboratories of the Bureau of Mineral Resources, and partly in the Department of Geology of the Australian National University, Canberra (under the sponsorship of the Bureau of Mineral Resources).

The Amadeus Basin

The Amadeus Basin is a large sedimentary basin in central Australia, extending from about longitude 128°E in Western Australia to about 135°E in the Northern Territory, and from Alice Springs in the north nearly to the South Australian border in the south (Fig. 1). It is approximately 800 km long and 270 km wide and covers an area of about 150,000 km^2.

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 maximum thickness of approximately 12,000 m. These sediments are fully described by Wells et al. (1970), who also give a comprehensive bibliography. Sedimentation was interrupted by two major orogenies, the Petermann Ranges Orogeny of late Proterozoic to early Cambrian age, and the Alice Springs Orogeny of late Palaeozoic age. The Lower Palaeozoic of the Amadeus Basin is divided into the Pertaoorrta and Larapinta Groups (Cambro-Ordovician).

The Larapinta Group consists of five formations, all thought to have been deposited in a shallow sea (Cook, 1970):

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

Previous Investigations of the Stairway Sandstone

The Larapinta Group was first defined by Tate & Watt (1896), who called it the Larapinta Series. Chewings (1935), who was the first to use the name 'Stairway', referred informally to the unit as the 'Stairway Ridge Beds' and the 'Stairway Quartzite'. The formation was formally named the Stairway Greywacke by Prichard & Quinlan (1962), and defined as '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 et al. (1965) described the formation in the Mount Liebig area and renamed it the Stairway Sandstone. It is described in other parts of the Amadeus Basin by Wells et al. (1966, 1967) and Ranford et al. (1965), and referred to briefly by Stelck & Hopkins (1962), Ranneft (1963), and Cook (1967a). It is

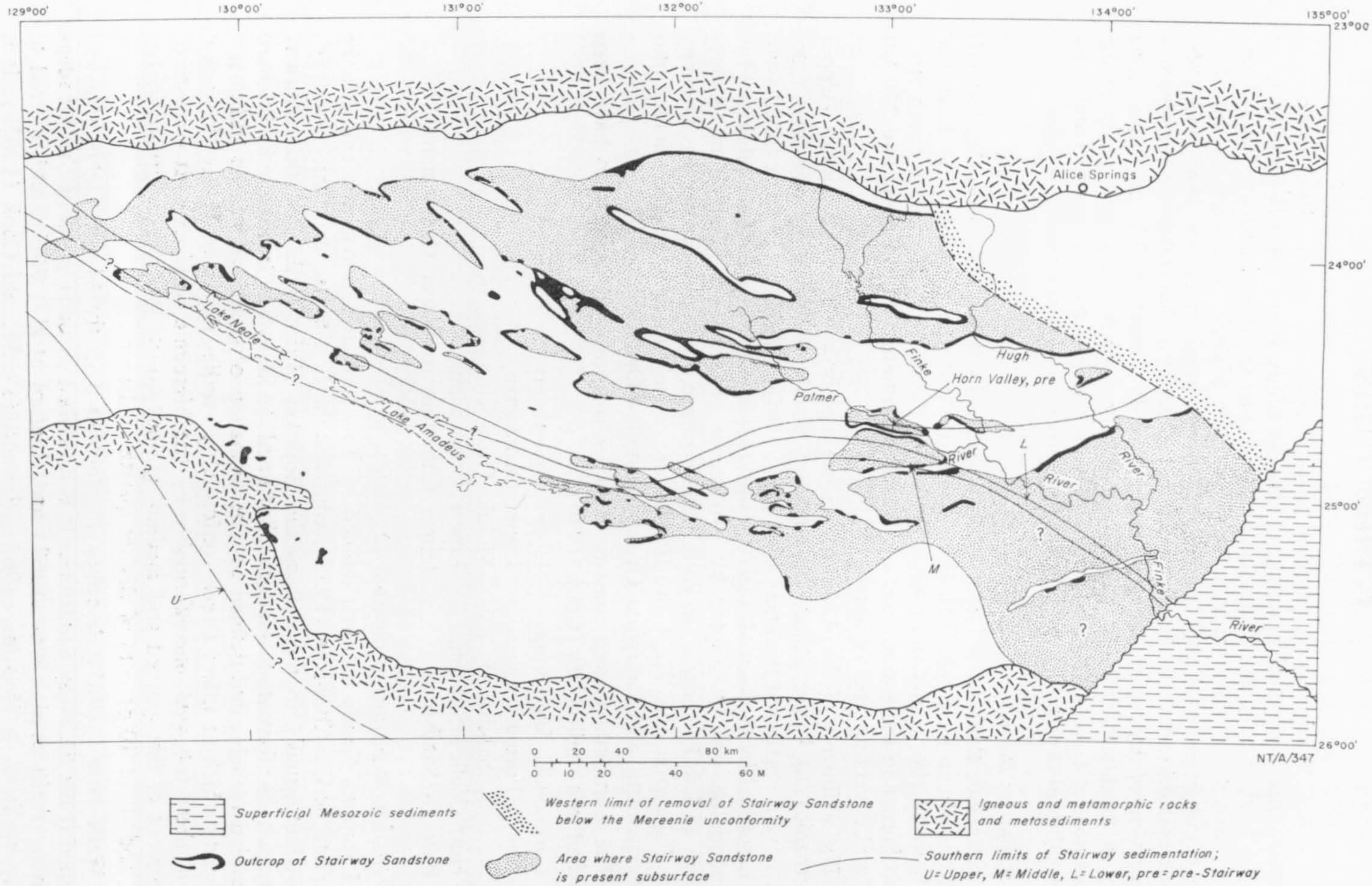

Figure 2. The surface and subsurface distribution of the Stairway Sandstone in the Amadeus Basin. The limits of lower, middle, and upper Stairway sedimentation are also shown.

also described in unpublished company reports by Gillespie (1959), Taylor (1959), Weegar (1959), Leslie (1960), Hopkins (1962), McNaughton (1962), and Haites (1963a).

Cook (1963) and Pritchard & Cook (1965) 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. Cook (1967b) investigated the texture of the phosphate pellets.

General Stratigraphy of the Stairway Sandstone

Although the areas of outcrop of the Stairway Sandstone only total some 7500 hectares, they are sporadically distributed over about 50,000 km^2 (Fig. 2). In the northern half of the Amadeus Basin the Sandstone rests conformably on the Horn Valley Siltstone (Fig. 3). To the south it lies disconformably on the Cambrian Pertaoorrta Group and unconformably on Upper Proterozoic sedimentary rocks. Farther south and west (e.g. Petermann Range), it rests unconformably on igneous and metamorphic rocks of the Musgrave Block. In most areas the Stairway Sandstone is conformably overlain by the Stokes Siltstone, but in the east, where epeirogenic movement and associated erosion occurred after the Larapinta Group was laid down, it is disconformably overlain by the Mereenie Sandstone.

The Stairway Sandstone ranges in thickness from about 550 m in the Idirriki Range on the northern margin to 30 m on the southern margin. The isopachous map (Fig. 4) clearly indicates that it originally occupied a considerably greater area than the present limits of the Amadeus Basin. The age of the Stairway Sandstone is Ordovician, with an estimated range of possible upper Llanvirnian to Llandeilian (J. G. Tomlinson, pers. comm.) equivalent to an interval of about 10 million years. Fossils include trilobites, brachiopods, pelecypods, gastropods, nautiloids, various trace fossils, and sponge spicules. Some of the macrofossils are notable for the size they attain. Trilobites with a pygidium up to 30 cm across and nautiloids up to a metre in length have been found in the northern part of the basin. P. J. Jones & E. C. Druce (pers. comm.) have found several species of microfossils at various intervals within the formation. Despite this wealth of palaeontological material it has so far proved possible to erect only one time-line within the formation. This divides it into what J. G. Tomlinson (pers. comm.) refers to as early Larapintan (equivalent to the upper part of the Pacoota Sandstone, the Horn Valley Siltstone, and the lower part of the Stairway Sandstone) and late Larapintan (equivalent to the upper part of the Stairway Sandstone, the Stokes Formation, and the Carmichael Sandstone).

The Stairway Sandstone is divided informally on lithological grounds into three units, a lower coarse sandstone, a middle phosphatic lutite unit (grading laterally into carbonates and redbeds), and an upper fine sandstone with minor silts. Figure 4 shows 31 representative stratigraphic columns across the basin, and where possible these three units are indicated.

The lower Stairway is about 25 m thick in the south (the Mount Charlotte area) and about 60 m in the north (the Idirriki Range area). It is predominantly a white or grey fine to very coarse sandstone, and is generally well rounded and sorted, although it is pebbly in places; it is thin to massively bedded, ripple-marked (Pl. 1, fig. 2), and cross-bedded. The basal sandstone is remarkable for the presence of pyrite oolites—up to 20 percent of the rock in places—generally

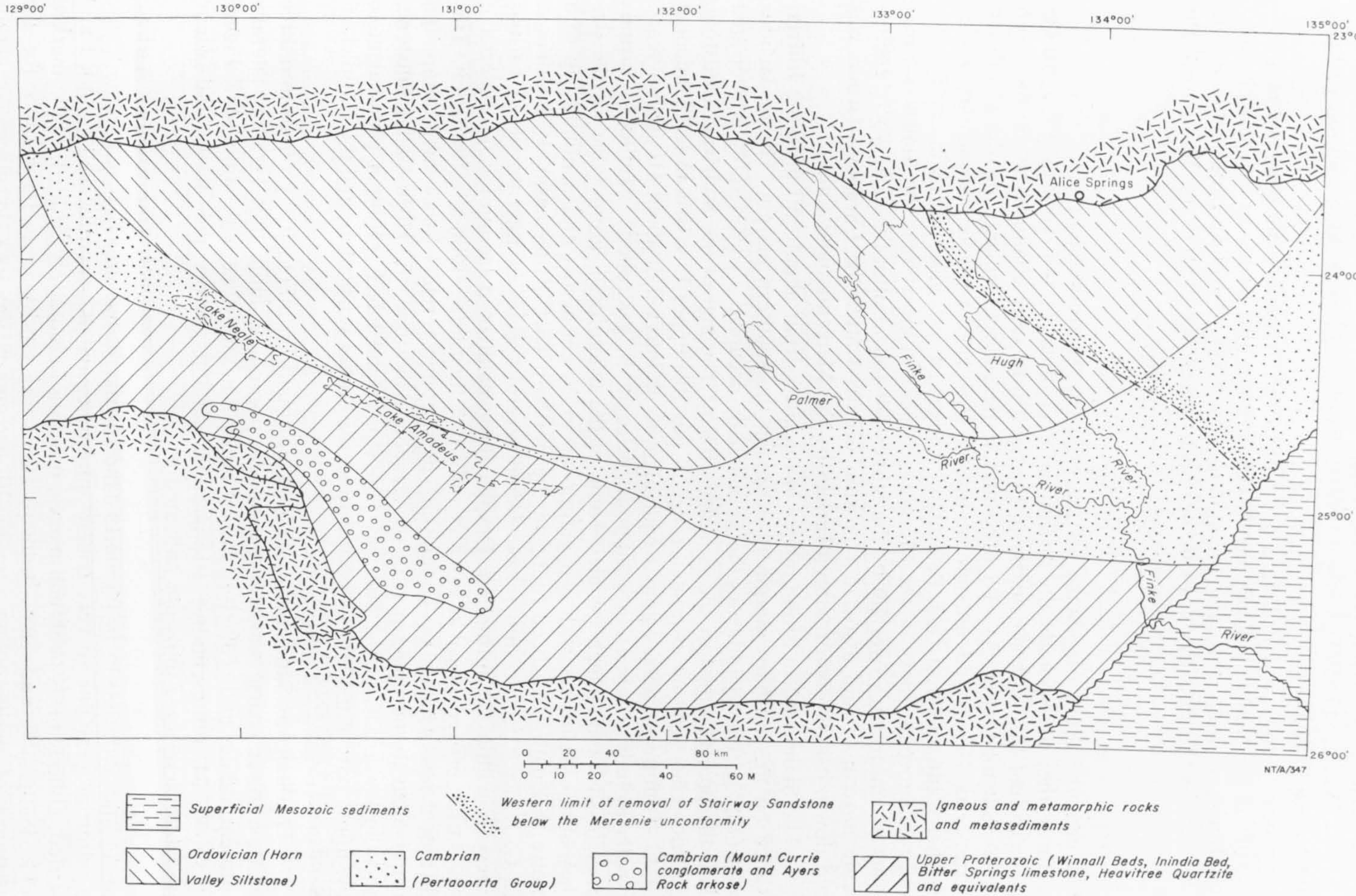

Figure 3. Palaeogeological map of the pre-Stairway Sandstone surface.

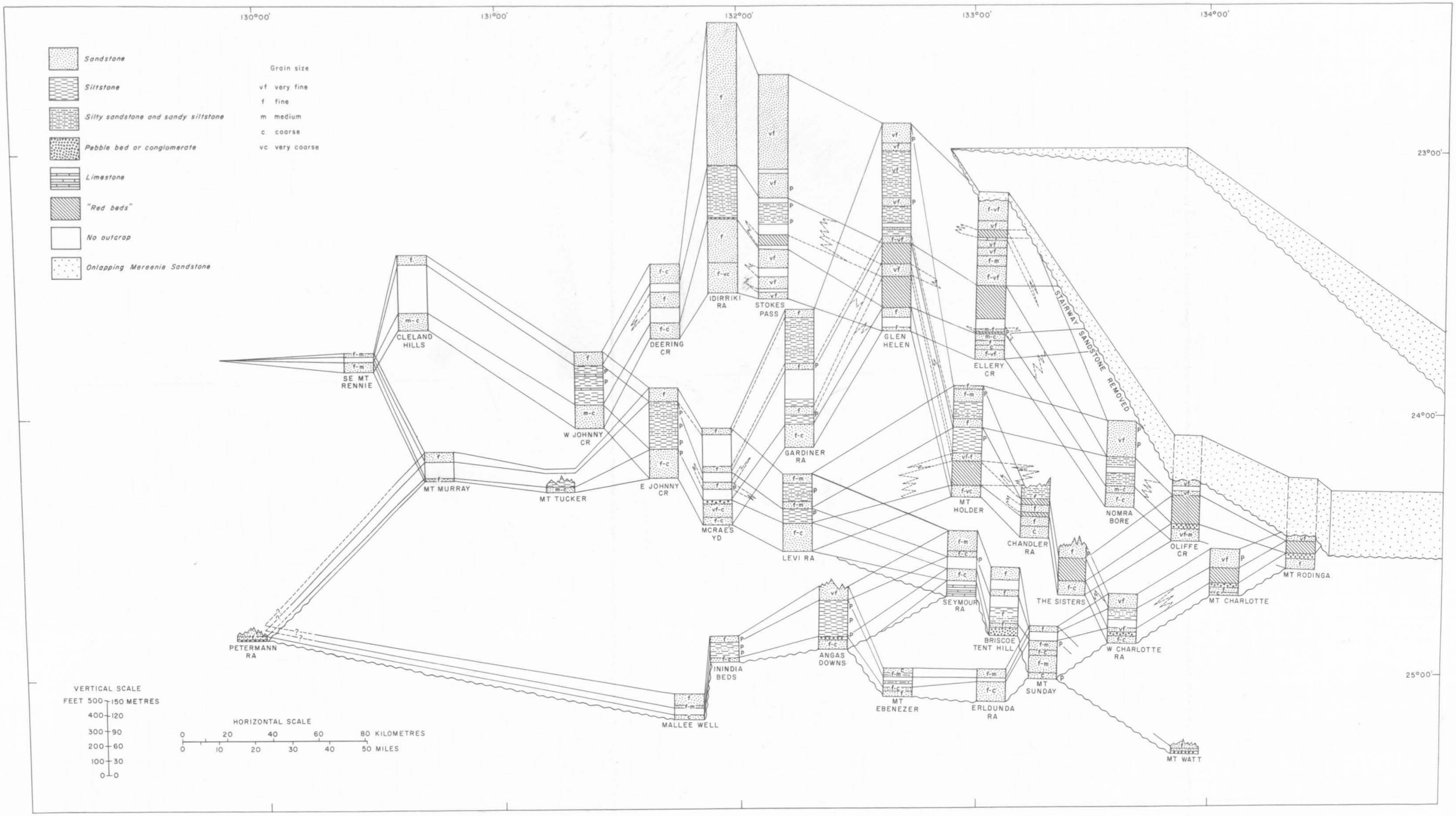

Figure 4. Stratigraphic sections of the Stairway Sandstone throughout the Amadeus Basin.

weathered out or altered to limonite. It contains a great variety of bedding-plane markings and indeterminate tracks and trails. One of the sandstones has a particularly characteristic texture referred to by Ranford et al. (1965) as 'ropey texture' (Plate 1, fig. 1). Because the lower Stairway is strongly silicified, it is well exposed and commonly forms a prominent escarpment.

The middle Stairway ranges in thickness from less than 30 m in the south to about 200 m in the north. It is lithologically the most varied of the three divisions. It is predominantly a lutaceous interval, with siltstone, mudstone, and claystone, which are grey and green at the surface but black in the subsurface. 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 sandstone, and grey, brown, or black pelletal and nodular phosphorite (Pl. 2, fig. 2). In the southeast (Seymour Range) thin yellow or brown dolomite and limestone (grey or white at depth) are common. Farther to the southeast, red and red-brown poorly sorted sandstone and lutite are well developed; in the Mount Charlotte area these redbeds make up the whole of the middle Stairway Sandstone. Fossils are fairly common in the middle interval; 'chewing' and 'churning' by infauna is well developed (Pl. 3, figs 1 & 2).

The upper Stairway ranges in thickness from less than 30 m to 300 m. It consists predominantly of white and grey very fine grained sandstone, cross-bedded in places, which crops out prominently when silicified. Interbeds of lutite, though generally minor, form a high percentage of the top part of the upper Stairway 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 rare. Fossils such as trilobites, brachiopods, and spicules (Pl. 2, fig. 1), and trace fossils such as *Diplocraterion* and *Cruziana* are common.

PALAEOCURRENT AND RELATED BASINAL STUDIES IN THE STAIRWAY SANDSTONE

Isopach and Lithofacies Studies

The isopachous map on the total thickness of Stairway Sandstone (Fig. 5) shows a considerable thickening to the north, but a marked cut-off in the Western Macdonnell Ranges due to the Alice Springs Orogeny. In the northeast corner of the basin, the formation has been removed by erosion after the Rodingan Movement. Despite varying rates of sedimentation, subsidence, and compaction, it is reasonable to assume that the isopachs reflect the approximate form of the Stairway Sandstone sea.

High sand:shale ratios in the northern part of the basin (Fig. 6) are due to the considerable thickening of the upper Stairway, whereas high sand:shale ratios on the southern margin are mainly a reflection of the absence of the silty middle Stairway. Figure 6 gives little information on source areas for the sediments, which could have come from any side of the basin except the northwest, where it was probably connected to the open sea.

Figure 2 shows the probable southerly limits of the lower, middle, and upper Stairway seas, and indicates that the upper Stairway sea was the most widespread.

It is apparent from the lower Stairway isopachous map (Fig. 7a) that after the deposition of the Horn Valley Siltstone, a large shallow embayment formed in the southeast part of the basin. The more or less uniform thickness of the lower

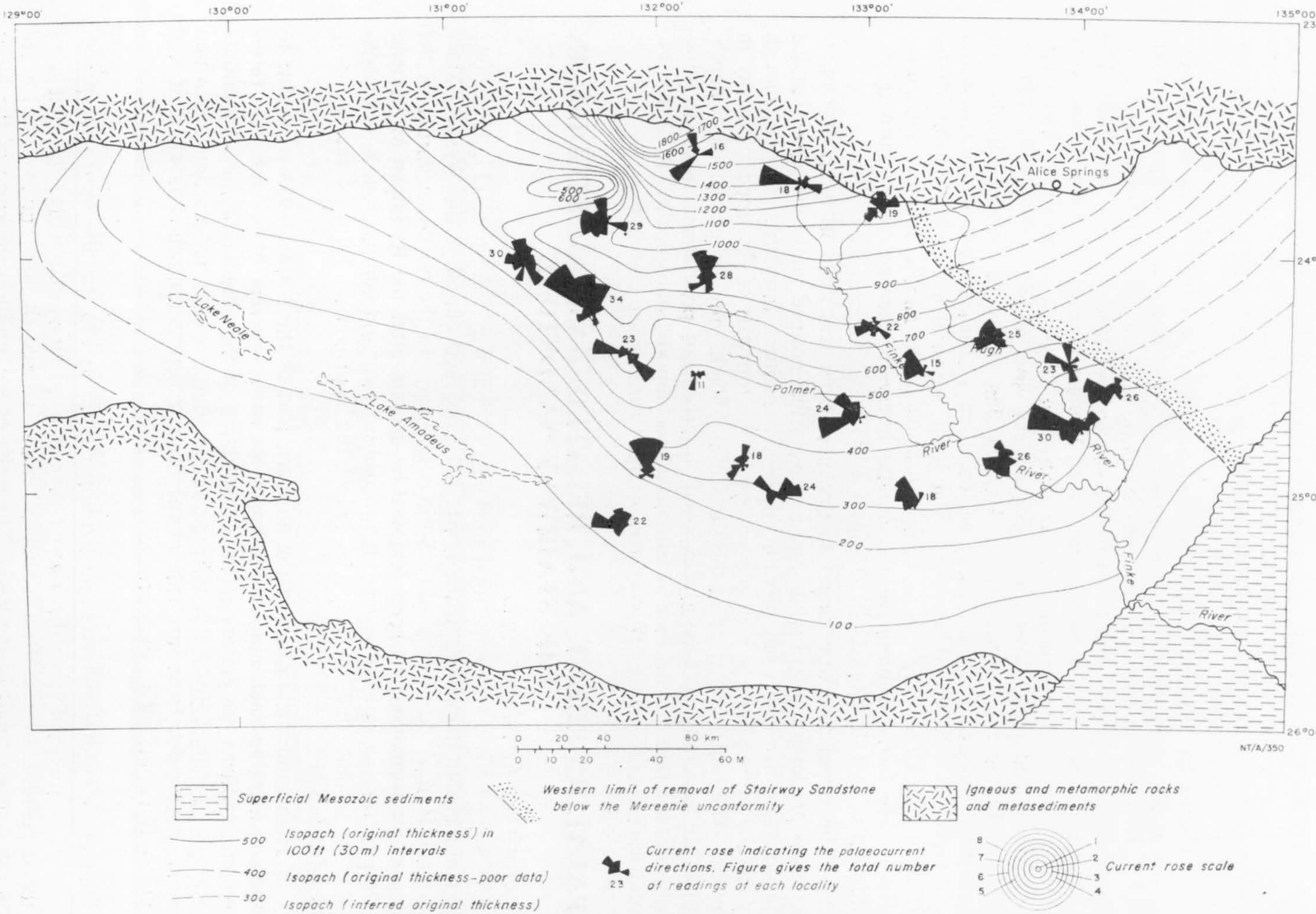

Figure 5. The total thickness of the Stairway Sandstone. Palaeocurrent directions are also indicated.

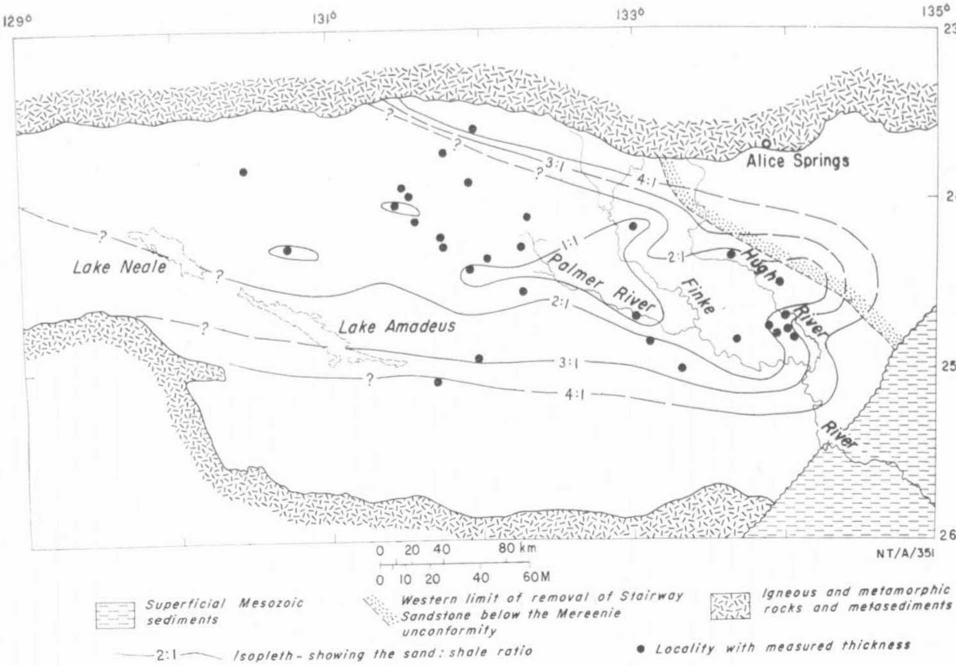

Figure 6. Lithofacies map, showing the sand-shale ratio for the Stairway Sandstone.

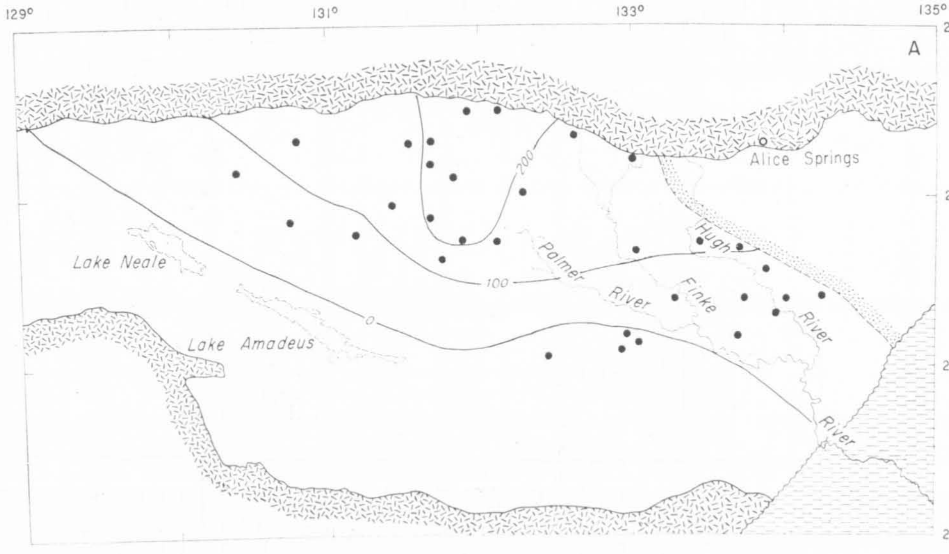

Figure 7a. The thickness of the lower Stairway Sandstone.

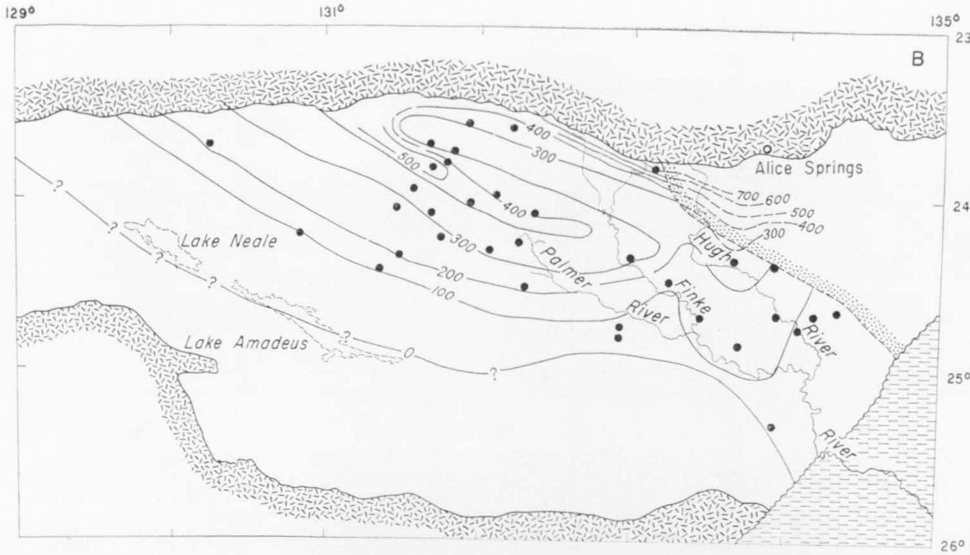

Figure 7b. The thickness of the middle Stairway Sandstone.

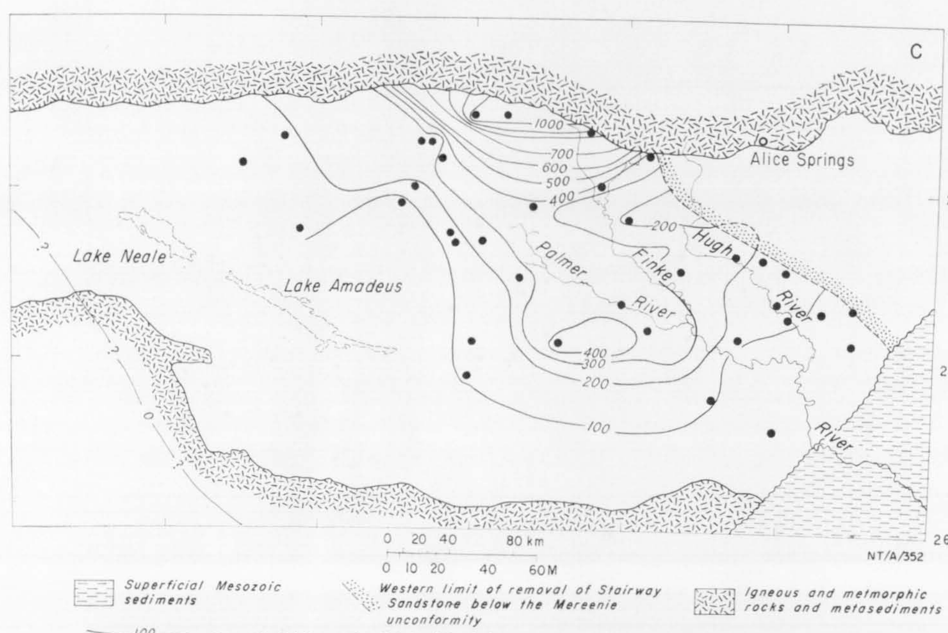

Figure 7c. The thickness of the upper Stairway Sandstone.

Stairway suggests that the palaeoslope was rather gentle and that the lower sand body was of the 'blanket' type with uniform sedimentation over a wide area. The palaeoslope was at the most 1 in 5000, apart from differential subsidence, and was probably originally considerably less. There are insufficient data to draw up sand-shale maps for the lower Stairway (or any of the other units) but it is likely that there is little lateral variation in the percentage of sand.

The isopachous map on the middle Stairway (Fig. 7b) indicates thinning along a zone north through the Seymour Range to the Chandler Range and then along a more conjectural northwest line through the northern part of the James Range. The zone, which is also the zone of maximum carbonate deposition (possibly due to the carbonates forming on a submarine ridge), divides the Amadeus Basin into a western basin with a fairly thick sequence of black marine lutites and with no evidence of restriction from the open sea; a northeastern area in which there is also a considerable thickness of sediments; and a southeasterly embayment with a very thin sedimentary sequence composed mainly of quartz sandstones and redbeds (Fig. 8). It is perhaps significant to note that Cook (1970c) postulates a

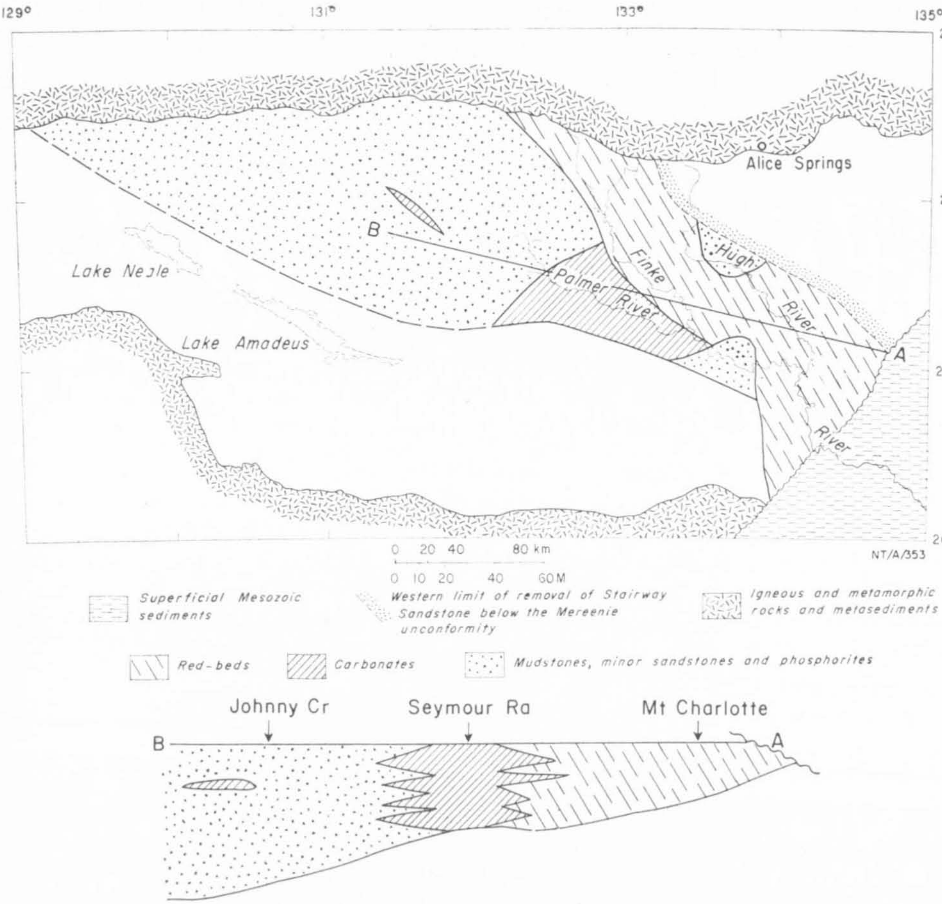

Figure 8. Distribution of middle Stairway rock types in the Amadeus Basin.

zone of thinning, running north across the Amadeus Basin, which corresponded to a hinge-line which was active throughout much of the lower Palaeozoic.

The variation in thickness of the upper Stairway (Fig. 7c) is rather different from that of the lower and middle Stairway. There appears to be a sub-basin in the southern part of the Amadeus Basin, although this has been delineated from only a few known thicknesses and the stratigraphy in parts of the southern margin (the Mount Sunday Range area) is uncertain. It would seem, however, that sediments thinned somewhat along an eastwest line through the middle of the basin. There is a definite thickening of the upper Stairway on the northern margin. The sand:shale ratio probably varies little in the upper Stairway, although there is a tendency for the amount of sand to decrease to the north and west, which would support a southerly or easterly provenance.

Palaeocurrent Studies

Except in the coarse sands of the lower Stairway, cross-beds are rare and poorly developed. Figure 5 shows that the currents came from the southeast. This direction is particularly evident in the southeast (where the palaeoslope gradient was probably minimal), and northwest parts of the basin. In several places it is parallel to the isopachs, suggesting longshore currents. In the centre of the basin the current pattern becomes less regular and there is a strong northerly component (together with a minor southerly component in places) directed down the palaeoslope.

Figure 9 gives mean palaeocurrent directions for sandstone of varying grain size and also for the three Stairway units. In all cases there is a wide spread of results (as is normally the case in shallow marine sediments), but it is evident that the mean current direction for the whole formation was from the southeast. The lower and upper Stairway conform to this, whereas in the middle Stairway the currents were from the northeast. Thus to some extent the development of the thick sands of the lower and upper Stairway was probably dependent on the palaeocurrent direction. Similarly the presence of phosphate in the middle Stairway may be dependent in part on the palaeocurrent: the northeasterly current may have carried little terrigenous material so that there was no dilution of phosphate.

There is also a suggestion from Figure 9 that the detrital grain size is in part dependent on the palaeocurrent direction. Coarse and very fine sands show a palaeocurrent from the southeast, but fine and medium sands generally show a direction from the east. This relationship may be due either to the variation of current velocity with the direction or to the change in provenance—that is, coarse and very fine sands derived from the southeast and fine and medium sands from the east.

Cross-bed Studies

Cross-beds were studied at localities throughout the basin and in addition to the dip and azimuth of the cross-bed sets (necessary for the determination of palaeocurrent directions), the type of cross-bedding, the thickness of the cross-beds, and the grain size of the cross-bedded units were noted. The cross-bed results were corrected for tectonic dip using a computer programme devised by T. Quinlan and the writer, modified from a programme by McIntyre (1963) for the rotation of spherical projections.

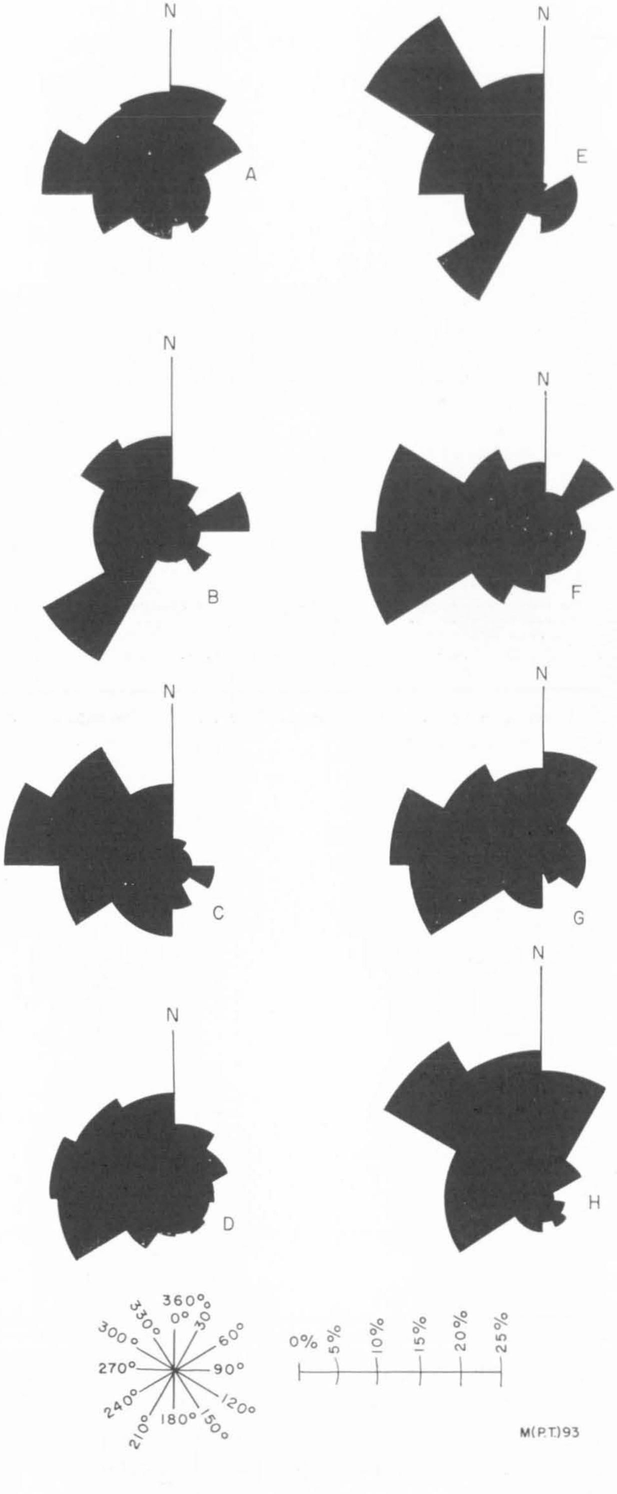

Figure 9. Variation of palaeocurrent direction with stratigraphic position and grain size. A—lower Stairway; B—middle Stairway; C—upper Stairway; D—whole formation; E—very fine sand; F—fine sand; G—medium sand; H—coarse sand.

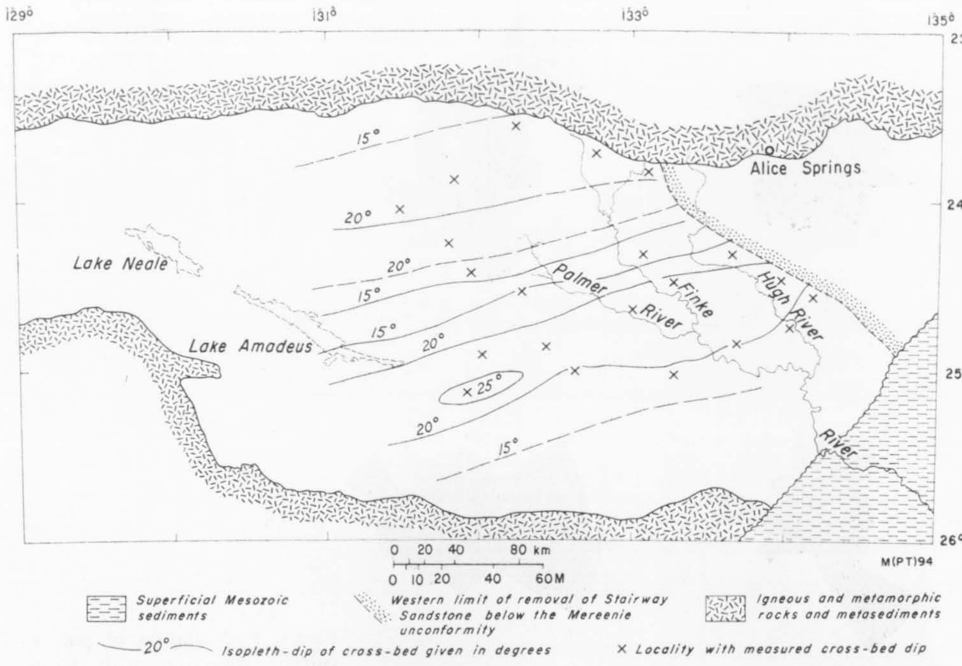

Figure 10. Variation in the dip of cross-beds in the Stairway Sandstone, throughout the Amadeus Basin.

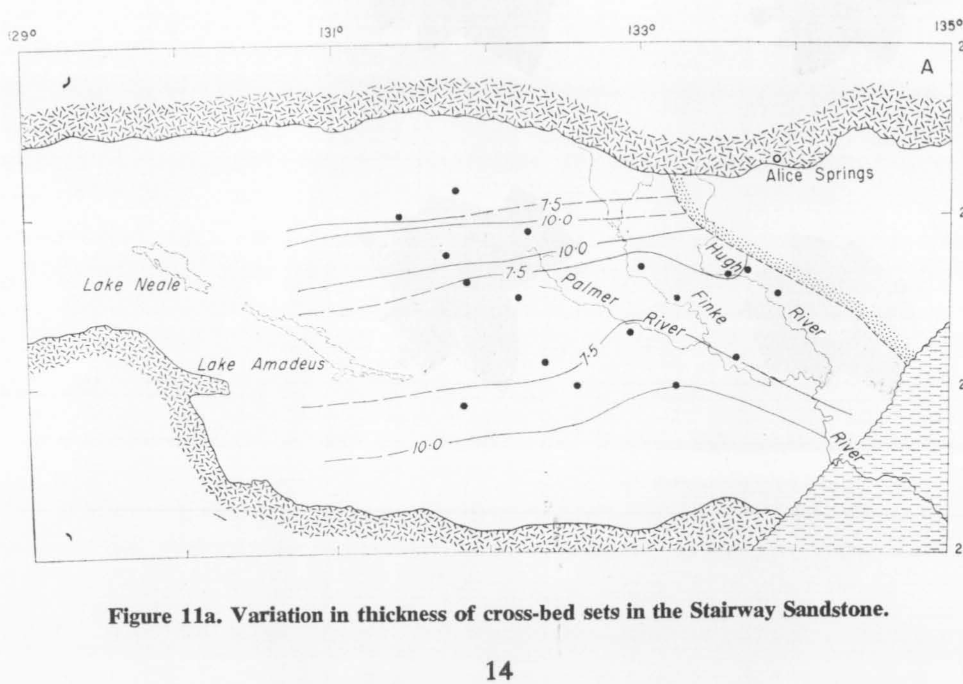

Figure 11a. Variation in thickness of cross-bed sets in the Stairway Sandstone.

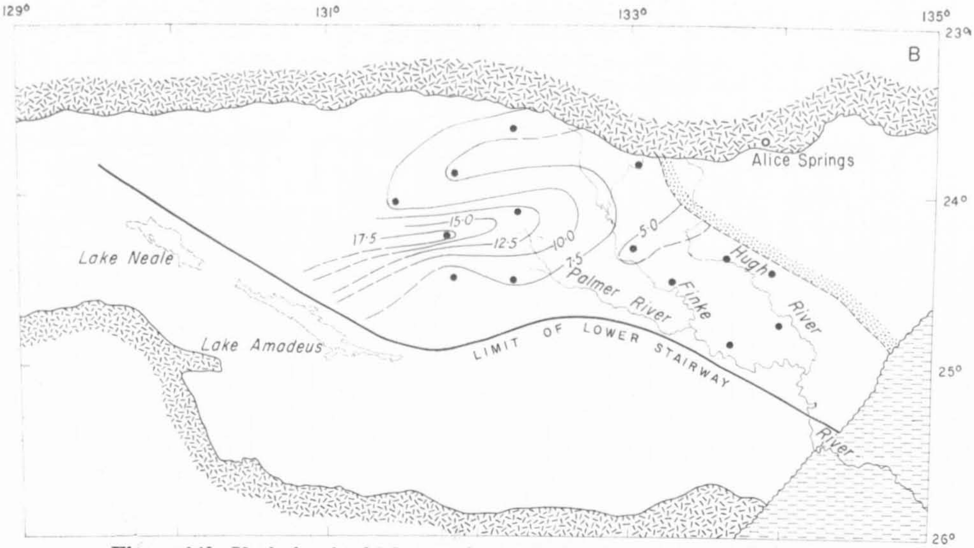

Figure 11b. Variation in thickness of cross-bed sets in the lower Stairway.

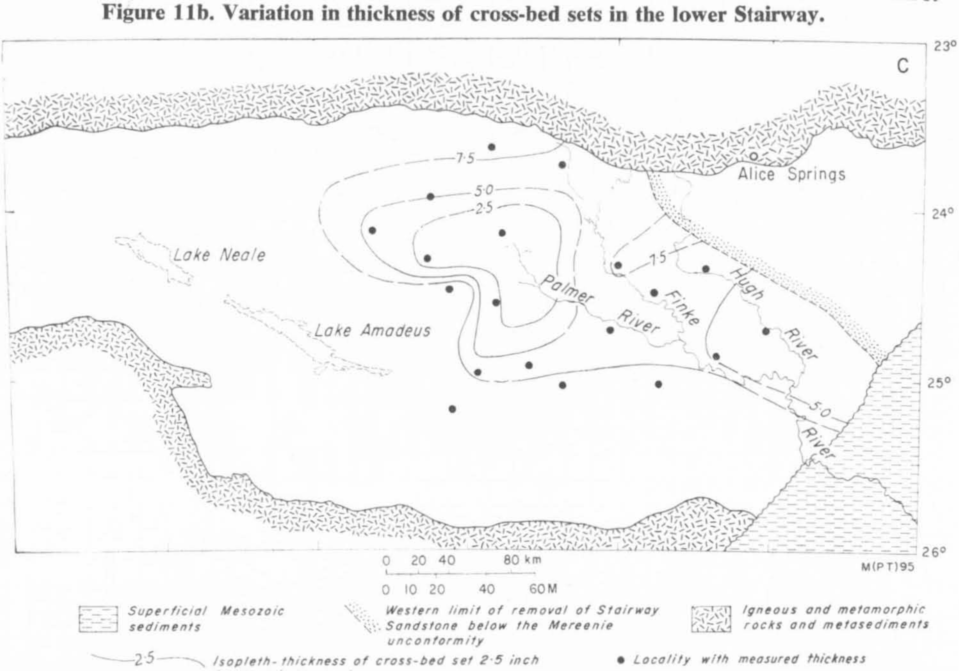

Figure 11c. Variation in thickness of cross-bed sets in the upper Stairway.

The cross-beds are mainly of the tabular and straight tabular type and are probably of subaqueous origin (Crook, 1957). The average dip of the cross-beds is 18°, with a range of 14° to 22°, again suggesting subaqueous deposition (McBride & Hayes, 1962).

The map (Fig. 10) indicating variation in the dip of the cross-bed sets shows an interesting though puzzling pattern in which there are three zones of low dip

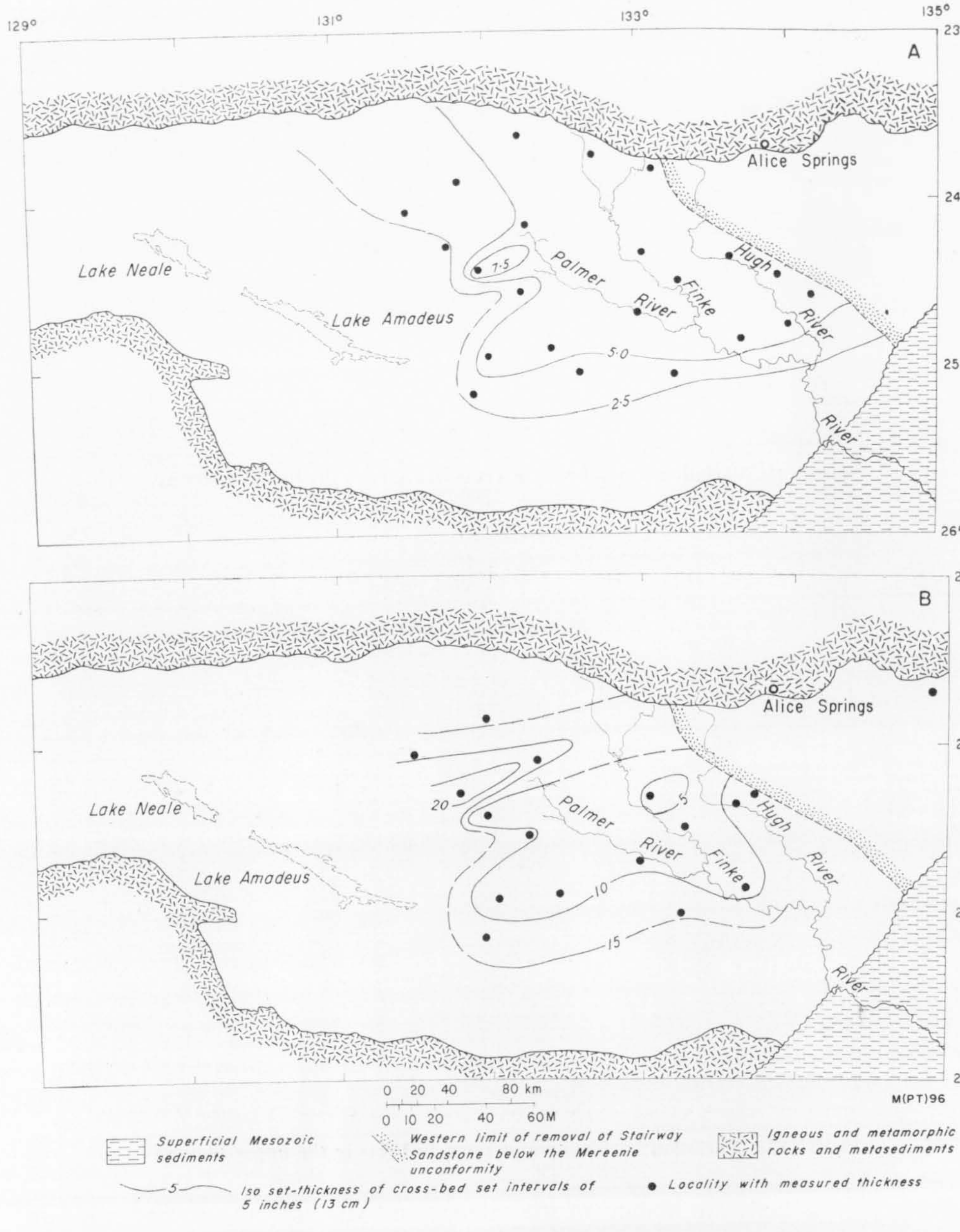

Figure 12. Maps showing the variation in thickness of cross-bed sets in (A) fine and very fine sandstones (B) coarse and very coarse sandstones.

(less than 20°) and two of high (more than 20°), trending southwest across the basin at right angles to the palaeocurrent direction (Fig. 5). Jopling (1963) has shown that the angle of cross-bedding is related to such factors as energy (an inverse relationship, the water depth, and the suspended load. Thus, currents and tides and the topography of the sea-bottom are likely to have influenced the form of the cross-bed sets.

The thickness of cross-bed sets was also investigated (Fig. 11). It was expected that the sets might thicken towards the postulated source area, but for the Stairway Sandstone as a whole the sets tend to form zones of maximum and minimum thickness running approximately northeast across the basin. Cross-beds in the lower and upper Stairway, on the other hand, generally thicken to the west. In the lower Stairway the sets are thinnest in the Mount Charlotte Embayment. In the upper Stairway the thinnest sets are found to occur in the area of maximum shale development (compare Figure 11 with Figure 6), where presumably lower-energy conditions were prevalent.

When cross-bed thicknesses are plotted for particular grain-sizes (Fig. 12) there is rather less regional variation, suggesting that set thicknesses are in part dependent on grain size, or, ultimately, on the current velocity. The majority of the cross-bed sets of the fine and very fine sands are 5.0 to 7.5 inches (12-20 cm) thick and thicken to the east. The coarse and very coarse sands have sets 10 to 15 inches (25-40 cm) thick and thicken to the west. This suggests that two hydrodynamic systems, one depositing coarse sand, the other fine sand, were operative within the same basic environment throughout Stairway Sandstone time. In addition, the movement in sea level (regressive in the lower Stairway, transgressive in the upper, see later) may also have been an important factor influencing the form and thickness of the cross-beds.

PHYSICO-CHEMICAL CONDITIONS

Rate of Deposition

The Stairway Sandstone has a maximum thickness of approximately 550 m and embraces a time-span of about 10 million years. This is equivalent to an average rate of deposition of about 0.05 mm per annum in the northern part of the basin (western Macdonnell Ranges area). In the vicinity of the AP1 drillhole, the average rate of deposition was about 0.01 mm per annum. However, the grain-size of many of the lower Stairway sands is approximately 0.5 mm, so that probably periods of erosion and non-deposition took up much of Stairway Sandstone time. Abundant cross-bedding in the coarse sands of the lower Stairway suggests that when sedimentation did occur, it was fairly rapid.

The form and frequency of infauna is considered to be of value in the interpretation of rate of sedimentation (Middlemiss, 1962): straight vermiform burrows (for example *Scolithus*) indicate rapid sedimentation, and contorted ones slow sedimentation (because the infauna had time to rework the sediments). If sedimentation were extremely rapid then the infauna would conceivably be unable to keep pace with it and be completely destroyed. On this basis, in the lower and upper Stairway, the lack of burrowing in places, and the vertical burrowing elsewhere, suggests rapid sedimentation (Fig. 13). The abundance of contorted burrowing (Pl. 3, figs 1 and 2) in the middle Stairway suggests slow sedimentation, as does the presence of phosphate: it is known from the Baja California phosphorites (D'Anglejan, 1967) that the rate of formation of phosphorites is extremely slow.

Current Velocities

Some idea of the current velocities during Stairway Sandstone time may be obtained from the grain-size by using the curves computed by Hjulstrom (1939). The modal grain-size suggests that current velocities ranged from 7 cm/sec in the lower and upper Stairway to 0.4 cm/sec in the middle Stairway. The current velocities obtained by using maximum grain-size range from 30 cm/sec in the lower Stairway and 10 cm/sec in the upper Stairway to about 1 cm/sec in the middle Stairway. If phosphatic pellets were detrital (as was suggested by Crook, 1964) velocities of up to 150 cm/sec must be postulated. This is inherently unlikely.

Bathymetry

The Stairway Sandstone has many indications of shallow-water sedimentation such as ripple marks, and tracks and trails of the mud-flat type. The environments with which the sedimentary sequence shows affinities (see pp. 36-48) are all shallow-water. Some of the lower Stairway is slightly glauconitic: Cloud (1955) believes that glauconite may form between depths of 5 and 1000 fathoms, but mainly between 10 and 200 fathoms. McKelvey et al. (1959) have suggested that phosphorite is formed between 200 and 1000 m. Most other workers suggest rather shallower depths; Kazakov (1937) considers that most phosphorites are deposited within a depth range of 50 to 200 m. Smith (1968) suggests 150 feet or less as the probable depth of formation of the Monterey phosphorites. Cook (1971b) considers that the Phosphoria phosphorites formed at depths of 20 to 200 m. Thus the presence of phosphorites also tends to indicate fairly shallow water.

Temperature

Phosphorites are generally found within the palaeolatitudes 40°N to 40°S (Sheldon, 1964), where the water temperatures in shallow seas range from moderate to very warm. Phosphorites are particularly common in the trade wind belt. The presence of carbonates suggests warm seas: and halite pseudomorphs in the Stokes Siltstone immediately above the Stairway Sandstone suggest warm arid conditions. Thus it would appear that the Stairway seas were probably warm.

Cloud (1955) has shown that glauconite is of little value as an indicator of palaeo-temperature, except that its formation is likely to be inhibited in 'markedly warm' waters.

Salinity

Mostly, the sea was normally saline. In a few places, such as within the Mount Charlotte embayment, there are indications of circumscribed and short-lived areas of high salinity during middle Stairway time.

Eh-pH Conditions

The work of Krumbein & Garrels (1952) has greatly assisted the delineation of the depositional conditions for chemical sediments. Minor authigenic pyrite, glauconite, and phosphorite are present in the lower Stairway. This suggests Eh values of —0.1 to —0.3 and a probable pH range of 7.0 to 7.8. In most places, the middle Stairway contains abundant phosphate, again suggesting a pH in the range of 7.0 to 7.8. However, in areas of carbonate deposition the pH probably reached 8.0 or

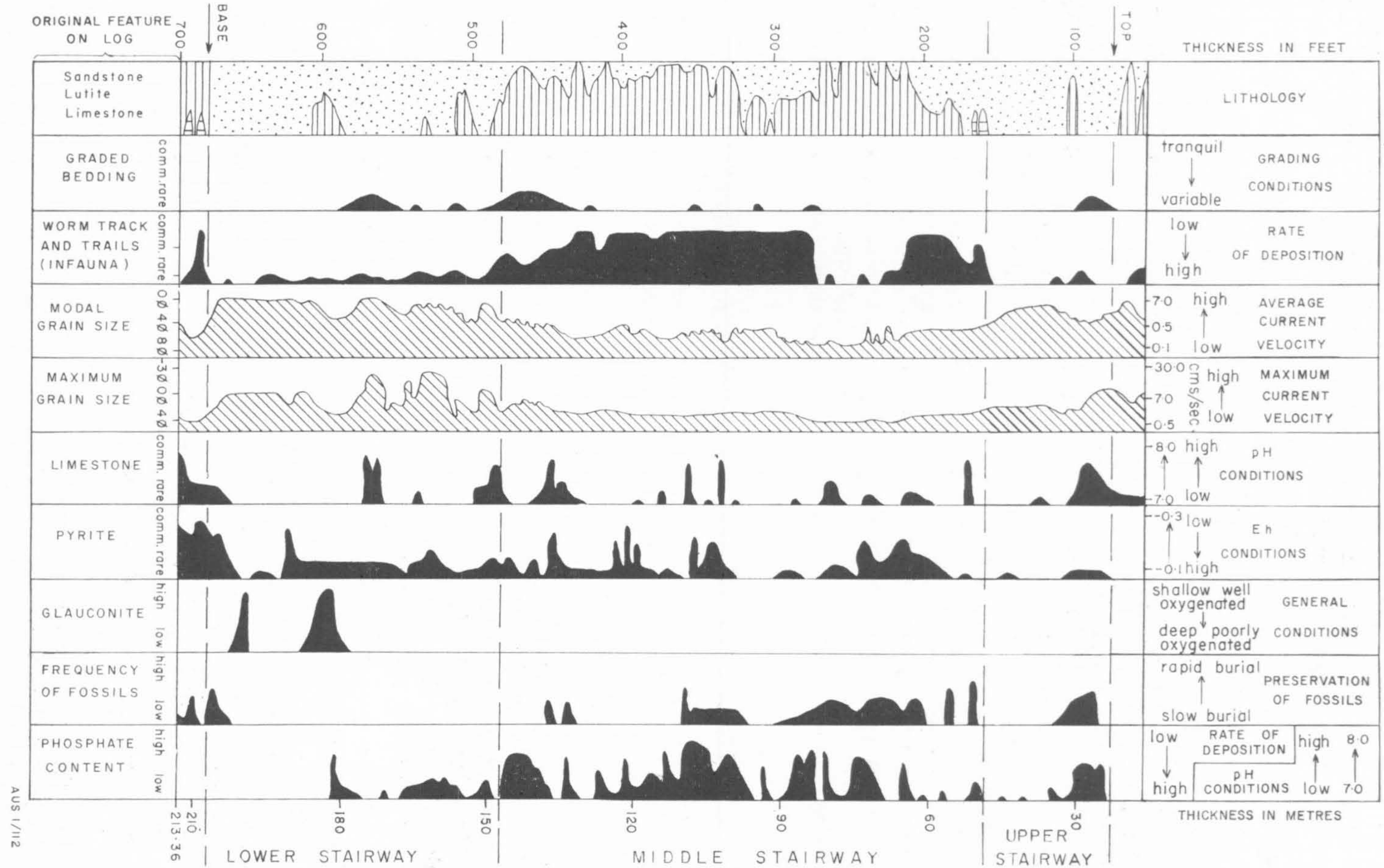

Figure 13. Vertical variation of physico-chemical conditions of deposition in the Stairway Sandstone.

greater. Similarly Eh conditions were probably variable, ranging from negative (perhaps as low as —0.4) in the western phosphorite facies, where there are abundant black organic-rich mudstones, to oxidizing conditions in the eastern redbed facies. The authigenic sediments of the upper Stairway (minor phosphate, pyrite, and glauconite), are similar to these of the lower Stairway, again suggesting reducing and slightly alkaline conditions.

Summary

The conditions of deposition for the three units may be summarized as follows. In lower Stairway time the rate of deposition was comparatively rapid, current velocities may have reached 30 cm/sec, the water was very shallow, the temperature warm, and the salinity normal marine. The water was slightly alkaline and the environment reducing (Eh down to —0.3). During middle Stairway time the rate of deposition was very slow, current velocities were small (maximum of 1 cm/sec), and the water was shallow and very warm. Salinity was normal, except in the southeast, where it was somewhat higher. The pH was generally in the range of 7.0 to 7.8 but increased to 8.0 and more to the southeast. Similarly, in most areas the Eh ranged from —0.2 to —0.4 but to the southeast became more positive. In upper Stairway time the rate of deposition increased somewhat, as did current velocities (now as high as 10 cm/sec at times). The water was very shallow, warm, and of normal marine salinity. Conditions were slightly alkaline and reducing (Eh down to —0.2).

PETROLOGY OF THE STAIRWAY SANDSTONE

The four basic rock types present are quartz arenite, lutite, phosphorite, and carbonates (mainly limestone with minor dolomite). The phosphatic sediments are dealt with later in detail.

Arenites

The vast majority of the arenites fall into the orthoquartzite class of Folk (1961) or the quartzose arenite class of Crook (1960). The arenites are for the most part remarkably 'pure' with little or no chert, feldspar, or rock fragments. A few fall into the subarkose field of Folk (1961); even fewer fall into the feldspathic sublabile arenite field of Crook (1960). In all subsequent discussion rocks are named in accordance with the scheme suggested by Folk.

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

The assemblage of minerals is extremely uniform: more than half the orthoquartzites contain less than 1 percent 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 Fig. 14). Metaquartzite grains are rare (Pl. 14, fig. 1); chert grains, though generally rare, do form up to 10 percent of the grains in some sandstones. The heavy mineral assemblage is a typical supermature assemblage of extremely well rounded tourmaline and zircon.

Both the lower and upper Stairway in hole AP1 are composed predominantly of siliceous mature orthoquartzites. There are, however, important differences between the two.

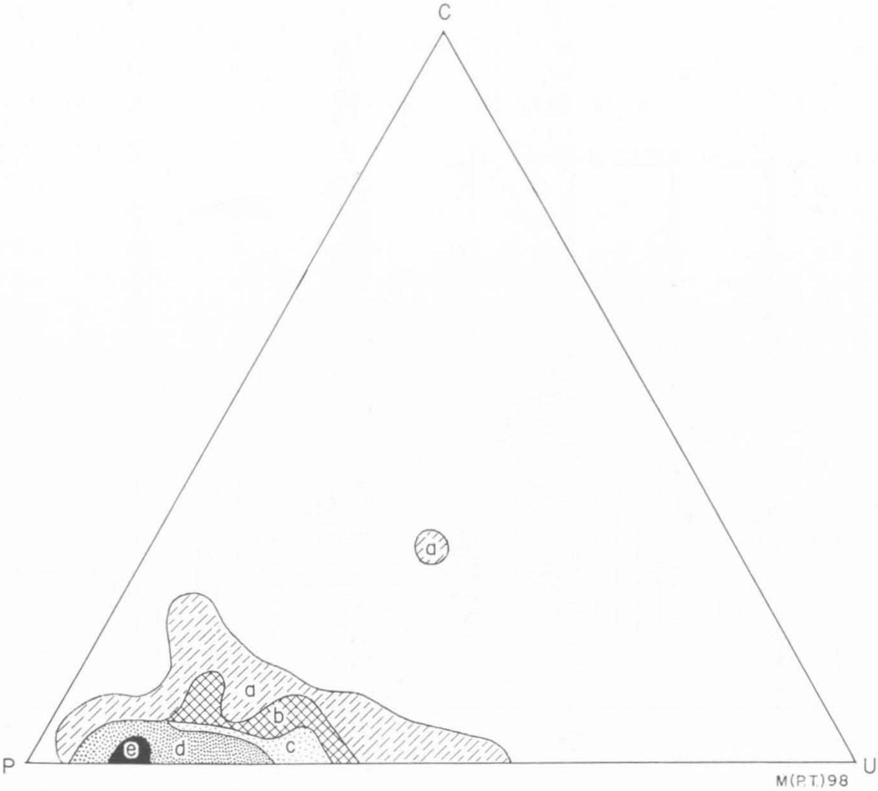

Figure 14. Quartz types in the Stairway Sandstone orthoquartzites.
P pole—plutonic or common quartz
U pole—undulose quartz
C pole—composite quartz
Blank areas—no points whatsoever
a—less than 1 point per unit area
b—1 to 2 points per unit area
c—2 to 4 points per unit area
d—4 to 8 points per unit area
e—8 to 16 points per unit area

The orthoquartzites of the lower Stairway typically have a modal grain size of 1ϕ to 2ϕ, the detrital grains are well rounded, bimodality is common (Pl. 4, fig. 2) and pyrite, glauconite, and to a lesser extent, collophane are abundant. Those of the upper Stairway on the other hand gave a modal grain size of 3ϕ to 4ϕ, rounding is poor, the sands are almost invariably unimodal, and pyrite, glauconite, and collophane are less abundant, but detrital feldspar and chert somewhat more (Fig. 15).

The orthoquartzites of the phosphatic parts of the Stairway Sandstone (i.e. Middle Stairway and the uppermost transitional Stairway) are very fine grained submature to immature orthoquartzites. Their grain size is variable, ranging from 1ϕ to 4ϕ; bimodality is fairly common; grains are subangular and sorting is moderate. The feldspar content ranges from 1 to 2 percent. Clay, carbonates, pyrite, and

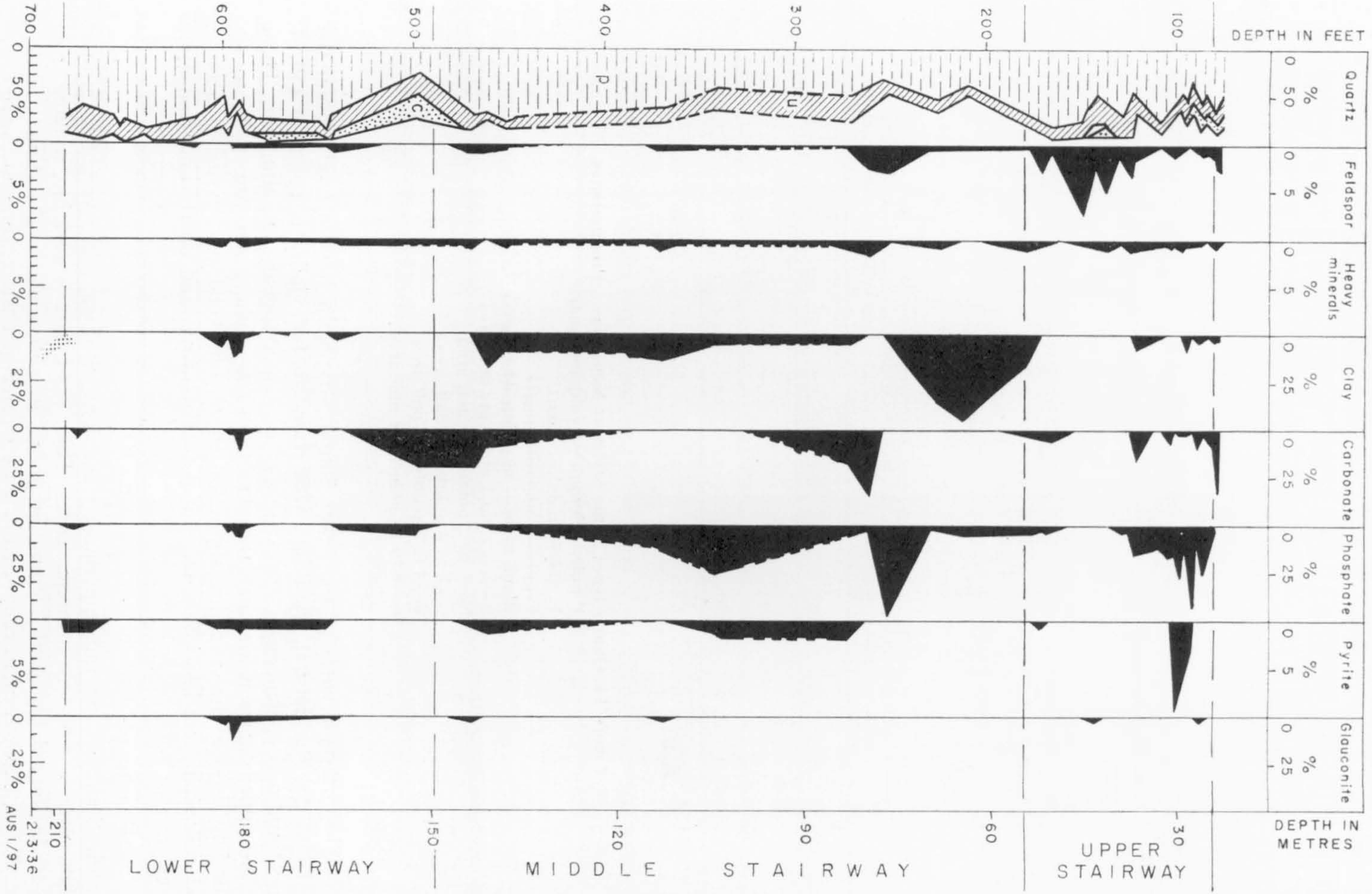

Figure 15. Mineralogical variation of Stairway Sandstone orthoquartzites in the AP1 core. P: plutonic or common quartz; U: undulose quartz; C: composite quartz.

collophane are all common. A number of inferences may be drawn from the characteristics of the orthoquartzites.

Provenance: Folk (1961) suggests that the lack of recognizable reworked grains of chert implies a granitic provenance; but abundance of 'common' (non-undulatory) quartz is considered by Blatt & Christie (1963) to be strong evidence of reworking of grains from a sedimentary source area. Non-undulating quartz is the commonest quartz type in the Stairway Sandstone and this together with the presence of chert in some of the orthoquartzites indicates that the provenance was in part, and perhaps predominantly, sedimentary.

Climate: The lack of feldspar can be interpreted as suggesting that the source area was intensely weathered in a humid tropical climate; or that 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 at the source area or the rate of abrasion, or both, may have changed somewhat in late Stairway Sandstone time.

Depositional energy: The coarseness, rounding, and sorting of grains in the basal orthoquartzite are greater than those in the higher orthoquartzites, and suggest a more vigorous depositional environment at the onset of Stairway time, or one in which the rate of sedimentation was so slow that the 'rounding mechanism' (such as abrasion within a beach environment) was able to keep pace with the sedimentation.

The presence of bimodality within the orthoquartzites suggests mixing of sediments formed in environments of different energy levels. Folk (1961) considers that this may occur in the neritic zone when, for instance, the sand grains on a sand bar are blown into a lagoon and are mixed with the finer sediments being deposited there. Folk (1968) has subsequently suggested that bimodality is a feature of many desert sands and uses some of the textural data from the Stairway Sandstone to support his hypothesis, implying that the bimodal Stairway material originally acquired its textural characteristics as a desert sand.

Diagenesis: Siliceous overgrowths in optical continuity with the grains are a common feature of orthoquartzites from both the surface and the subsurface. In places they may replace clay or carbonate cement, but generally there is no evidence of replacement and the quartz appears to be mainly pore-filling. The siliceous cement has reduced porosities and permeabilities in the potential reservoir rocks of the Stairway Sandstone. B. A. McKay (pers. comm.) carried out more than 30 porosity and permeability determinations on the Stairway Sandstone. His results give an average porosity of 8.5% with an overall range of values of from 3% to 23%. These results are considerably less than the theoretical maximum porosity of more than 40% for a sandstone, due to the siliceous cement. Permeabilities are also low, and in 80% of the samples no permeability could be detected. Values range from zero to 20 millidarcys, with an average of approximately 1 millidarcy.

The reduction of the reservoir characteristics of the Stairway Sandstone is a matter of some significance as the formation is a gas producer in the Mereenie and Palm Valley Gas Fields and consequently it is important to know when silicification took place. Many of the Amadeus Basin sediments were silicified during the Tertiary era, but the Stairway is strongly silicified at depths of several thousand feet, whereas the Tertiary effect is comparatively superficial. There are several possible causes of the silicification: it may be due to subaerial exposure and weathering of the Stairway Sandstone shortly after deposition; or the environment of deposition may have been slightly siliceous; or it may be the result of post-depositional pressure and other diagenetic reactions produced by the depths of burial and the Alice Springs Orogeny. The first two possibilities are remote; but the third could undoubtedly produce the physico-chemical changes necessary to dissolve and reprecipitate the silica. There is no correlation between the variation in porosity and permeability and depth of burial or geographical position; so the silicification probably cannot be attributed to a single cause.

Correns (1950) has shown that at a pH greater than 9, silica is quite soluble. Walker (1960, 1962) suggests that pH is important in influencing diagenesis but that the effects of raised temperature and pressure should not be minimized. Heald (1956) found no relationship between faulting and cementation, but considered that pressure solution occurred during structural deformation or under sufficient overburden. Siever (1959) agrees with Heald's conclusion and further asserts that it is impossible for the cementing silica to have come from sea water. Thus, it seems most likely that the silicification is a diagenetic feature produced by changes in the interstitial physico-chemical conditions.

Subarkose (5-25% feldspar; 0.5% metamorphic rock fragments; 75-95% quartz)

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

The few arkoses are in the very fine grained sand range and are subangular and moderately to poorly sorted; they occur mainly in the upper Stairway arenites.

The quartz of the subarkose group is predominantly of the plutonic or undulose variety; there is, however, an indication that the percentage of chert, though low, is somewhat higher in the subarkose than in the orthoquartzite. Heavy minerals are rare and allochemical minerals (clays, carbonates, etc.) are absent. The determinable feldspar is microcline, and there is a little that is unidentifiable. The relative abundance of microcline suggests that the source area was in part plutonic. 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, so the climate may have been fairly arid at the time of their deposition.

Redbeds

The redbed sediments are very fine grained sandy or silty immature orthoquartzites, but have a distinctive red colour. They are restricted to the middle Stairway, in the southeast corner of the basin (Fig. 8).

The grain size ranges from 3ϕ to 5ϕ; the grains are angular and sorting is moderate to poor (Pl. 6, fig. 2). The quartz types are those of the 'normal' orthoquartzites except that composite quartz and chert are slightly less common. Only a few samples contain feldspar (up to 2%). Heavy minerals are present only in very small quantities. Pyrite, glauconite, phosphate, and carbonate are absent, but ferruginous clay forms 5-20% of the total rock, and imparts the red

* Subsurface core sample numbers have the drill hole number (AP1 etc.) as prefix; the second number identifies the sedimentation unit and the third gives the distance in inches from the top of the sedimentation unit. Hence, specimen AP1/112/11 was collected from 11 inches below the top of sedimentation unit 112 in the AP1 core. The prefix on the surface sample number indicates the 1:250,000 Sheet area from which the sample was collected; thus LA 188 was collected from the Lake Amadeus Sheet area.

colour to the sediments. Generally, quartz grains are not in contact and each grain is coated by red ferruginous clay (Pl. 6, fig. 2). Some quartz grains, however, are found in groups with no matrix, but a red coating round each group.

Observations made on the AP2 and AP3 cores suggest that in places redbeds have a gradational boundary with the more normal white sandstones. There is abundant evidence from other studies (Walker, 1967a,b; Walker et al., 1967, 1969) that most redbeds form as a result of in situ alteration, particularly in a hot arid climate. One of the puzzling features of the Stairway Sandstone redbeds is a lateral facies change from redbed to carbonate to phosphorite. Precisely the same facies change occurs in the Phosphoria Formation (Sheldon, 1963), and there might therefore be some environmental control. An alternative explanation is that a hot arid source lay to the southeast and supplied iron-bearing detrital grains such as hornblende and biotite, from which the red authigenic hematitic matrix was derived.

Lutite

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

Siltstone

Siltstones do not differ markedly in mineralogy from the orthoquartzites and may be considered as orthoquartzite-type siltstones. The only differences are in grain size (4ϕ to 8ϕ), the subangular form of the grains, a slightly higher percentage of feldspar, and the very much higher percentage of clay matrix (Pl. 5, fig. 1). The detrital grains may also be less well sorted and rounded. There was probably little difference in provenance or climate between the orthoquartzite and the siltstone. The siltstone is less mature texturally, probably because it was deposited in a less vigorous environment than the orthoquartzite—possibly fairly deep neritic or lagoonal, as is suggested by the relatively high percentage of clay matrix.

Claystone

Claystone may form as much as 10-20 percent of the total thickness of the formation. Detrital quartz of very fine sand or silt size commonly forms 5-10 percent of the claystone, the quartz being the usual assemblage of plutonic (common) and undulose quartz with only very minor composite quartz and chert. A small percentage of feldspar and heavy minerals is present. Fine flakes of mica are common, pyrite is rare, phosphatic material varies from 0 to 5 percent, and glauconite is absent. The percentage of carbonate (calcite, dolomite, or siderite) is generally low. Plate 5, figure 2, is an example of a sideritic claystone, with patches of ?authigenic siderite about 0.05 mm across. X-ray diffraction analysis by Crook (1964) has shown that the dominant clay mineral is illite (70-100%) with minor kaolinite (0-30%) and chlorite (0-12%). The abundance of illite is consistent with marine sediment, although the presence of chlorite suggests it may be fairly near shore. However, the clay mineral data are insufficient for any far-reaching conclusions to be drawn.

Carbonates

Calcite and dolomite are known to occur as thin interbeds within the Stairway Sandstone but are not common. Patchy developments of siderite occur in the claystone. Both the limestone and the dolomite may contain significant amounts of terrigenous quartz ranging from very fine sand to coarse silt. The quartz is predominantly the usual plutonic and undulose varieties and is angular to subround and moderately sorted. Feldspar and heavy minerals form a very minor part of the terrigenous fraction, but clays may form 0-20 percent of the rock. One to two percent of phosphate and pyrite are commonly present and the phosphate content may be as high as 10 percent. Glauconite is absent. The composition of the terrigenous fraction suggests little or no change in provenance or climate during the deposition of the carbonates.

The limestones are mainly micrites and biomicrites, but clayey micrites (e.g. AP1/184/0) and ?dismicrites (e.g. AP1/74/1) are known. Fossils are mostly brachiopods, gastropods, and pelecypods, and generally occur as large fragments or whole fossils, with few signs of severe fragmentation. This, together with the micritic nature, suggests that the calcite (or perhaps aragonite originally) was laid down in a low energy environment. Folk (1961) considers that there are four environments where this type of sedimentation occurs: in shallow protected lagoons, on broad shallow platforms in the lee of barriers, in moderately deep water in geosynclines, and in areas of organic baffling. The fossil content suggests that the first or second possibility is the more likely. The fact that the limestone beds are very thin and commonly alternate with arenites is further evidence in favour of the lagoonal environment.

The dolomites range from aphanocrystalline to coarsely crystalline. The rhombic form of much of the dolomite (Pl. 6, fig. 1) suggests that it is secondary, formed by the diagenetic replacement of calcite in response to changes in the physico-chemical conditions.

HEAVY MINERAL STUDIES

Forty-two samples from the AP1 core were disaggregated and the heavy minerals separated off, using bromoform. Authigenic minerals such as collophane and pyrite were common contaminants; counting of a minimum of 200 grains was restricted to the detrital minerals. The heavy minerals constitute a typical supermature assemblage composed primarily of tourmaline and zircon. Very small amounts (1-2%) of apatite, garnet, and rutile are also present in some samples. Pettijohn (1949) has shown that diagenesis can markedly affect the heavy mineral suite and thought that the more unstable minerals (hornblende, etc.) are removed in progressively older rocks. Thus, it is not surprising that the assemblage in Ordovician rocks is primarily tourmaline and zircon.

Tourmaline occurs as brown, green, blue, grey, pink, or colourless forms, of which the brown and green are the commonest. Zircon occurs in two common clear forms, and the rarer purple type. Most grains are extremely well rounded (Pl. 7, figs 1 & 2) either by prolonged abrasion or chemical action or both, or more probably from the reworking of older sediments. The occurrence of both euhedral and well rounded zircon in a single sample at a depth of approximately 350 feet (120 m) in AP1 suggests that at times there was a mixed crystalline and sedimentary source area. It was observed that the diameter of tourmaline is commonly two to three times that of the zircon grains, presumably because the tourmaline has a more tabular habit and a considerably lower specific gravity than zircon. A few overgrowths on tourmaline, of a type described by Awasthi (1961), were noted. Various types of inclusions are common.

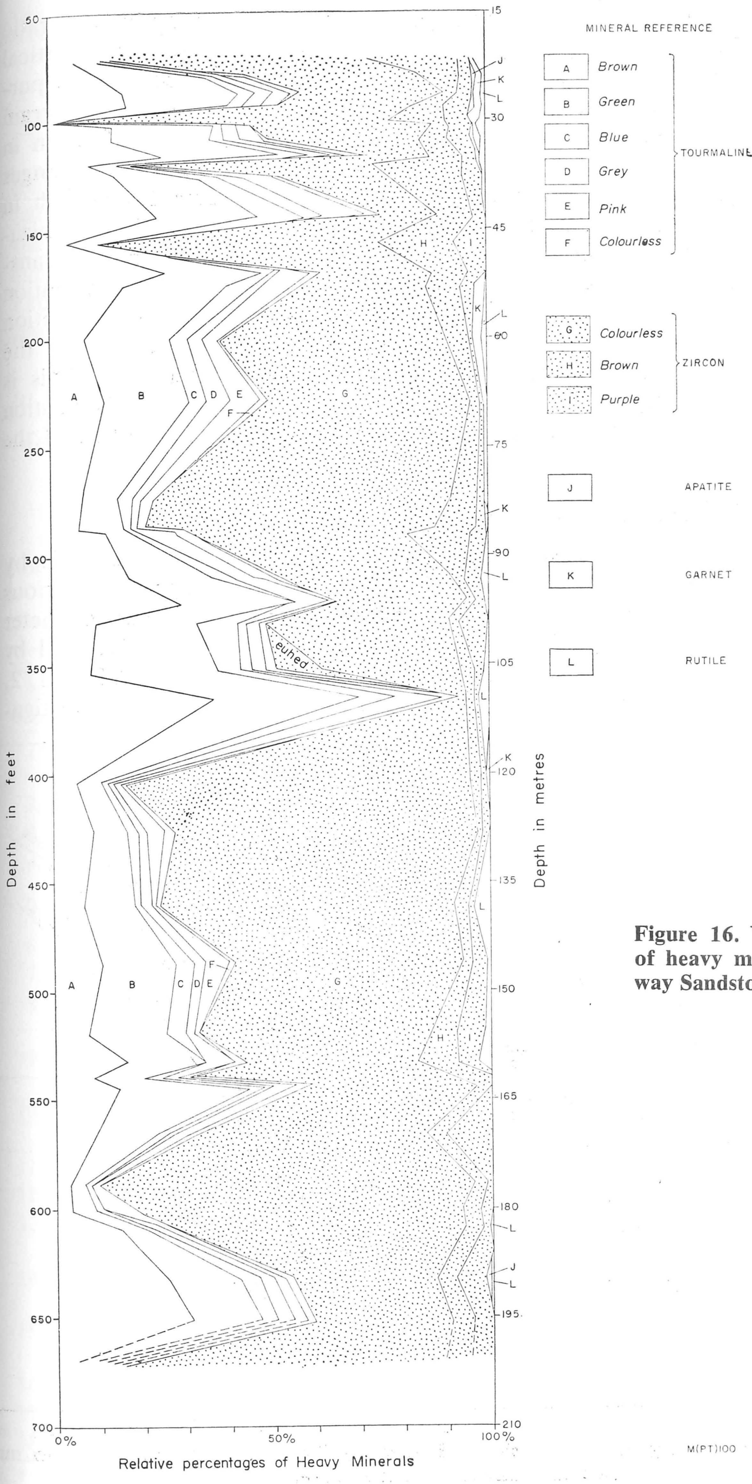

Figure 16. Vertical distribution of heavy minerals in the Stairway Sandstone of the AP1 core.

There are numerous marked variations in the tourmaline:zircon ratio throughout the AP1 core (Fig. 16); the changes occur over such short vertical distances that heavy mineral studies are likely to be little use for correlation purposes in the Stairway Sandstone. The variations were not influenced by grain size. Possible causes include changes in the source area such as modification in the drainage pattern or climatic changes (unlikely in view of the rapid changes in the ratio); progressive erosion of stratiform rocks with some layers rich in tourmaline and others rich in zircon (again unlikely because of the homogenization which sediments undergo during transport and deposition); and minor transgressions and regressions. Bruckner & Morgan (1964) showed that the distribution of heavy minerals on the west African continental shelf was related to the position of the strand-line. Similarly in the Stairway Sandstone minor changes in the strand-line would superimpose a previously lateral heavy mineral suite. This is supported by the similarity between Figure 16, showing the vertical distribution of the heavy mineral suite, and Figure 20, showing the vertical distribution of the sedimentation units.

DETAILED TEXTURAL ANALYSES

Twelve thin sections from AP1 were subjected to detailed textural analysis by Packham's (1955) method, using a six-spool Leitz integrating stage. The various percentiles (ϕ_{95}, ϕ_{84}, etc.) were obtained and the values for mean diameter (Mz), standard deviation (d_1), skewness (sk_1) and kurtosis (Kg) calculated by the method of Folk & Ward (1957). Some of the 18 analyses (those on AP1/51/2, AP1/112/70, AP1/601/0, and AP1/755/0) were made as part of the investiga-

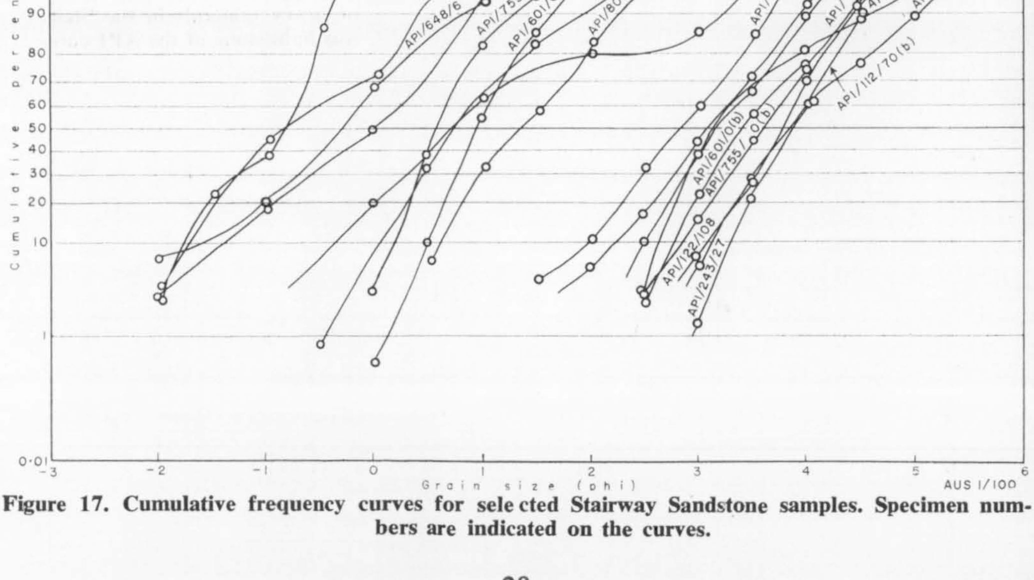

Figure 17. Cumulative frequency curves for selected Stairway Sandstone samples. Specimen numbers are indicated on the curves.

tions into the origin of phosphorites and are discussed in some detail by Cook (1967b). All values are expressed in phi (ϕ) units (equivalent to the negative log to the base 2 of the grain diameter in mm; Krumbein, 1934, see also McManus, 1963).

The cumulative frequency curves (plotted on probability paper), of the 18 analyses are shown in Figure 17. There are two main textural groupings. On the extreme left of the coarse group the sediments are mainly phosphatic pellets. On the right side of the coarse group the sediments comprise mainly the coarse basal sands plus the coarse sands associated with phosphorites. The fine group on the extreme right of the graph is made up of fine and very fine sands from the upper middle Stairway and from within phosphatic pellets.

The discussion here on the significance of the textures is limited primarily to the non-phosphatic sediments.

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, while the middle and upper Stairway sands are in

TABLE 1. NUMERICAL VALUES OF TEXTURAL PARAMETERS FOR SELECTED SAMPLES IN THE STAIRWAY SANDSTONE

Specimen No. API/	*Lithological type*	*Median Diam. (phi)*	*Mean Diam. (phi)*	*Standard Deviation (phi units)*	*Skewness*	*Kurtosis*
1*. 51/2	Pellets included in grain count	0.72	1.13	1.34	0.33	0.93
2. 108/110	Indurated fine sandstone	3.12	3.13	0.66	—0.02	1.05
3. 112/70 (a)	Indurated fine sandstone	3.86	3.84	0.54	—0.01	0.93
4. 112/70 (b)	Detrital grains within pellets	3.20	3.21	0.57	0.08	0.96
5. 112/108	Indurated fine sandstone	3.78	3.77	0.53	—0.01	1.21
6. 243/27	Sandy mudstone	3.85	4.03	0.67	0.39	1.00
7. 472/18	Bimodal sand	3.17	3.36	0.78	0.47	1.17
8. 601/(a)	Only detrital grains outside pellets	1.35	1.35	0.67	0.07	0.90
9. 601/0 (b)	Detrital grains within pellets	0.97	1.00	0.45	0.17	1.20
10. 601/0 (c)	Phosphatic pellets and detrital grains	3.38	3.48	0.63	0.27	0.90
11. 601/0 (d)	Only phosphatic pellets	0.31	0.01	1.03	—0.35	0.86
12. 648/6	Lower Stairway Sst	—0.85	—0.67	0.98	0.28	0.84
13. 755/0 (a)	Grains outside phosphatic pellets	—0.33	—0.33	0.99	—0.05	1.33
14. 755/0 (b)	Detrital grains within pellets	0.65	0.66	0.44	0.16	1.24
15. 755/9 (c)	Phosphatic pellets & detrital grains	3.60	3.59	0.58	—0.02	1.00
16. 761/13	Lower Stairway Sst	0.03	—0.14	0.90	—0.25	0.94
17. 792/66	Lower Stairway Sst	2.85	2.84	0.68	—0.05	1.07
18. 803/5	Lower Stairway Sst	0.80	0.88	0.75	0.23	1.15

* 1-5 upper Stairway, 6-11 middle Stairway, 12-18 lower Stairway

the very fine sand range (Table 1). This suggests that vigorous conditions prevailed in lower 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. d_1 ranges from 0.54 to 0.99 phi units. All the sands fall into the moderately well sorted range of Folk & Ward (1957). The finer sands tend to be slightly better sorted than the coarser. Friedman (1961) has shown that the environment of deposition of moderately sorted coarse sand such as that present in the lower Stairway may be river, beach, or continental shelf.

The environment of deposition of moderately well sorted very fine sands, of the type for instance of the middle Stairway, 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 a measure of the asymmetry of a curve about the modal grain size and 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 API/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 suggests that the environment in which they were deposited and acquired their textural characteristics was not later modified by winnowing or other processes. The strongly fine skewed sands in the middle Stairway suggest that there sands from two different environments may have been mixed to produce a bimodal sediment.

Kurtosis (Kg)

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

The Stairway sands have a kurtosis range of 0.90 to 1.33, but most are mesokurtic (ranging from 1.10 to 1.33). The lower sands range from platykurtic to leptokurtic; the middle and upper sands are mesokurtic or leptokurtic. Winnowing might have produced some of the leptokurtic values, but the mesokurtic form of many of the sediments supports the earlier suggestion that most of the non-phosphatic sediments acquired their textures in the environment in which they were finally deposited. The textures were not, in other words, inherited from an earlier environment (as appears to be the case with some of the sands associated with the phosphorites). The lack of any extreme skewness or kurtosis values suggests that any mixing has occurred between similar (and probably adjacent) environments, and 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.

Mason & Folk (1958) were able 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. 18A and B) but in neither case was there any environmental separation. However, a definite separation of points is achieved by plotting standard deviation against mean diameter (Fig. 19A) and standard deviation against kurtosis (Fig. 19B). Two fields (I and III—phosphatic pellets and coarse sands, associated with pellets) are common to both plots, but Fields II and IV (coarse lower Stairway and fine middle to upper Stairway sands respectively) are unique to the standard deviation/mean diameter plot and Field V (mixed sands plus the fine sandy material found within phosphate pellets) is unique to the standard deviation/kurtosis plot.

Standard deviation against kurtosis produces a 3-field separation (Fig. 19B), the implication of which is that fairly similar environmental processes produced all the non-phosphatic sediments, but that two distinct processes produced the textures of the phosphatic pellets, and the coarse sands associated with the pellets. The position of Field V between I and III may indicate that the textures represented by 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 (Fig. 19A). It is apparent from the splitting of the mixed fine and coarse Field V into Fields II (coarse sands) and IV (fine sands) that different depositional processes are acting within the same basic environment. Field IV appears to be the environment in which the phosphate is precipitated, but is modified by, for instance, winnowing to produce the field in which the phosphate pellets are concentrated. This is discussed in more detail by Cook (1967b).

A number of attempts have been made to distinguish between depositional environments by substituting textural parameters into various formulae. One of the more recent attempts has been made by Sahu (1964), who has introduced the use of the 'discriminant function' (Yu) into the determination of depositional environments in ancient and recent sediments. Using various equations, Sahu maintains that it is possible to distinguish between aeolian, beach, shallow marine (down to depths of 100 m), fluviatile, and turbidity current environments.

On substituting the textural parameters for the Stairway Sandstone (Table 1) into the four equations given by Sahu, it was found that the sediments fell into the shallow marine field, the beach field, or the fluviatile field (Table 2). In addition, almost every sediment fell into the turbidity current field; this last result is completely inconsistent with every depositional feature of the Stairway Sandstone and suggests that the equations are of somewhat doubtful value when applied to the Stairway Sandstone.

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 marine field and the beach field and AP1/684/6 has a value of the discriminant function which indicates a fluviatile environment (the coarse sands associated with phosphatic sediments give discriminant function values consistent with a beach environment).

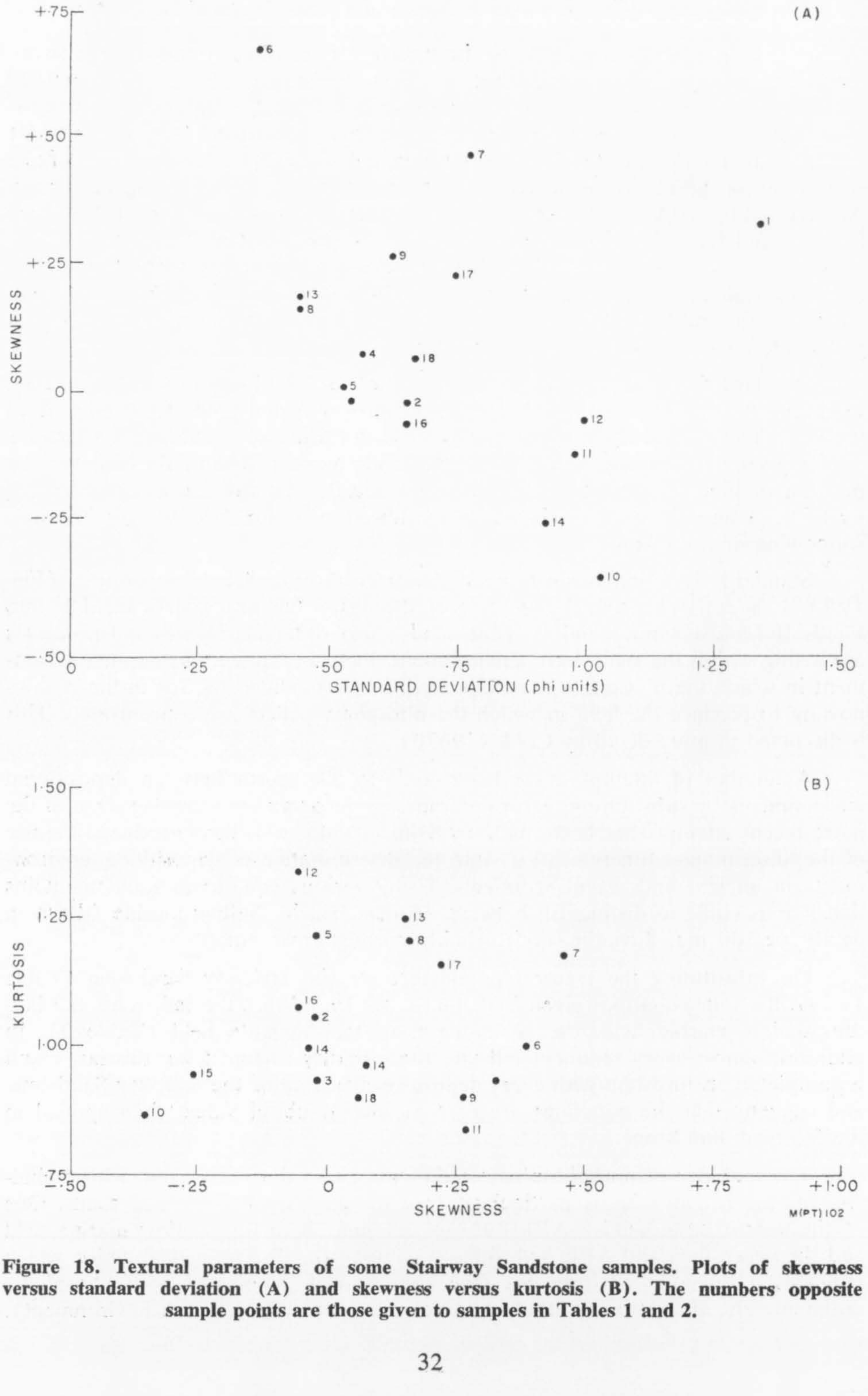

Figure 18. Textural parameters of some Stairway Sandstone samples. Plots of skewness versus standard deviation (A) and skewness versus kurtosis (B). The numbers opposite sample points are those given to samples in Tables 1 and 2.

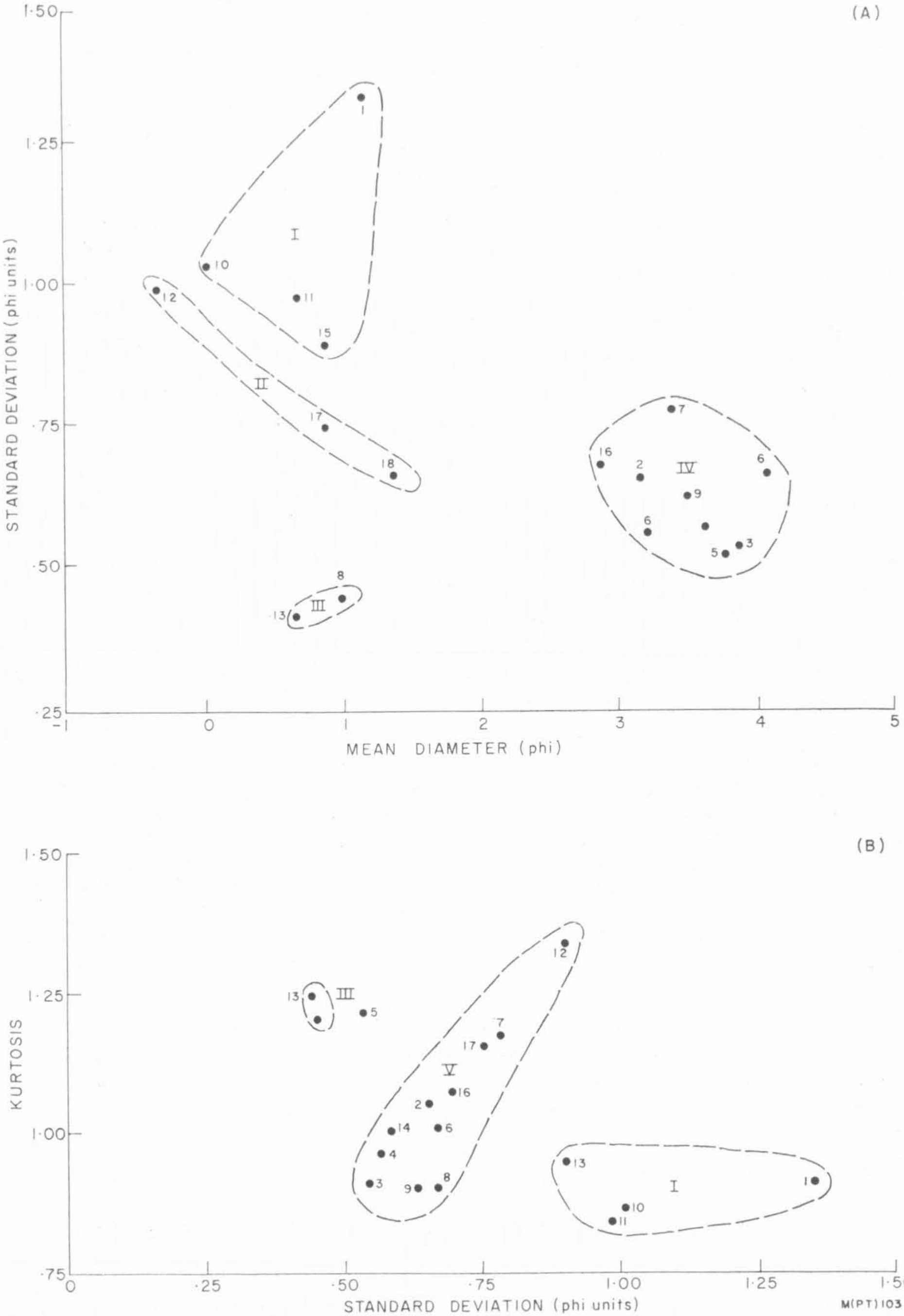

Figure 19. Textural parameters of some Stairway Sandstone samples. Plots of mean diameter versus standard deviation (A) and kurtosis versus standard deviation (B). The sample equivalents of the point numbers are given in Tables 1 and 2.

TABLE 2. DETERMINATION OF DEPOSITIONAL ENVIRONMENTS FROM THE TEXTURAL PARAMETERS

Specimen No. API/	*Values obtained for discriminant function (Yu)* beach vs aeolian	beach vs shallow marine	shallow marine vs fluviatile	Inferred environment
1. 51/2	—1.3270	159.1490	—17.0159	Beach
2. 112/70 (a)	—6.2310	96.9745	—2.8134	Sh marine
3. 112/70 (b)	—9.7142	96.1936	—1.4494	Sh marine
4. 118/110	—7.4484	90.4870	—1.6320	Sh marine
5. 122/108	—8.6715	99.6209	—1.2705	Sh marine
6. 243/27	—10.4130	118.2148	—4.6529	Sh marine
7. 472/18	—7.0664	123.5812	—6.6289	Indeterminate
8. 601/0 (a)	0.5547	54.0786	—2.2409	Beach
9. 601/0 (b)	—8.6973	102.3000	—3.7895	Sh marine
10. 601/0 (c)	7.2924	79.3843	—9.1110	Fluviatile
11. 601/0 (d)	7.9785	73.2065	—0.9307	Fluviatile
12. 648/6	12.4483	85.4085	—8.2647	Fluviatile
13. 755/0 (a)	1.8764	48.6583	—2.1396	Beach
14. 755/0 (b)	—8.4097	96.4243	—1.9137	Sh marine
15. 755/0 (c)	6.9438	63.9000	—5.8672	Sh marine
16. 761/13	2.0799	93.5761	—3.2087	Sh marine
17. 792/66	2.0353	76.0166	—5.7368	Sh marine
18. 803/5	—1.3185	59.6551	—3.8563	Beach/sh marine

Thus it is apparent that the coarse basal sands have some beach, shallow marine, and possibly fluviatile characteristics. There is no evidence from any other source to support fluviatile influences in the Stairway Sandstone. It is conceivable that tidal channel sediments may acquire some of the textural characteristics of fluviatile sands. It can be seen from Table 2 that pelletal phosphorites have Yu values consistent with fluviatile sedimentation; this is also rejected as most unlikely. Thus, again it is apparent that the equations of Sahu (1964) can be applied to the Stairway Sandstone only with a great deal of caution, although the relatively large diameters of the pellets probably introduced an artificial element compatible with high flow regime into the system.

The middle and upper Stairway fine-grained sands consistently give Yu values compatible with a shallow marine environment. The moderately sorted fine skewed leptokurtic or mesokurtic nature of the middle Stairway sands also suggests some mixing of sediments such as might occur in a very shallow near-shore, or transitional environment. The basal sands were deposited under rather more vigorous shallow-water conditions.

ENVIRONMENTAL RECONSTRUCTION FROM THE GRAPHIC LOG

The basic tool used here for the reconstruction of the Stairway depositional environment is the detailed graphic log (Pls 15-22). Detailed graphic logs have been used by Bouma (1962) for the delineation of turbidity current environments, but have seldom been used in the interpretation of shallow marine sediments. Any interpretation of the graphic log of a vertical sequence such as that in AP1 hinges on the application of Walther's Law of Facies (Walther, 1893-94) which in effect states that where there are no time breaks, sediments which succeeded each other vertically must also succeed each other laterally, that is, the vertical sequence is a reflection of the lateral sequence.

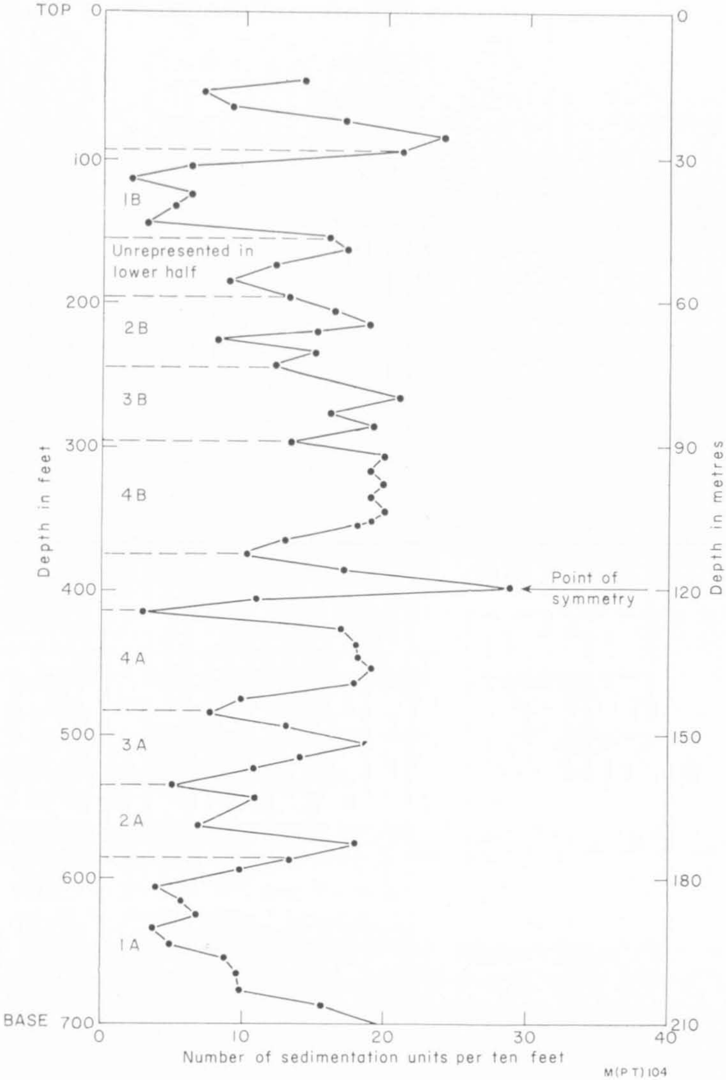

Figure 20. Vertical variation in the number of sedimentation units per unit 10-foot (approximately 3 m) interval, in the AP core.

It is already apparent from the petrography, the fossils, the general lithological picture, and the size analyses, that the Stairway Sandstone is a shallow marine sequence, and therefore the search for models may be limited to Recent shallow marine sediments. The shallow marine facies, however, includes such diverse environments as open shelf, marine deltaic, tidal flats, lagoonal, and estuarine.

Though it may be possible to distinguish between any two of these by a method such as size analysis, no single method can be used to distinguish between all the possible environments, despite intensive studies of shallow marine sediments (e.g. van Andel & Curray, 1960; Shepard, 1960). Therefore it is necessary to look at the overall picture of sedimentation before reconstructing the specific shallow marine environment in which the Stairway Sandstone was laid down.

The first point which must be established is whether the sequence is transgressive or regressive or a combination of both.

Evidence of repetition is 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 Figure 20. The plot of the vertical variation of thickness of sedimentation units has been constructed from graphic log data and could conceivably give a qualitative guide to the stability or changeability conditions—the greater the number of sedimentation units per 3 m (10 ft) standard interval, the greater the instability. However, changes in grain size, diastems, and erosion also affect the thickness of the sedimentation unit. What the plot does undoubtedly show is that the upper part of the formation is the mirror image of the lower part, with a point of symmetry at about 120 m, 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 (B) is shown in Figure 21. Such bilateral symmetry obviously precludes a three-fold sequence such as transgression-regression-transgression and can only be a response to a transgressive-regressive or regressive-transgressive cycle. If the lower half of the formation is considered, it is apparent from Figure 13 that there is a vertical variation (and from Walther's Law a lateral variation also) in a number of features.

These upward changes from lower to middle Stairway are:—

(i) From coarse arenites to fine lutite.
(ii) From 'unchewed' sediments to strongly chewed sediments.
(iii) From non-phosphatic to phosphatic sediments.
(iv) From glauconitic to non-glauconitic sediments.

Such features are regarded by Visher (1965) as suggesting that the sequence is regressive. This is supported by the fact that the coarsest sediments are found near the top of the lower Stairway: in transgressive sands Visher finds that the coarsest sands occur at the base of the sand sequence. Also, in general, blanket sands such as the lower Stairway generally form in a regressive sequence. Further proof is available from field data, for the southern limit of the Horn Valley Siltstone (below the Stairway Sandstone) coincides with the southern limit of the lower and middle Stairway. This would not be the case had a major transgression occurred at the base of the lower Stairway Sandstone. By contrast, there is substantial onlap by the upper Stairway (Fig. 2). Therefore we can conclude that the Stairway Sandstone is a regressive-transgressive shallow marine sequence. Having established the 'mega-environment' it is possible to determine the macro and micro-environments from the graphic log.

The Sedimentation Unit

Otto (1938) defines the sedimentation unit as 'that thickness of sediment which was deposited under essentially constant conditions'. The smallest sedimentary division of the graphic logs is equivalent to the sedimentation unit, and in all over 800 have been recognized in the Stairway Sandstone (Pls 15-22). Very few of these 800 units are exactly the same and therefore it is difficult to work out a simple environmental picture for a sedimentation unit or for a group of sedimentation units. In addition, as each sedimentation unit has up to 30 parameters within it, such as graded bedding, modal grain size, maximum grain size, etc., there are approximately 25,000 sedimentary features to consider in the whole formation. The handling of such a mass of data proved difficult.

In order to group the data into a more manageable form, the incoming of phosphate was taken as indicating an important environmental event. The base

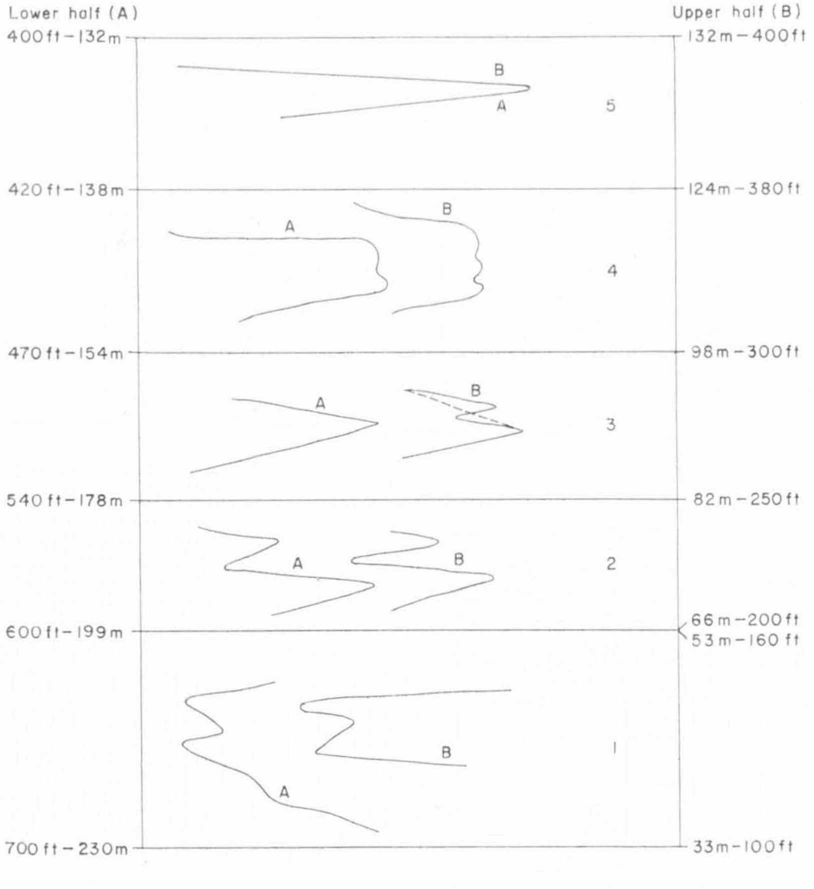

Figure 21. Comparison of various parts of the plot in Figure 20 to indicate the presence of mirror symmetry in the sedimentation unit frequency plot.

of each composite sedimentation unit is marked by the incoming of a new phosphate band. There are a total of 192 composite sedimentation units, each made of two or more simple sedimentation units. Qualitative consideration of the characteristics of the composite units reveals six basic types referred to as A, B, C, D, E, or F. Some of the characteristics of the six units are summarized in Table 3. The order of the composite sedimentation units was established essentially on their order of occurrence.

TABLE 3. AVERAGE VALUES OF SOME LITHOLOGICAL PARAMETERS OF THE SIX COMPOSITE UNITS MAKING UP THE COMPOUND SEDIMENTATION UNIT

Composite Sedimentation Unit	*Part of Sequence*	*Thick-ness (cm)*	*% of units with sedimentary structures*			*Detrital grains*		*CaCO$_3$ present*	*Porosity*		*Degree of induration*	*Pyrite*	*Phosphate material*	
			Biotur-bation	*Cross-bedding*	*Graded bedding*	*Mode*	*Maximum diameter (phi)*		*Inter-granular*	*Vuggy*			*amount present*	*Maximum diameter of pellets (phi)*
F	(non phos-phatic)	38	58%	0	0	fine silt	2.8	40	low	nil	4	rare	nil	
	(phos-phatic)	83	55%	0	0	clayey-silt	2.1	no	low	nil	4	rare	4.46%	—2.3
E	(non phos-phatic)	256	72%			clayey-silt	3.3	no	low	nil	4	rare	nil	
	(phos-phatic)	7	10%	0	0	very fine sand	2.5	very minor	low	nil	4	rare-common	13.8%	—2.5
D	(non phos-phatic)	14	45%	0	0	clayey-silt	3.3	no	nil	nil	4	rare	nil	
	(phos-phatic)	5	20%	0	0	fine sand	1.7	very minor	low	nil-rare	4	rare-common	11.8%	—1.1
C	(non phos-phatic)	28	55%	0	10%	very fine sand	2.1	very minor	low-moderate	nil-rare	4	rare	nil	
	(phos-phatic)	17	28%	0	0	medium sand	1.3	no	low-moderate	nil-rare	3-4	rare	7.2%	—1.5
B	(non phos-phatic)	350	16%	7%	0	fine sand	1.5	minor	low-moderate	rare-common	4	rare	nil	
	(phos-phatic)	13	0	0	0	medium sand	0.4	no	low	nil	4	rare-common	7.1%	—1.3
A	(non phos-phatic)	38	33%	0	30%	fine sand	1.5	no	moderate	rare	4	rare	nil	
	(phos-phatic)	137	35%	24%	30%	medium sand	0.5	no	moderate	common	3-4	rare	2.8%	—2.1

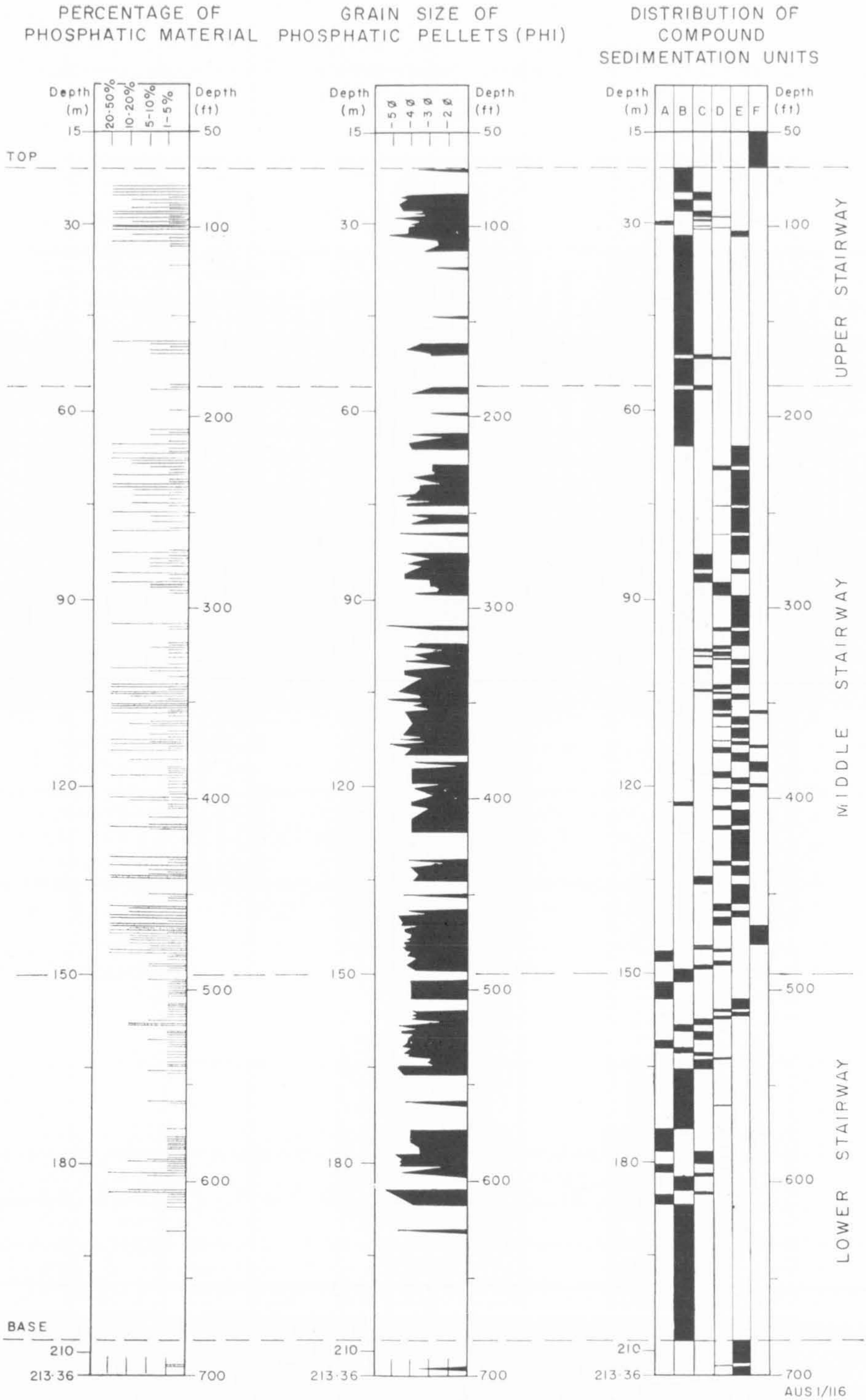

Figure 22. Vertical distribution of various parameters in the Stairway Sandstone of the AP1 core.

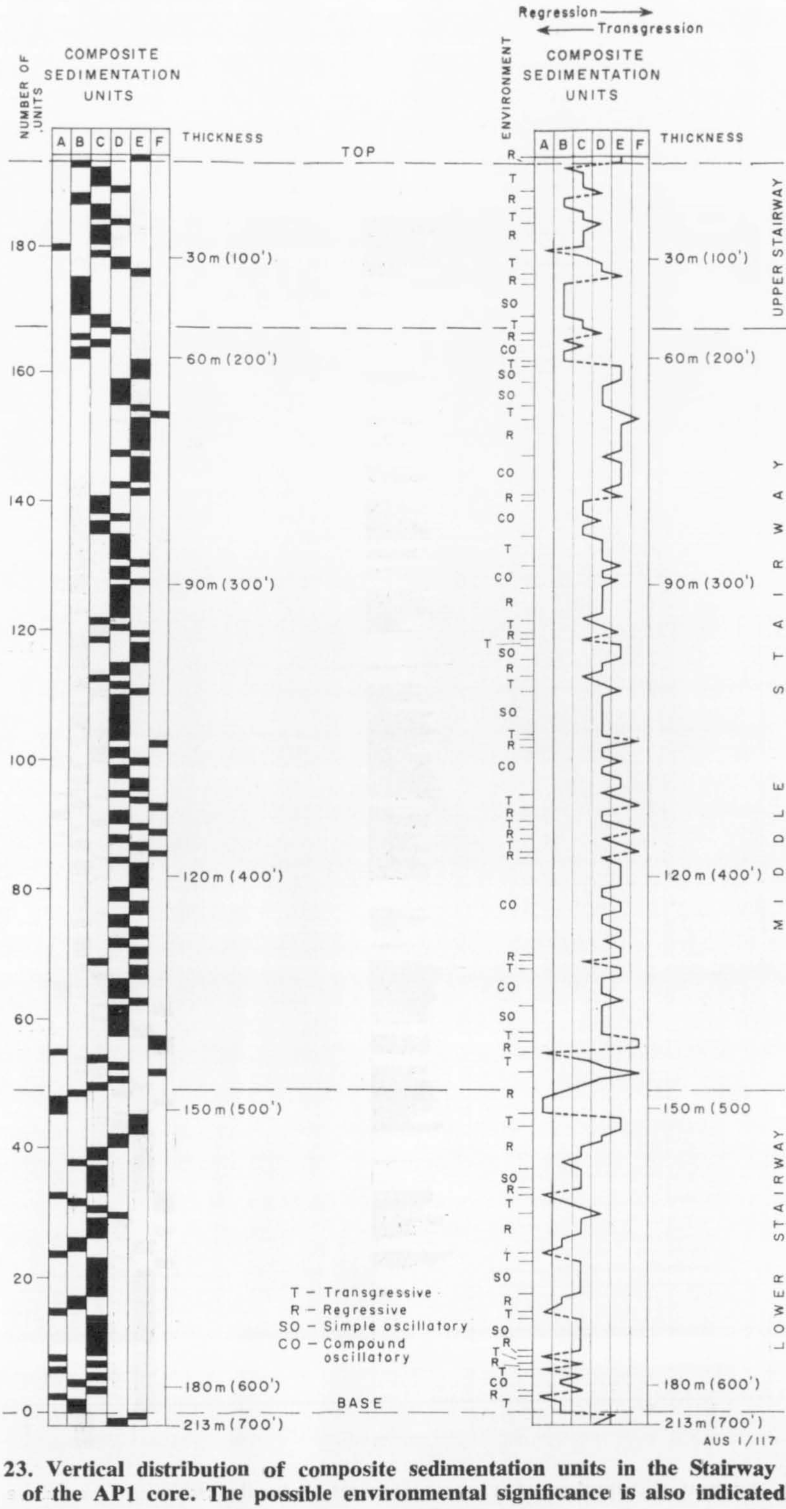

Figure 23. Vertical distribution of composite sedimentation units in the Stairway Sandstone of the AP1 core. The possible environmental significance is also indicated.

The vertical distribution of the six composite sedimentation units is shown in Figure 22. 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 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 from Figure 22 that in the lower half of the formation (below about 120 m) there is an ascending sequence of A-B-C-D-E-F. In the upper half of the formation the ascending sequence F-E-D-C-B-A is present. As it has already been established that the basal sequence is regressive, then the A-F sequence must be regressive, and the F-A sequence transgressive.

The vertical distribution of the composite sedimentation units is shown in Figure 23. The vertical scale is the number of composite sedimentation units; a non-linear metric scale gives the approximate position in AP1. The actual form of the cyclicity is now apparent and it can be seen that there is not one major regression-transgression only, but a series of smaller regressions and transgressions.

The Compound Sedimentation Unit

The compound sedimentation unit is made up of the 6 composite units A, B, C, D, E, and F. It is an idealized complete sequence for as can be seen from Figure 23 there are few complete, unbroken A-F sequences in the formation. Many of the sequences shown in Figure 23 cannot be designated as indicating regressive (R) or transgressive(T)for they are made up of the same unit repeated (C-C-C-C etc.), which is designated 'simple oscillatory' (SO), or of repeats of adjacent composite sedimentation units (C-D-C-D-C-D etc.), designated 'compound oscillatory' (CO). Within the Stairway Sandstone there is evidence of 25 episodes of significant regression and transgression, 9 separate episodes of simple oscillatory sedimentation, and 8 episodes of compound oscillatory sedimentation.

The compound sedimentation unit A-F (Fig. 24), can then be compared with sedimentological models. To do this 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. There is also a more hypothetical epeiric sea model which suffers from the lack of a modern counterpart, but which has been described in some detail from the geological record. The subfacies and their composite sedimentation equivalent are given in Table 4.

The Intertidal Flat Model

The intertidal flat environment of the Wash Estuary of East England, and its subfacies, is well documented by Evans (1965). The suggested correlations of units A to F are given in Table 4 and also in Figure 25. Let us look briefly at the various facies as described by Evans and the possible Stairway equivalents.

(A) *The lower sand flat* (j). This is a zone of minor reworking by boring organisms, with slow sedimentation, minor wave action, and strong tidal currents, which produce well developed mega-ripples. Had such currents been operating during the deposition of composite unit A they would have produced cross-bedding indistinguishable in the core from any other form of cross-bedding and could have brought in phosphatic pellets from other parts of the basin. Bioturbation was evidently more common in unit A than in the lower sand flat.

(B) *The lower mud flat* (k). This is a zone of little reworking by waves or organisms; consequently there would have been little reworking and winnowing of any phosphatic pellets which might be present. Therefore one would expect little concentration of phosphatic pellets in unit B. In addition the lower mud flat is a zone of rapid sedimentation; this is consistent with the low phosphorite:sand ratio found in unit B. The main discrepancy between unit B and lower mud flat sediments lies in the fact that unit B is composed primarily of medium to fine sands.

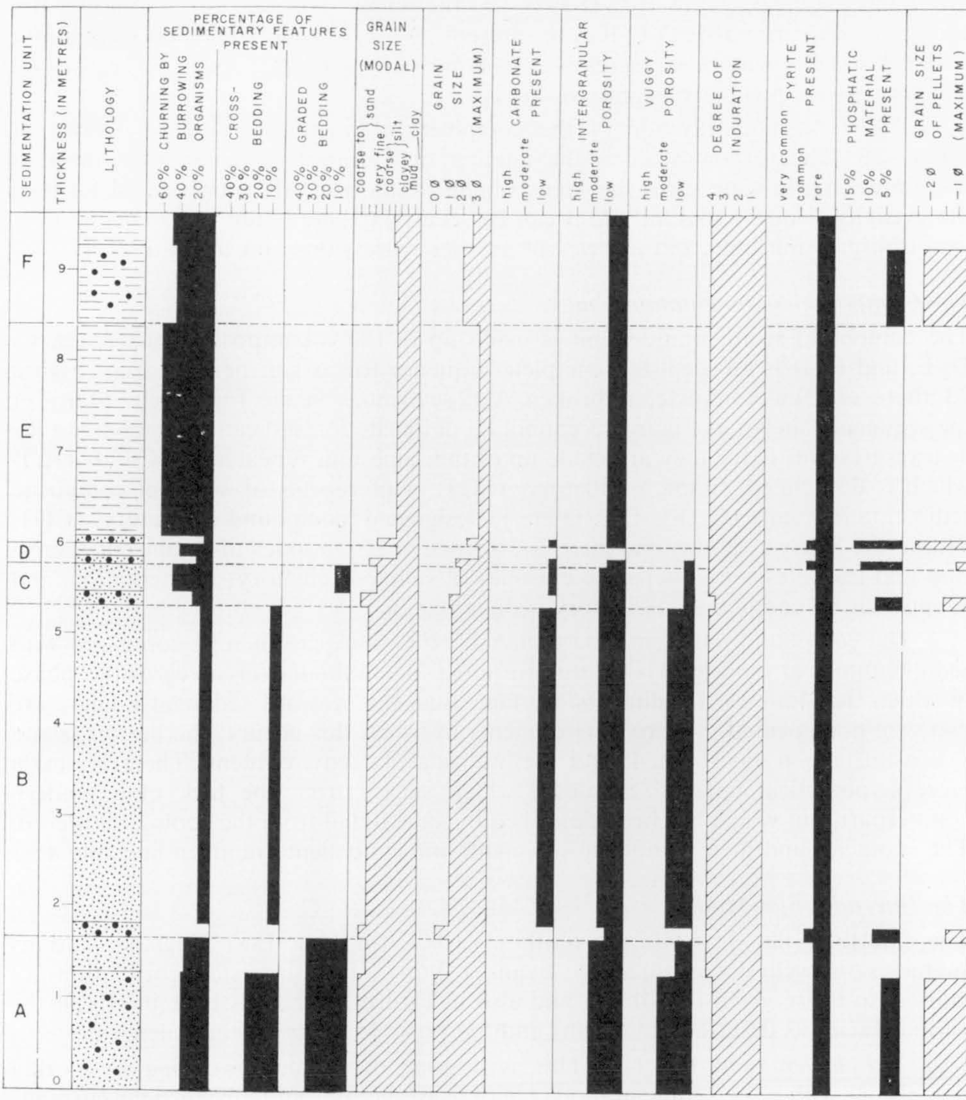

Figure 24. The basic compound sedimentation unit sequence of the Stairway Sandstone.

(C) *The Arenicola sand flat* (l). This zone is composed of well sorted sands, with poorly developed laminae, and an abundant infauna, especially *Arenicola* (a living form similar in morphology to the Ordovician *Diplocraterion,* a common trace

Figure 1. Sandstone in the lower Stairway, with a characteristic 'ropey texture' due to extensive bioturbation. George Gill Range. Scale is marked in inches.

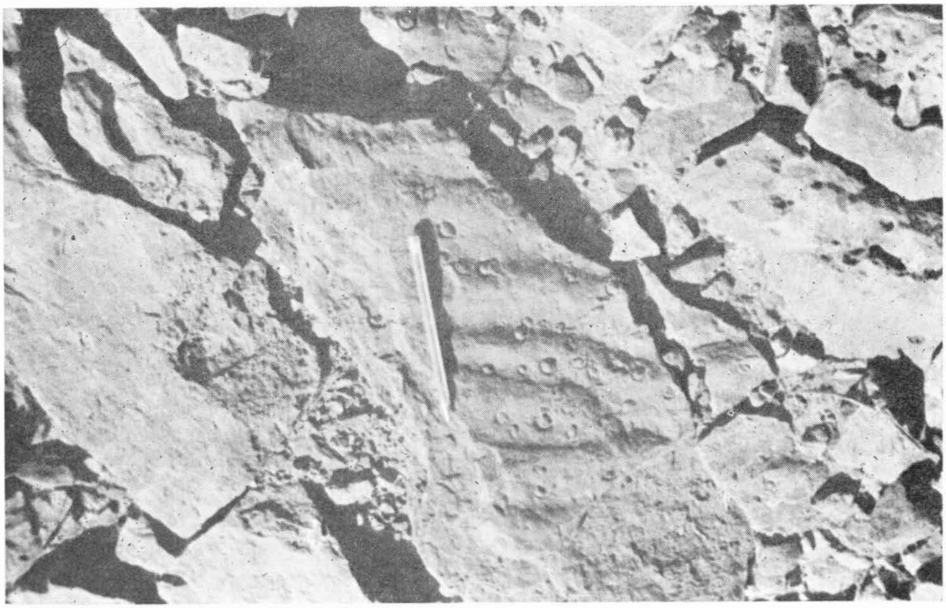

Figure 2. Ripple marks and worm tubes in the lower Stairway. The pen is approximately 12 cm long.

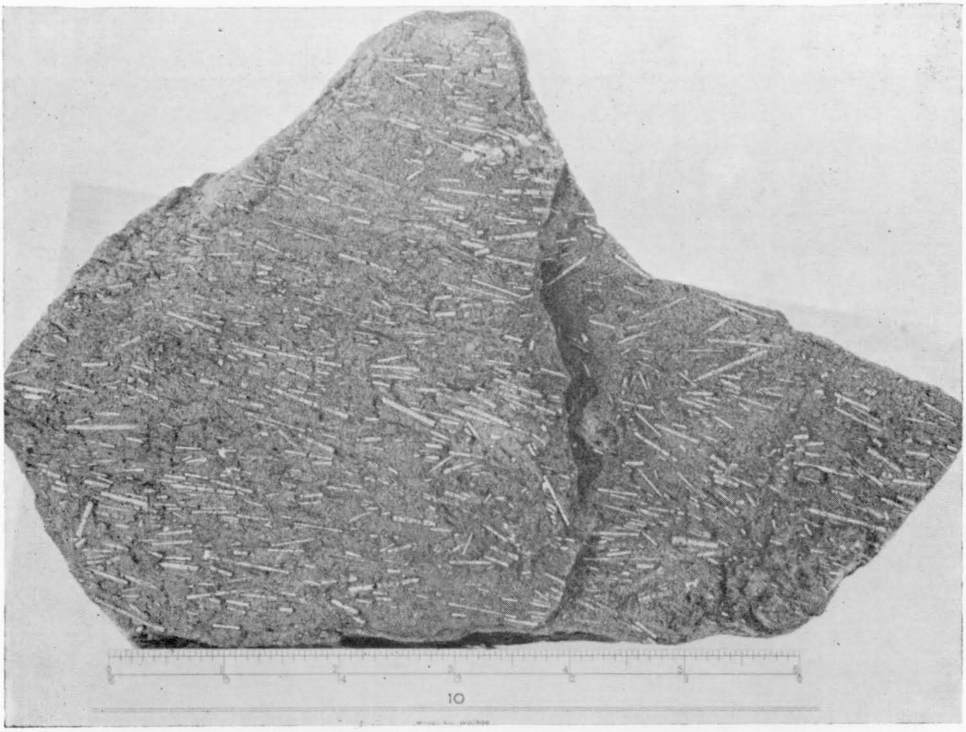

Figure 1. *Hyalostelia australis* **('sponge roots') showing a well developed current lineation, in a slightly phosphatic sandstone. Scale in inches.**

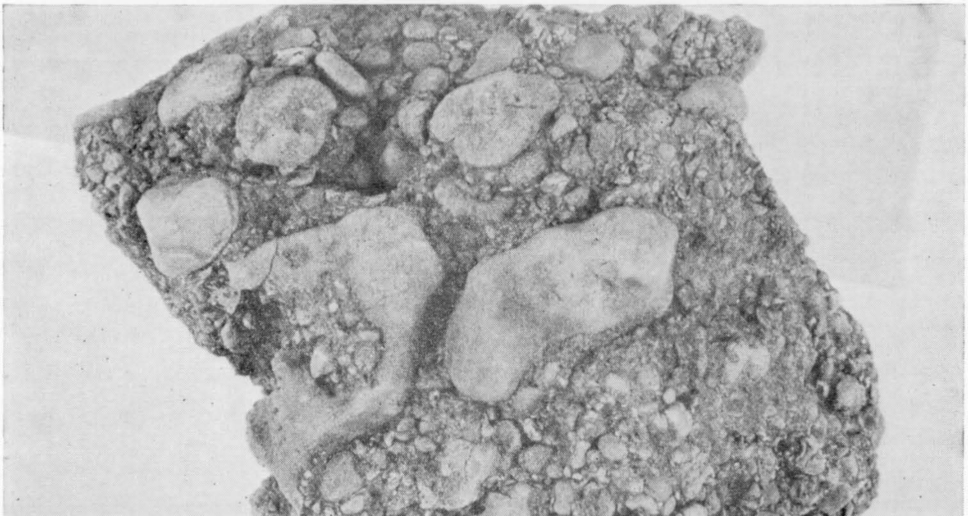

Figure 2. Coarse nodular phosphorite from the middle Stairway of Johnny Creek area.

PLATE 3

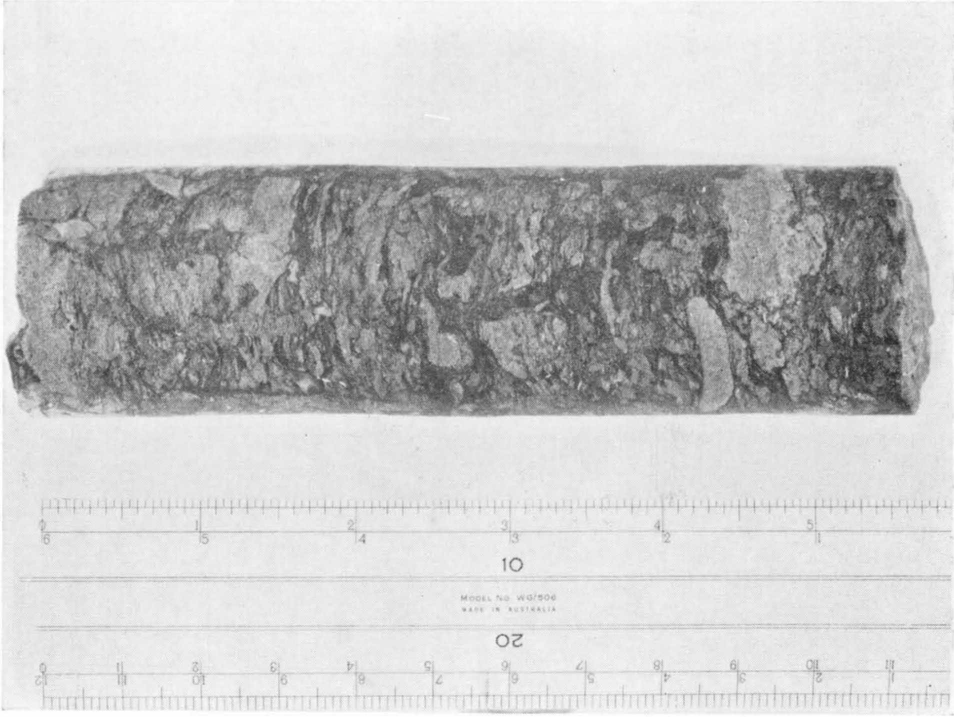

Figure 1. Disturbed laminae in middle Stairway sandy mudstone. Scale in inches.

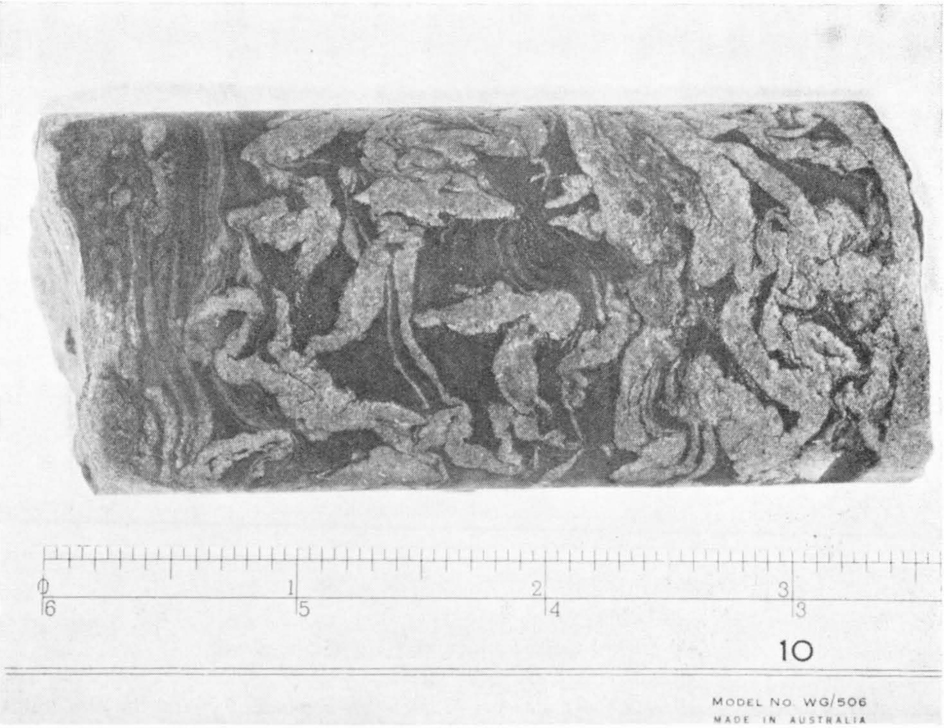

Figure 2. Middle Stairway sandy mudstone strongly disturbed by bioturbation, but also possibly with some slumping and load casting.

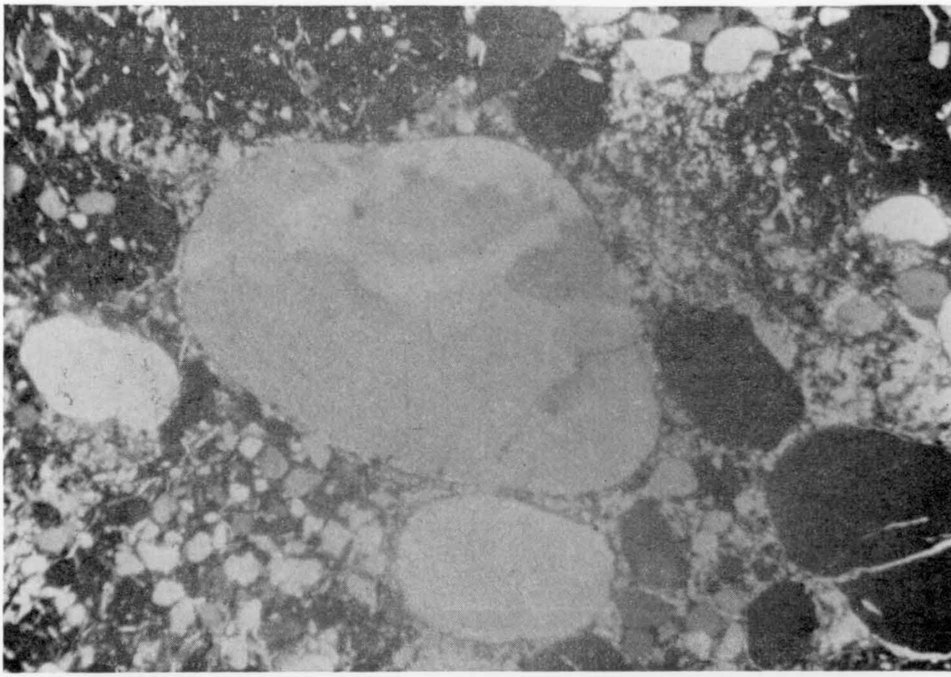

Figure 1. Poorly sorted orthoquartzite from the lower Stairway. Note the coarse, well rounded grain of metaquartzite in the centre of the field of view. Polarized light x 40. Sample LA133.

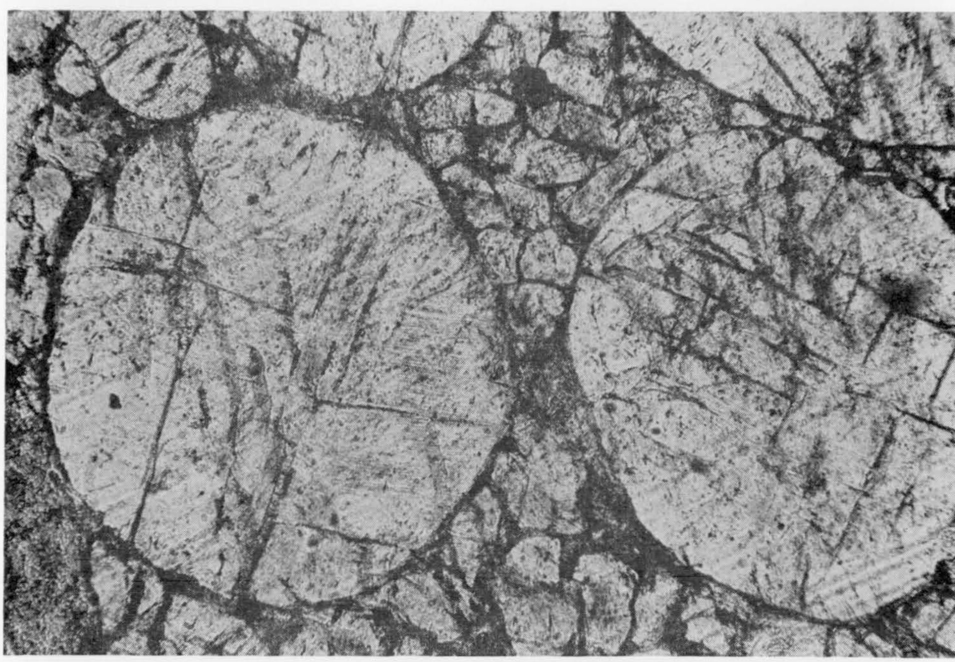

Figure 2. Bimodal orthoquartzite from the Stairway Sandstone (precise stratigraphic position unknown). The coarse well rounded grains have a diameter of about 1 ϕ and the fine grains about 3.5 ϕ. The deformation lamellae visible in the quartz grain are a result of crypto-explosion (the sample was collected from the Gosses Bluff crypto-explosion structure). Ordinary light x 40. Sample H1.

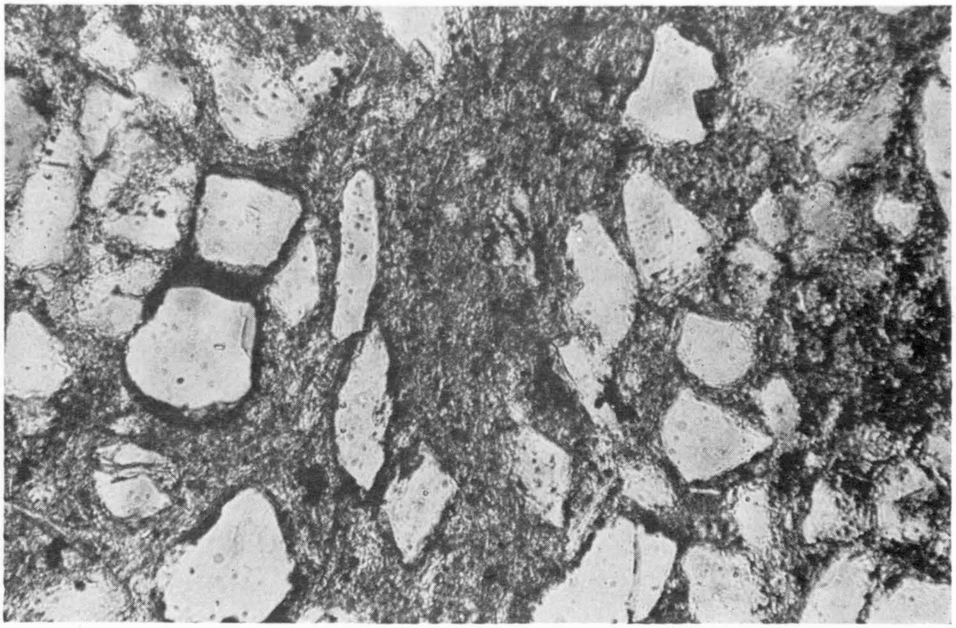

Figure 1. Typical middle Stairway sandy mudstone. Ordinary light x 150. Sample AP1/214/0.

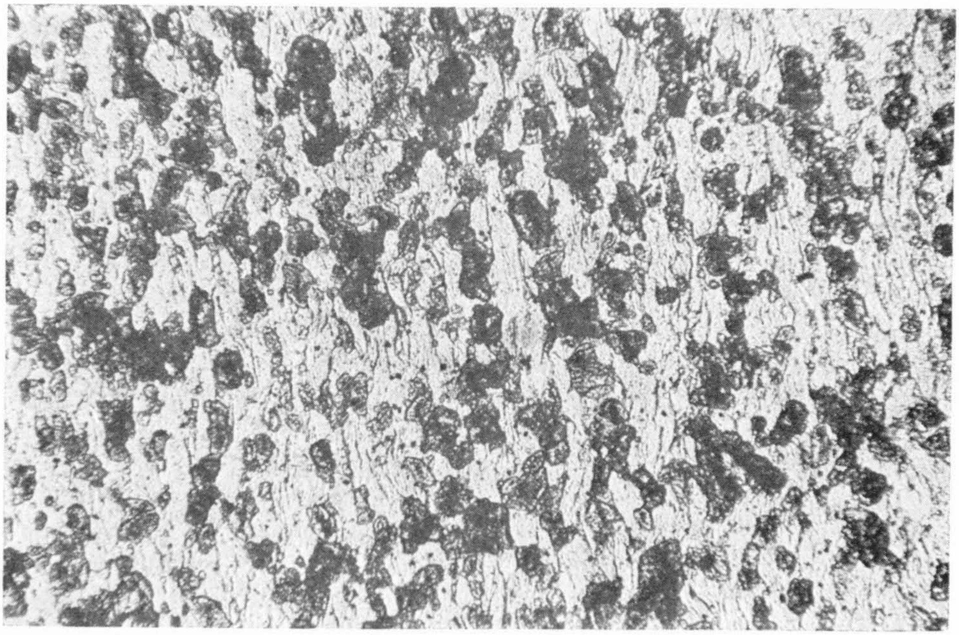

Figure 2. Sideritic mudstone from the upper Stairway. Ordinary light x 80. Sample AP1/110/0.

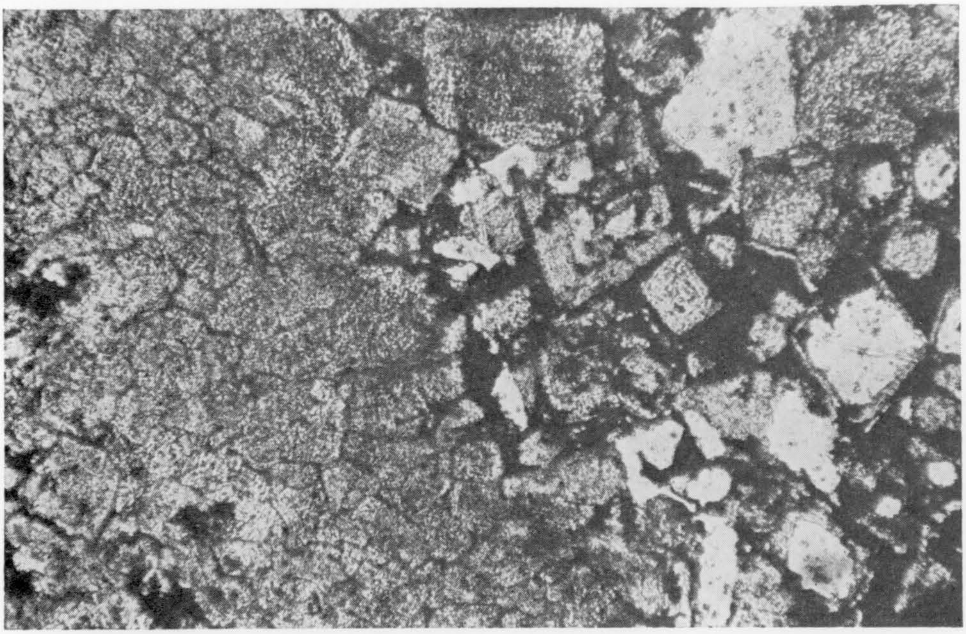

Figure 1. Partially recrystallized dolomitic limestone. The dolomite has a well developed rhombic form. Ordinary light x 80. Sample LA188.

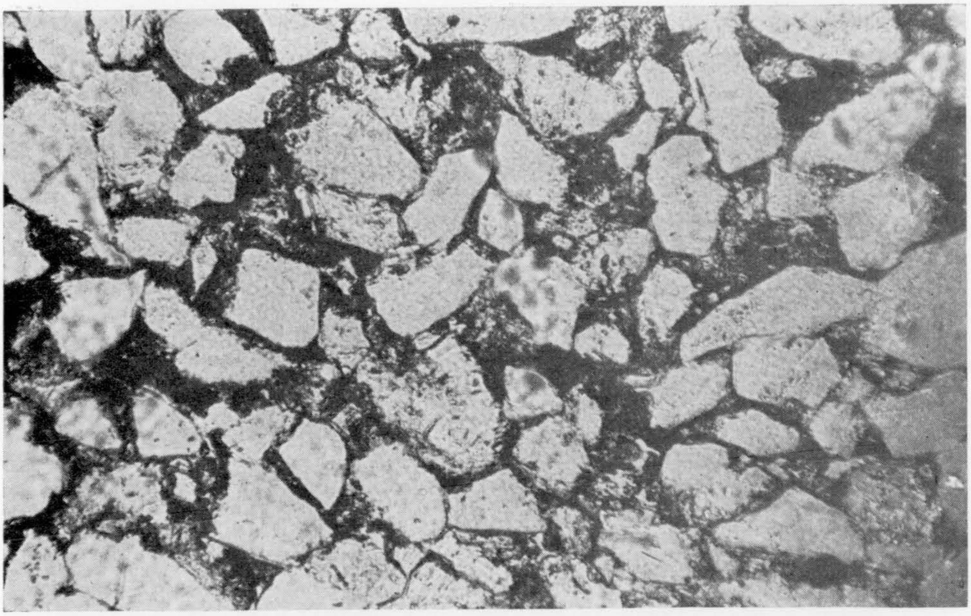

Figure 2. Immature very fine grained middle Stairway sandstone (redbed) with poorly rounded grains, and a ferruginous cement. Ordinary light x 80. Sample Rd. 148.

Figure 1. Well rounded tourmaline grains in a heavy mineral concentrate from the lower Stairway. Ordinary light x 400. Sample AP1/628/6.

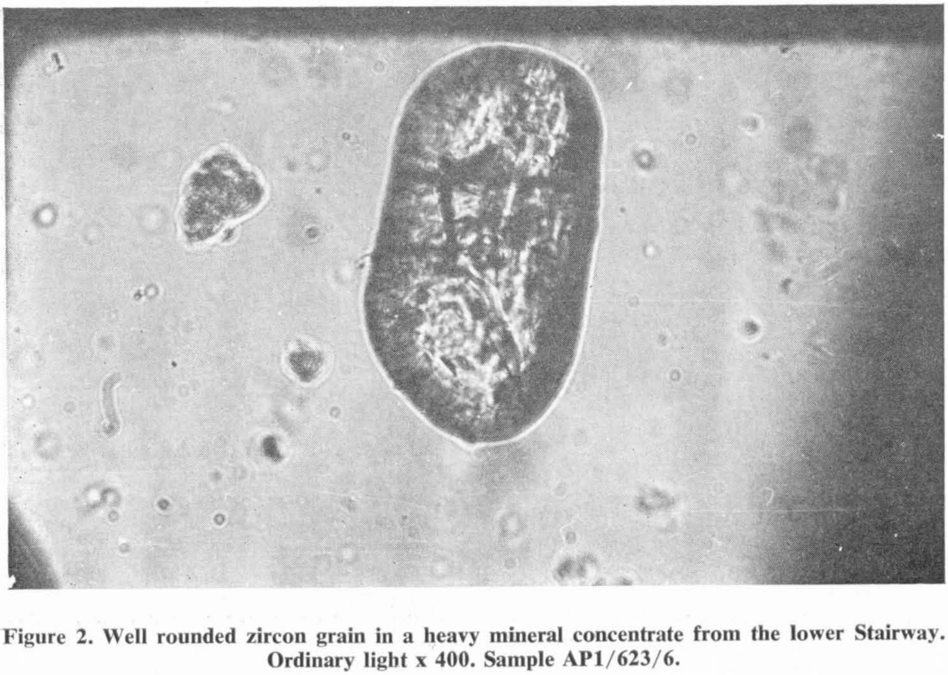

Figure 2. Well rounded zircon grain in a heavy mineral concentrate from the lower Stairway. Ordinary light x 400. Sample AP1/623/6.

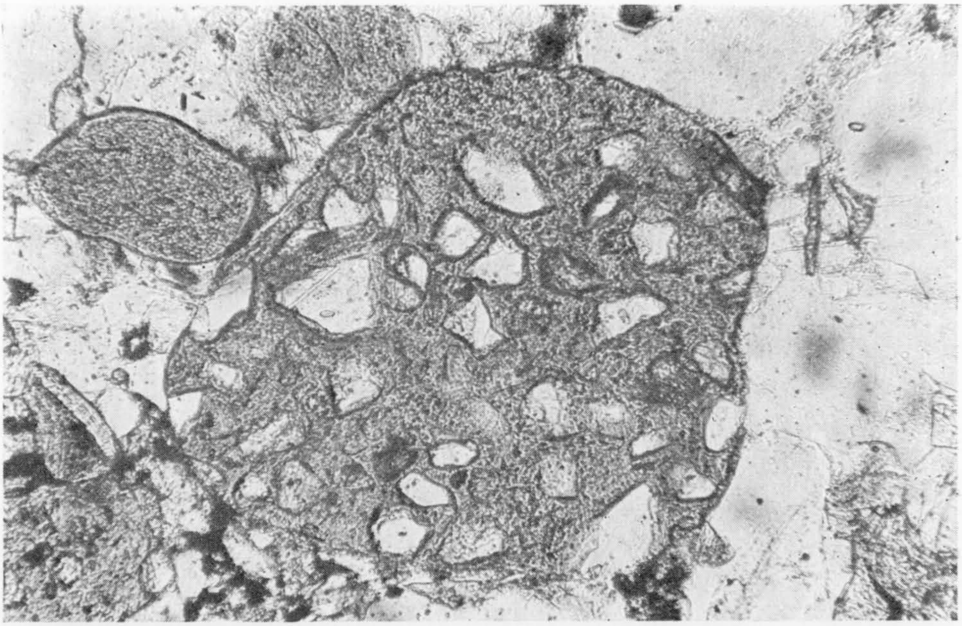

Figure 1. Sandy phosphatic pellet. The light grains are quartz, the dark material collophane (carbonate fluorapatite). Ordinary light x 80. Sample AP1/52/2.

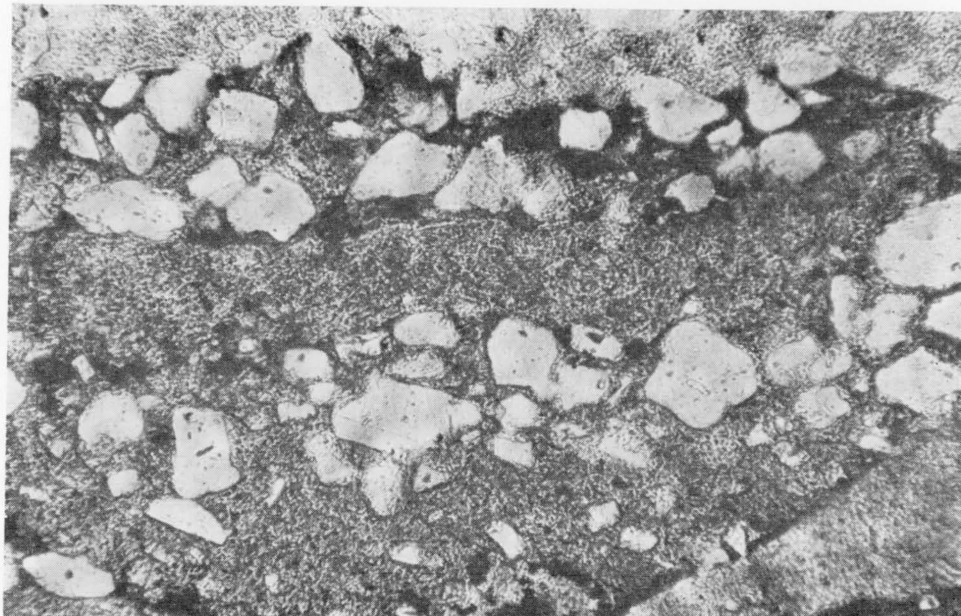

Figure 2. Sandy phosphatic pellet showing relict banding of the included detrital quartz grains. Ordinary light x 80. Sample AP1/98/1.

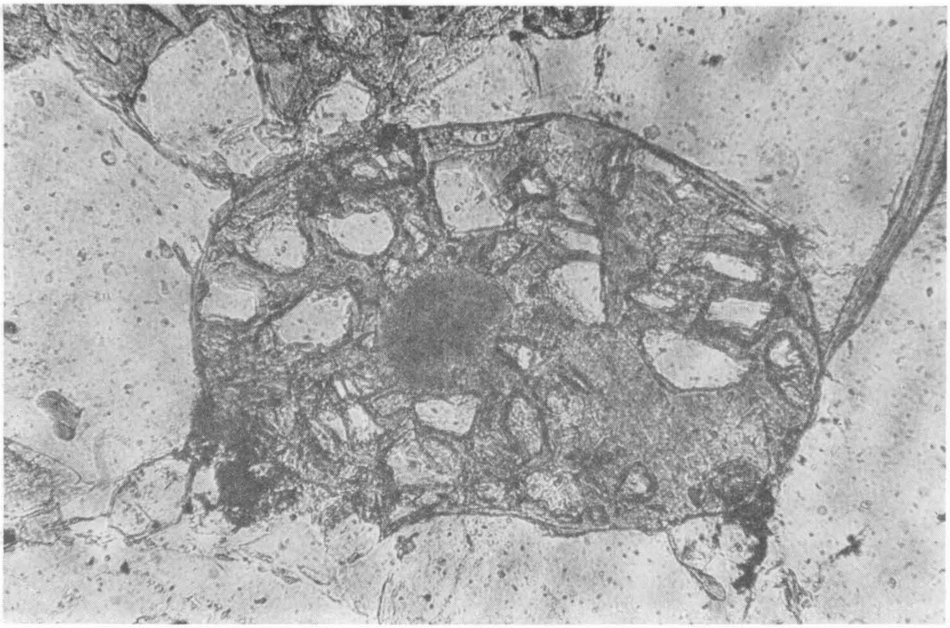

Figure 1. Sandy phosphatic pellet with an included glauconite grain (dark) showing a gradation boundary due to marginal phosphatization. Ordinary light x 150. Sample AP1/51/2.

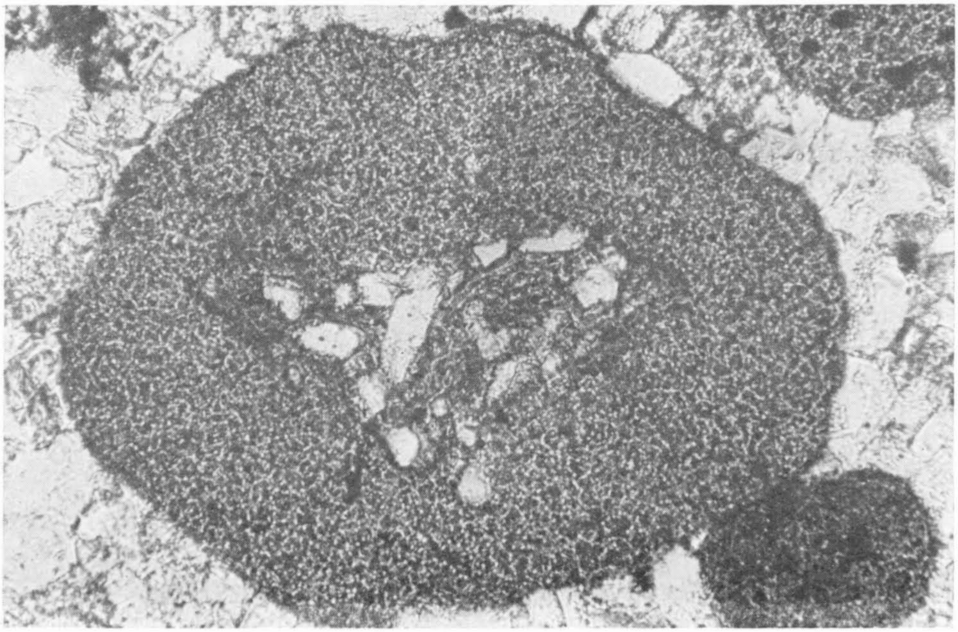

Figure 2. Phosphatic pellet with a sandy nucleus and an ovular margin. Ordinary light x 150. Sample AP1/244/0.

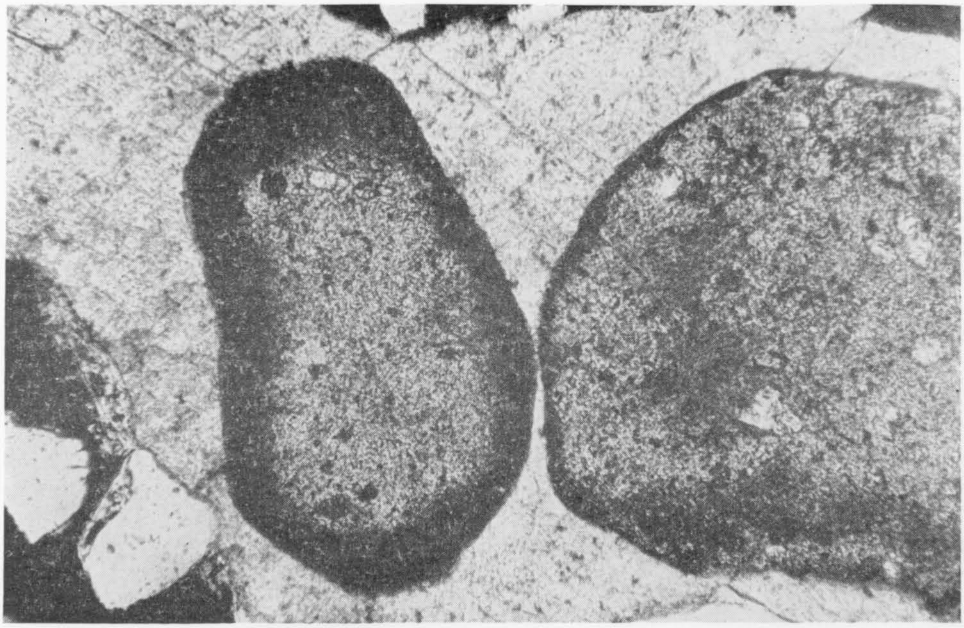

Figure 1. Ovule showing a prominent dark rim possibly due to the diagenetic migration of organic matter. The ovules are surrounded by a coarse calcitic cement. Ordinary light x 150. Sample AP1/97/1.

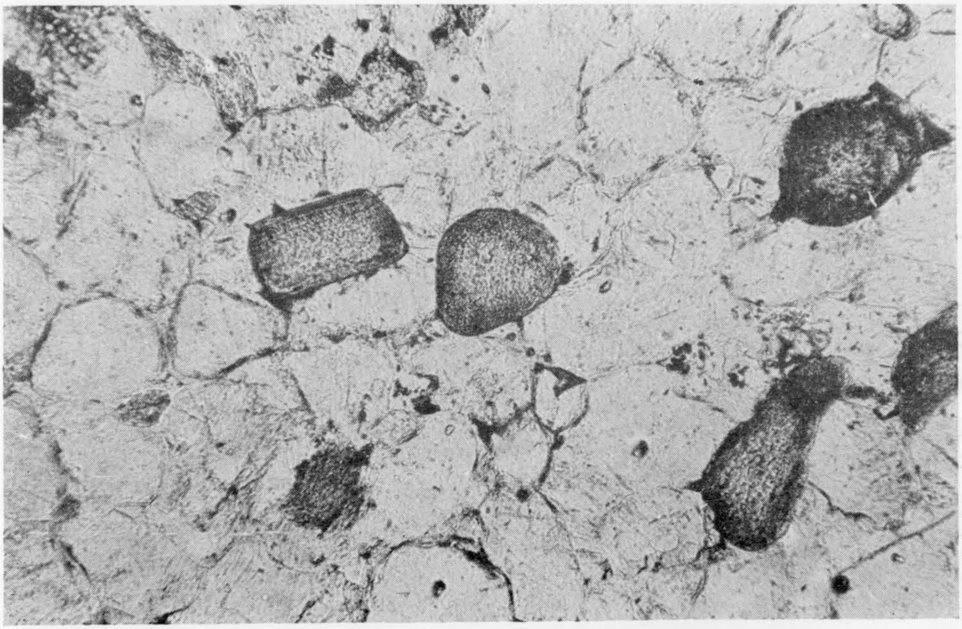

Figure 2. Ovules (dark) in a sandy matrix (light). The ovules and the quartz grain are approximately the same size, suggesting that the phosphatic material is detrital. Ordinary light x 80. Sample AP3/44/0.

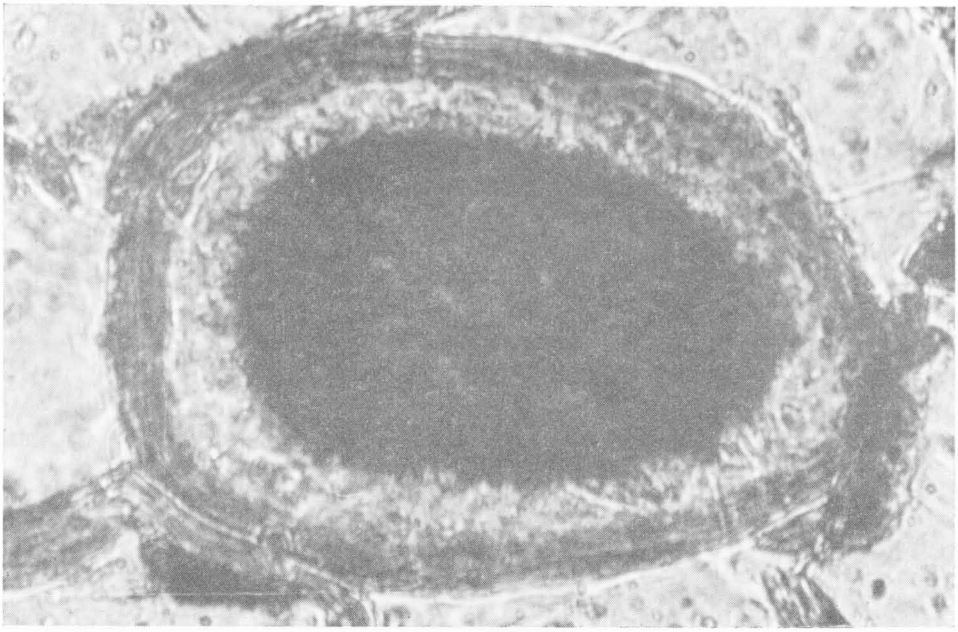

Figure 1. Phosphatic oolith showing well developed concentric banding around the perimeter. Ordinary light x 700. Sample AP+/398/0.

Figure 2. Irregular compound pellet composed of numerous small phosphatic ovules. The light grains are detrital quartz. Ordinary light x 80. Sample AP1/97/3.

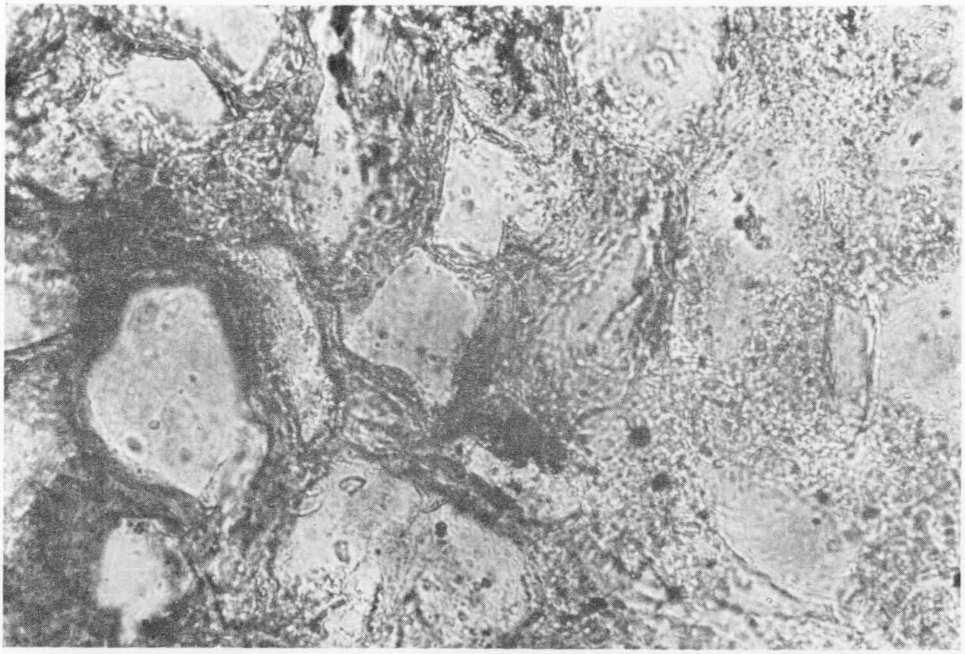

Figure 1. Dark phosphatic cement grading into light clayey cement. The light grains are composed of detrital quartz. Ordinary light x 400. Sample AP1/244/0.

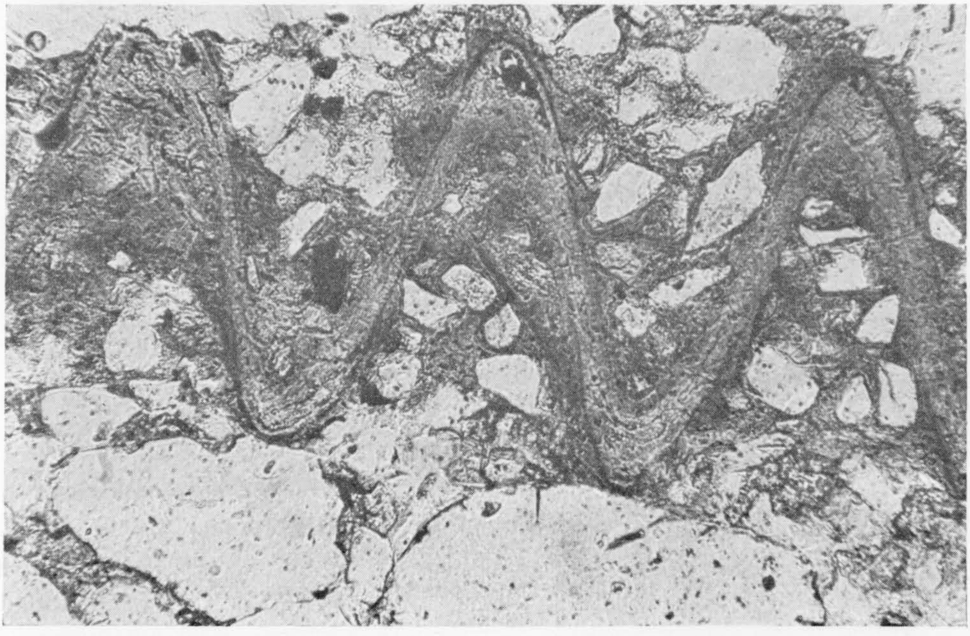

Figure 2. Fragment of an originally calcareous brachiopod or bivalve, now completely phosphatized. Ordinary light x 150. Sample AP1/746/10.

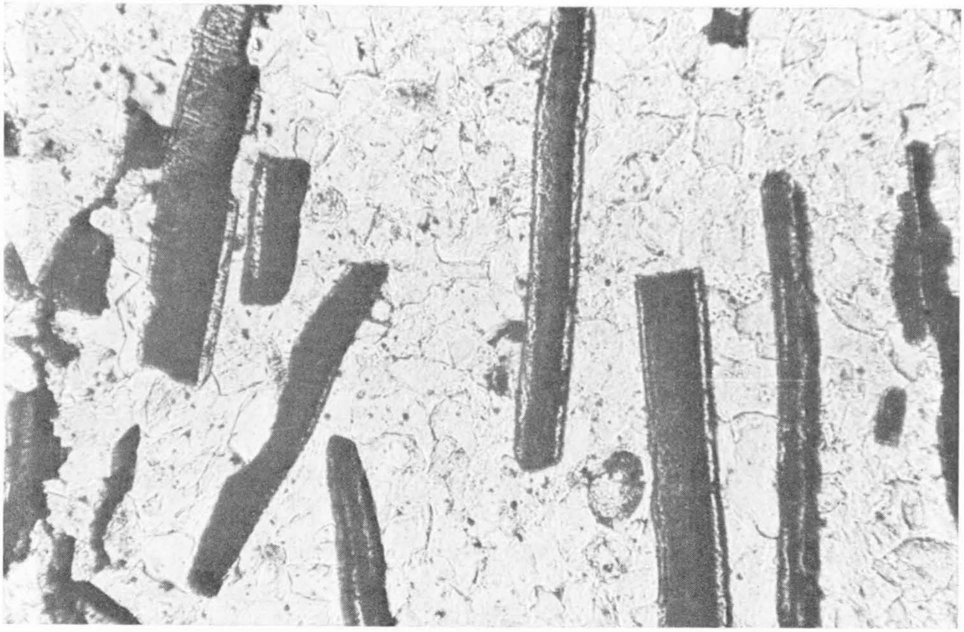

Figure 1. Phosphatic (or phosphatized) tripartite fossil fragments from the middle Stairway. These fragments may have been originally siliceous sponge spicules (similar to the type shown in Pl. 2, fig. 1). Ordinary light x 150. Sample AP1/149/0.

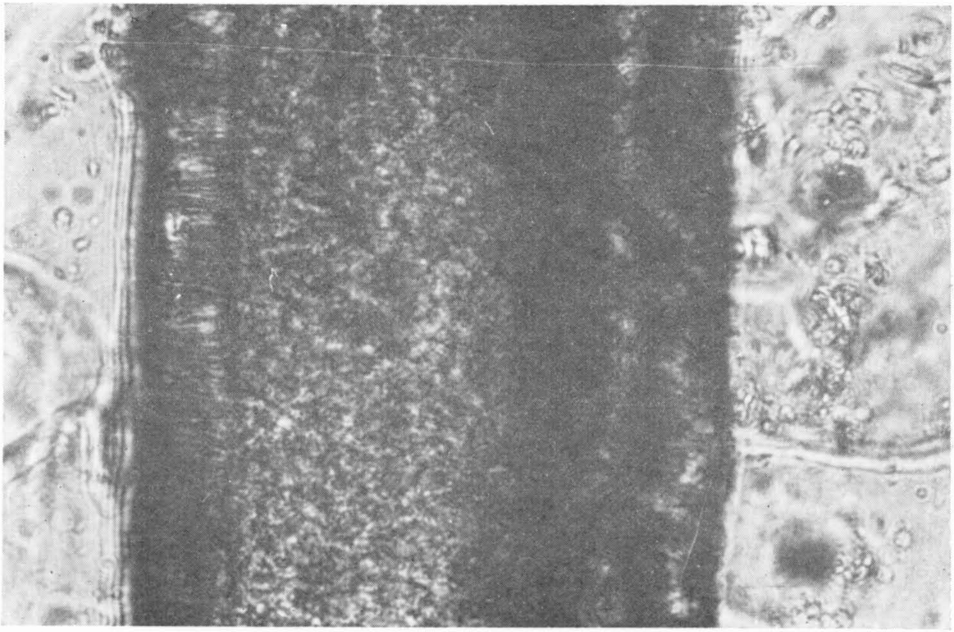

Figure 2. Phosphatized ?spicules showing the fine elongate crystallites in the outer layers, at right angles to the main axis. Ordinary light x 700. Sample AP1/149/0.

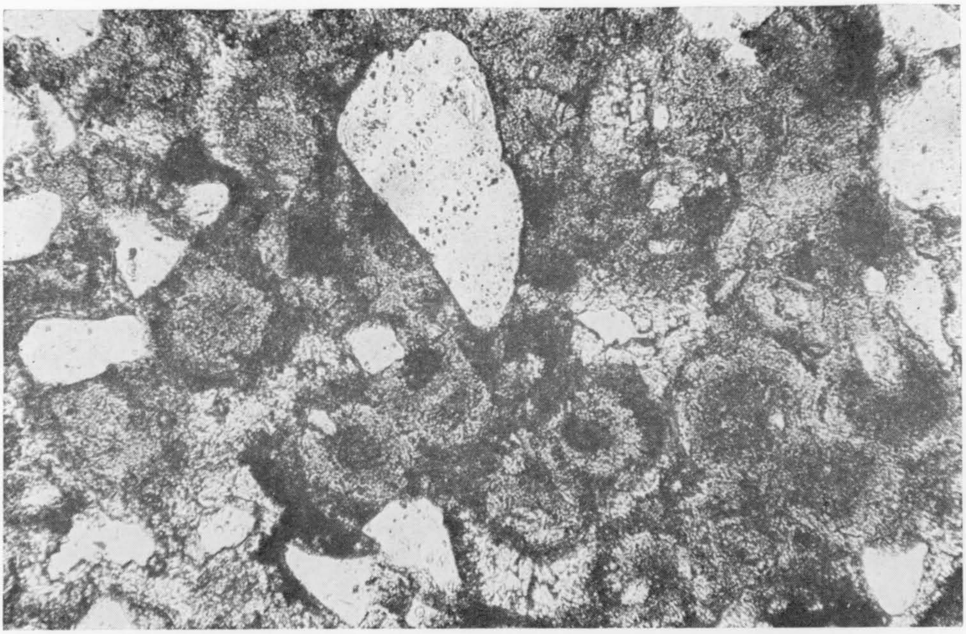

Figure 1. Secondary aluminium phosphate with a pseudo-oolitic form. Ordinary light x 150. Sample HY762.

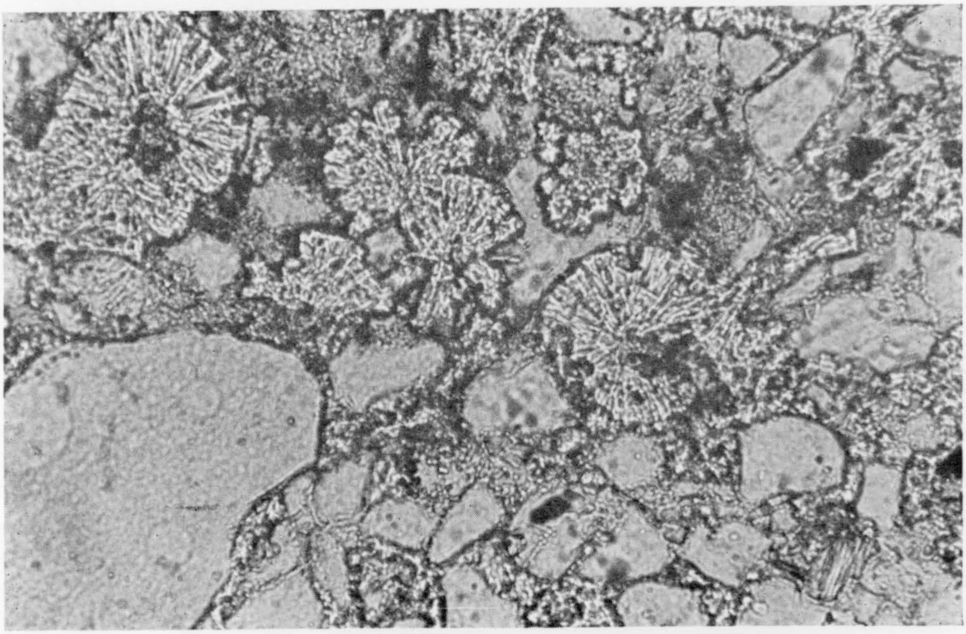

Figure 2. Secondary variscite(?) with a high relief, spherulitic form. The low relief white material is detrital quartz. Ordinary light x 150. Sample Rd.111(3).

fossil in the Stairway Sandstone). The *Arenicola* sand flats are subject to strong current action at times—by analogy, composite unit C would be subject to current action, which would winnow away sand to produce enriched pelletal bands. This, together with a slow rate of sedimentation, would explain the high phosphorite-arenite ratio found in unit C.

TABLE 4. COMPARISON OF THE STAIRWAY SANDSTONE MODEL WITH POSSIBLE DEPOSITIONAL EQUIVALENTS

		Hypothetical Equivalent		
	Stairway Sandstone *Composite Sedimentation Unit*	*Intertidal Flat Model (after Evans, 1965)*	*Barrier-Lagoon Model (after Rusnak, 1960)*	*Epeiric Sea Model (after Irwin, 1965)*
F	slightly phosphatic fine silt	higher mud flat or salt marsh	upper bay	inner low energy zone (Z)
E	very sparsely phosphatic clayey silt	higher mud flat	central bay	middle low energy zone (Z)
D	richly phosphatic clayey silt	inner sand flat	shallow bay	outer low energy zone (Z)
C	richly phosphatic very fine sand	*Arenicola* sand flat	shallow bay	inner high energy zone (Y)
B	very sparsely phosphatic fine sand	lower mud flat	barrier flats	middle high energy zone (Y)
A	slightly phosphatic medium sand	lower sand flat	barrier flats	outer high energy zone (Y)

(D) *The inner sand flat* (m). There is an abundant infauna in the inner sand flat environment, particularly *Corophium* sp., which leaves a trail not unlike that of *Scolithus*. Similarly, unit D has been intensely burrowed. There is some reworking by wave action in the inner sand flat environment of the Wash. Such wave action could result in the type of winnowing of phosphorites apparent in composite unit D. The slow rate of sedimentation would also assist in producing the high phosphorite:lutite ratio. The main disparity between composite unit D sediments and these of the inner sand flat is in the fact that unit D sediments are much finer grained.

(E) *The higher mud flat* (n). This is a zone of laminate muds with an average median diameter of 4.51 ϕ (coarse silt), compared with the clayey silts of unit E. The lack of organisms reported by Evans in the higher mud flat environment contrasts with the abundant infauna of unit E. The absence of wave activity and a rapid rate of sedimentation is however entirely compatible with the situation in unit E, where a low phosphorite:lutite ratio suggests that little winnowing has occurred. Any reworking which did take place in the environment may have been in response to an exceptionally high tide or storm.

(F) *The higher mud flat or lower part of the salt marsh* (o). The correlation of unit F with an intertidal subfacies is rather uncertain. Its position above unit E (the equivalent of the higher mud flat environment) would suggest that it should be correlated with the salt marsh environment. This is also supported by the grain size; the median grain size is in the range 6ϕ to 7ϕ for unit F and 5.8ϕ to 7.6ϕ for the salt marsh environment. In the salt marsh environment, there is no reworking by waves. This is entirely in accord with the distribution of the phosphatic pellets within unit F—the pellets have formed in situ and have not been reworked to give major concentrations. However, Evans also considers that infauna is rare, which does not fit in with the evidence of abundant infauna found in unit F; nor is there any evidence of subaerial exposure in unit F. In addition, the salt marsh environment is not one in which phosphorite pellets would form in situ. Conditions of

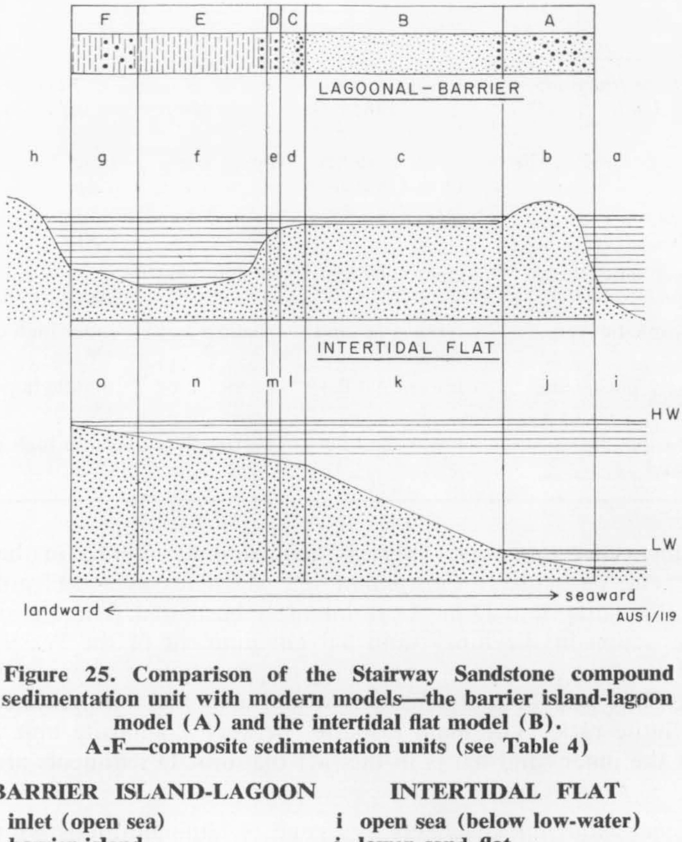

Figure 25. Comparison of the Stairway Sandstone compound sedimentation unit with modern models—the barrier island-lagoon model (A) and the intertidal flat model (B). A-F—composite sedimentation units (see Table 4)

BARRIER ISLAND-LAGOON	INTERTIDAL FLAT
a inlet (open sea)	i open sea (below low-water)
b barrier island	j lower sand flat
c barrier flat	k lower mud flat
d shallow bay (1)	l *Arenicola* sand flat
e shallow bay (2)	m inner sand flat
f central bay	n higher mud flat
g central/upper bay	o higher mud flat or salt marsh
h upper bay-beach	

pH of 7.1 to 7.8 (necessary for the formation of phosphorites according to Krumbein and Garrels, 1952) are not attained in salt marshes. Therefore perhaps unit F, like unit E, is equivalent to the higher mud flat environment. There are, however, marked differences between the lithological characteristics of unit E and unit F (see Table 3) which would be unlikely in sediments deposited in the same environment.

In summary, it is possible to fit the compound sedimentation unit of the Stairway Sandstone into an intertidal model such as that given by Evans (1965), in a fairly general way. There are, however, problems such as a marked discrepancy in grain size (this might be a difference in energy level rather than mechanism), the degree of bioturbation, and the position of unit F. Therefore the intertidal model is not entirely satisfactory.

The Barrier Island-Lagoon Model

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 Figure 25 and Table 4 together with the Stairway Sandstone equivalents.

(A) *Barrier Island* (b). It is apparent from Figure 24 that unit A is the most strongly cross-bedded part of the compound sedimentation unit. This is completely in accord with a barrier island sand. The presence of minor graded bedding and bioturbation suggests that some inlet sands have been included within unit A. Some of the phosphate pellets in unit A may be detrital, reworked from some other part of the basin and then incorporated into the barrier beach sands by wave action on the seaward side of the barrier island. The barrier island may also have been in part submarine. The sediments in both unit A and the modern barrier island fall into the coarse sand class.

(B) *Barrier bay* (c). Bioturbation is more common in the barrier bay sediments than in unit B, but other features of the two models are compatible. A fairly rapid rate of deposition in the zone generally precludes the development of rich phosphorites except for a thin band at the base of the unit. This concentration is probably the consequence of winnowing, as a result of onshore winds, or waves, or currents that swept across the barrier bay environment after the barrier island was breached.

(C) *Seaward side of the shallow bay* (d). Features such as an increase in bioturbation, a decrease in grain size, and a decrease in thickness of sediments deposited are shown by both unit C and the shallow bay facies of Rusnak (1960). Phosphatic pellets were able to form in the unit C environment and moderate concentrations of phosphorites were produced, possibly after the barrier island was breached, when currents were able to winnow the sands.

(D) *Landward side of the shallow bay* (e). This portion of the modern bay environment is beyond the zone of appreciable arenite sedimentation. Similarly unit D is predominantly lutaceous. The zone is, however, still comparatively close to the barrier island, and as a result, subject to some winnowing whenever the barrier island was breached.

(E) *Central bay* (f). This is a subfacies composed in the Laguna Madre model of silty clay, with a fairly abundant fauna. This is similar to composite unit E, in which most of the sediment falls into the clayey-silt class, and bioturbation is very common. It is to be expected that in the deepest part of the barrier-bay facies there would be little or no winnowing and consequently a lack of concentration of phosphatic material. This results in the low phosphorite:lutite ratios present in unit E.

(F) *Upper bay* (g). A slight increase in grain size and decrease in bioturbation in unit F compared to unit E suggests that it is probably equivalent to the upper bay subfacies of Rusnak (1960). 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 has not, however, taken place, as the environment represented by unit F was perhaps too far removed from the sea for the winnowing effects of currents or waves to be felt to any great extent.

Thus the compound sedimentation unit of the Stairway Sandstone fits fairly satisfactorily into the barrier-bay model of Rusnak (1960). There are, however, difficulties in this concept such as the size of the lagoon. It can be seen in the Stairway Sandstone of AP1 (Fig. 23) that the interval from about 140 m to 60 m is made up of simple oscillatory or compound oscillatory sequences of D, E, or F so that in middle Stairway time, on this model, a central bay (with minor shallow bay and upper bay) environment of the Laguna Madrê type apparently covered an area of about 50,000 km^2. This is unlikely; it is much more probable that the various subfacies repeatedly transgressed and regressed over the entire area, so that only a small percentage of the total area was covered by any one subfacies at a particular time. This is supported by Figure 23, which indicates repeated minor transgressions and regressions within the overall major pattern of regression-transgression.

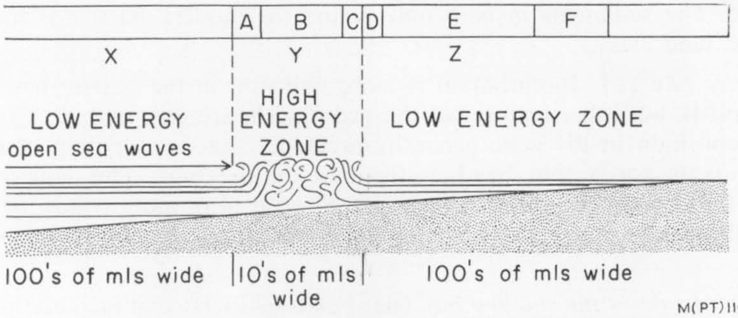

Figure 26. Comparison of the Stairway Sandstone compound sedimentation unit with an epeiric sea model.
A, B, C, D, E, F—composite sedimentation units (see Table 4)
X, Y, Z—the energy zones of Irwin (1965)
a—sediment picked up at strand line
b—sediment carried by long-shore
c—very fine grained sediments in low energy environment
d—sediment being winnowed by oceanic currents so that only coarse sands remain
e—winnowed-out fines are carried into deeper water

The Epeiric Sea Model

The environmental implications of epeiric sea sedimentation have been set out by Shaw (1964) and Irwin (1965), who consider that there are three basic environments X, Y, Z, delineated by their hydraulic energies (see Fig. 26). The outer zone (X) is a wide low-energy zone below open sea wave-base. Y represents the fairly narrow high-energy zone where the oceanic waves impinge on the sea-floor; coarse well rounded well sorted sediments (biogenic in part) are deposited here. The inner zone (Z) is a wide shallow zone of very low energy in which the tidal range is negligible. The sediments are all extremely fine grained and in places evaporites may form.

In the compound sedimentation unit of the Stairway Sandstone the sequence is regressive coarse into fine, units A, B, and C 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 present in the sequence; they might be represented by the predominantly silt/clay sediments of the underlying Horn Valley Siltstone. Consider now the equivalence of the Stairway compound sedimentation unit and the epeiric sea model in more detail:

Composite sedimentation unit A represents the seaward side of the high-energy zone, where there is a great deal of reworking of sediments to produce coarse-grained sands. Irwin (1965) considers that this high-energy zone is the zone of highest porosity (due to the winnowing action); and in the Stairway Sandstone, unit A does in fact have the highest porosity (Fig. 24). Phosphorites may not be precipitated in this zone but pellets are reworked.

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; consequently winnowing is less important. It is also the zone of maximum arenite accumulation, and this coupled with the decreased winnowing action produces a thick sand sequence with only rare, thin, pelletal bands.

Unit C is on the edge of the high-energy zone; consequently currents are not very active and sediments are little reworked. But since little arenite is deposited, the ratio of phosphorite to terrigenous sediment is fairly high. High-energy currents occasionally impinge on this unit so that phosphorites are winnowed (and subsequently enriched) at times. This is a zone of slow sedimentation and therefore of increased bioturbation.

Unit D is situated on the seaward side of the low-energy zone Z, outside the zone of arenitic sedimentation. High-energy conditions can occasionally impinge upon this subfacies, and together with the slow rate of sedimentation produce a moderately high phosphorite to lutite ratio.

Unit E is well within the low-energy zone Z; sediments are predominantly lutites, sedimentation is slow, infaunal activity is considerable. Because of its position within zone Z, unit E is seldom subjected to high-energy winnowing. Consequently enrichments of phosphatic pellets are rare and the proportion of phosphorite to lutite is low.

Unit F is the most shoreward development of the low-energy epeiric sea environment represented in the compound sedimentation unit of the Stairway Sandstone. It is evident that the environment is one of extremely restricted circulation. Infaunal activity is appreciably less in unit F than in unit E, suggesting less congenial conditions. Grain size increases slightly, perhaps because of proximity to the land. Little terrigenous sediment is supplied, so that phosphatic deposits are not 'masked', despite the absence of winnowing in a zone far from the high-energy zone Y.

The compound sedimentation unit therefore appears to be compatible with a modified terrigenous epeiric sea model. Concentrations of phosphatic pellets are regarded primarily as a result of the migration of the high-energy zone, perhaps in response to a relative rise in sea level or storms. The abundance of pellet bands would tend to support the storm hypothesis.

In conclusion, all three models are reasonably compatible with the Stairway compound sedimentation unit. The intertidal model is perhaps the least satisfactory of the three because of the marked discrepancy in grain size, the differences in degree of bioturbation, and the lack of a suitable correlative of unit F.

In evaluating the merits of the epeiric sea model one must conclude that the various sub-environments appear to correspond to units A-F. The model does, however, suffer from an important disadvantage in that it does not have a present-day counterpart. The epeiric sea model as built up by Shaw (1964) is constructed primarily from theoretical considerations. It can be argued that none of the extremely shallow epeiric seas of the past exist at the present day owing to the rapid post-glacial rise in sea-level. The barrier island-coastal lagoon model on the other hand suffers from no such disadvantages; it is a well-documented environmental situation with numerous modern counterparts. For this reason the barrier island-coastal lagoon model is the more credible of the two, but the epeiric model should not be completely dismissed.

THE STAIRWAY SANDSTONE PHOSPHORITES

The occurrence of phosphorites in the Stairway Sandstone was first noted in 1961 by Wells et al. (1965b). Subsequent work by Cook (1963), Barrie (1964), and Prichard & Cook (1965), showed that the Stairway Sandstone is slightly phosphatic throughout but that phosphorites occur mainly in the middle Stairway (see Fig. 22).

The phosphorites are characteristically pelletal or nodular, and generally grey or brown in colour, but rarely purple (the Mount Charlotte area) or white (the Sisters area, west of the Mount Charlotte Range). The phosphatic beds range in thickness from less than 1 cm to about 20 cm but average from 5 to 10 cm. Most beds are probably of little lateral extent, although poor exposures make it impossible to be sure of this. Boundaries between phosphatic and non-phosphatic sediments are sharp, particularly the lower boundary. Current-induced sedimentary structures such as ripple marks and crossbeds are rare in the phosphorites, but fairly common in associated sediments. Worm burrows are present in a few of the slightly phosphatic sandstones.

The nodules vary in size, shape, and P_2O_5 content. They range in size from less than 1 cm to 13 cm. The two main types are grey and brown. The grey nodules have a rather irregular form, with pitted re-entrant surfaces. The brown nodules are smoother than the grey; they tend towards an ellipsoidal shape, whereas the grey pellets are flatter and more disc-shaped. The grey nodules are more phosphatic than the brown, because the brown contains more detrital quartz grains; the detrital grains are also coarser in the brown nodules. Grey nodules generally have a P_2O_5 content of about 19% and brown nodules about 13%.

In the subsurface all the nodules are black (chroma N3-N3) and it was not possible to distinguish the two types. In the AP1 core, boundaries between phosphatic and non-phosphatic sediment are sharp. In addition, 16 bands showed good positive grading (i.e. coarse pellets at the base and fine pellets at the top) and 8 bands negative grading.

A total of 90 outcrop samples and subsurface samples have been analysed for P_2O_5 by colorimetric methods, using molybdo-vanadate (Ranford et al., 1965; Wells et al., 1967; Barrie, 1964). 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 LA535(9) from the Johnny Creek area of the Lake Amadeus Sheet. Most nodular bands fall into the range 10 to 18% P_2O_5. Throughout the Stairway Sandstone all rock types have P_2O_5 contents at least two to three times above the average value for sediments of similar type. Barrie (1964) suggests that there may be some secondary enrichment of the P_2O_5 content of beds at the surface, because so far the highest value obtained for a subsurface sample is about half that obtained for surface samples.

Fourteen samples of Stairway Sandstone sediments have been spectrochemically analysed for nickel, cobalt, copper, vanadium, and lead (Ranford et al., 1965). Many of the samples have higher than average values of these trace elements, e.g. sample ML37, with a P_2O_5 content of 18%, contains 400 ppm of lead and 100 ppm of copper. McKelvey et al. (1959) have shown that there is a correlation between phosphate and trace element concentrations in the Phosphoria Formation, and in the Stairway Sandstone the few results available suggest that there may be a similar correlation (Fig. 27). X-ray data indicate that the phosphate mineral is primarily carbonate fluorapatite. Aluminium phosphates are common as secondary minerals.

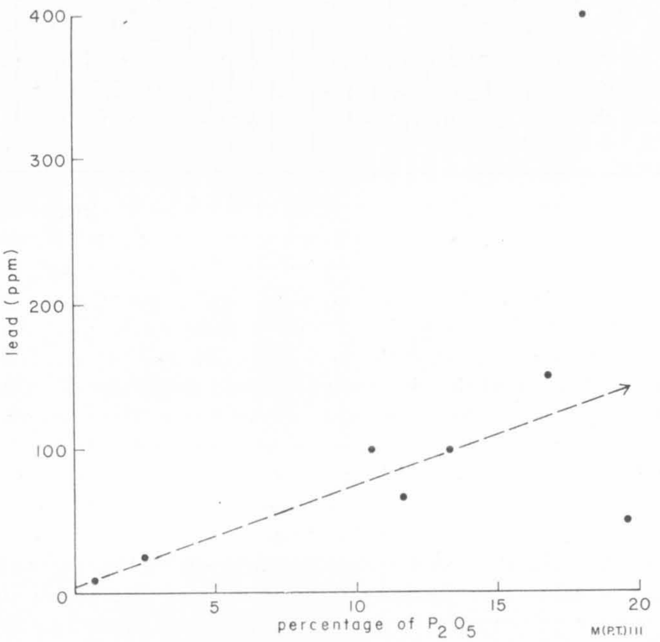

Figure 27. Variation of lead content of phosphorites, with the percentage of P_2O_5.

PETROLOGY

There are eight main modes of occurrence of phosphatic material in the Stairway Sandstone, most of which are pelletal (diameter of less than 2 mm) or nodular (diameter greater than 2 mm). The types are similar to those of other phosphorites, and where possible, the terms used by Mabie & Hess (1964) and Cook (1971b) for the Phosphoria phosphorites are used here.

Sandy pellet

I have previously referred to pellets of this type as 'polynucleated' (Cook, 1971b) but the term 'sandy' seems more appropriate for pellets composed primarily of detrital sand-size grains (predominantly quartz) with a phosphatic matrix. This is the commonest type of phosphate pellet in the Stairway Sandstone (Pl. 8, fig. 1). Some of the pellets are of intraclastic origin; this is demonstrated by, for instance, the presence of banding in detrital material within the pellet which is inclined to the primary banding of the unit (Pl. 8, fig. 2). Such sandy pellets generally have a round or subround outline. Others are believed to have formed by accretion below the sediment-water interface; their outline is irregular and detrital grains both inside and outside the pellets have the same texture and composition.

It is found that in many instances the detrital grains within the pellets are much finer than those in the surrounding non-phosphatic sediments. This appears to suggest that the pellets are allochthonous; but detailed textural analysis shows that in fact the textural differences are produced not by transport of the pellets but by the winnowing of the surrounding sediments to produce a lag deposit of coarse sand and phosphorite pellets and nodules. This is discussed in more detail later.

The indurated detrital grains invariably have a grain size of 3ϕ to 4ϕ (very fine sand) (Pl. 9, fig. 1). This constant association suggests either that phosphate preferentially occurs in an environment in which very fine sand is being deposited, or that grains in the 3ϕ to 4ϕ range aid in some way the precipitation of phosphate. The latter seems more likely, though I cannot suggest a precise mechanism.

Ovule

An ovule is a phosphate pellet showing little or no internal structure. This is the commonest type of pellet in most other phosphorites, but in the Stairway Sandstone forms only a minor percentage of the phosphatic material. Some pellets were sandy pellets initially but subsequently became more ovular owing to continuation of phosphate precipitation (Pl. 9, fig. 2), but most show no internal structure apart from progressive darkening around the periphery (Pl. 10, fig. 1). Emigh (1958) attributes these dark rims to the diagenetic outward migration of organic carbon. In some instances the pellets have the same grain size as the surrounding detrital quartz grains, suggesting that the ovules are also detrital (Pl. 10, fig. 2). However, this is rare, and in most cases the ovules are considerably larger than the associated detrital grains. The ovules are thought to have formed in situ, some as primary precipitates due to the localized supersaturation of the Stairway seas by phosphate. Other ovules are thought to have formed diagenetically below the sediment-water interface by the complete phosphatization of the mud so that no silt and sand size detrital grains remain. A few of the ovules may also result from the phosphatization of faecal pellets.

Nucleated pellet

A nucleated pellet is one in which precipitation of phosphate has occurred around a single nucleus, usually a detrital quartz grain or, less commonly, a fossil fragment. This pellet type is uncommon.

Compound pellet

A compound pellet is one composed of two or more pellets or fragments of pellets. This type is fairly rare in the Stairway phosphorites. In some cases the compound pellet has resulted from cementation produced by the growing together of pellets in a manner analogous to grapestone in carbonates (Pl. 11, fig. 2). Some compound pellets appear to be of intraclastic origin; pellet bands have formed, lithified, and subsequently been torn up (either by current action or bioturbation) and then rounded to form compound pellets.

Phosphatic oolith

A phosphatic oolith is a phosphatic pellet showing internal concentric banding. Unlike calcareous deposits, ooliths are rare in most phosphorites. Some pellets have a pseudo-oolitic appearance due to the diagenetic movement of organic matter. However, the true oolith develops by an accretion mechanism as shown by the occurrence of elongate included grains (such as mica and zircon) arranged with their long axis concentric to the perimeter of the pellet (Pl. 11, fig. 1). Some ooliths have a nucleus, but most do not, either because they never had one, or because phosphatization has destroyed it.

Phosphatic cement

There is no pelletal outline in this mode of occurrence, and the phosphate has obviously formed in situ. Some of it may be a primary cement with detrital (mainly quartz) grains being deposited and phosphate precipitated, penecontemporaneously. However, much phosphatic cement is believed to be diagenetic, forming by the phosphatization of mud just below the sediment-water interface (Pl. 12, fig. 1). Some of it may also be a late weathering development produced as a near-surface interstitial precipitate from remobilized apatite. The two types of post-depositional cement are in some cases difficult to differentiate, although the late-stage cement is commonly more coarsely crystalline.

Phosphatic fossils

Phosphatic fossil fragments are fairly common in the Stairway Sandstone. Some of them were originally phosphatic (mainly inarticulate brachiopods), but most were calcareous in life, and phosphatized either before or soon after burial (Pl. 12, fig. 2). Phosphatized fossils of this type include bivalves, inarticulate brachiopods, and numerous indeterminate fossil fragments. A particularly common form is composed of thin elongate laths and laminae, which may represent sponge spicules. They are variable in size, ranging up to 2 mm long and from 0.05 mm to 0.1 mm thick. The laminae are commonly aligned with their long axes parallel (Pl. 13, fig. 1). Many show a tripartite division into thin upper and lower layers, in places showing very fine micro-laminations at right angles to the axis of the macro-laminae (Pl. 13, fig. 2), and a thick structureless middle layer. The outer layers of many of the laminae show signs of corrosion, of either micro-organic or chemical origin.

Secondary phosphate

Secondary phosphate has received little attention to date. Probably the commonest secondary phosphate mineral is apatite, which frequently has a well-developed hexagonal habit. Aluminium phosphates have also been identified in the lower unit of the Stairway Sandstone both from electron microprobe studies (R. England, BMR, pers. comm.), and from their diffractometer patterns. On the weathered surface the lower Stairway phosphorites containing the secondary phosphates have a green or white colour. In thin section the secondary phosphate may be seen to occur as green blebs and patches (Pl. 14, fig. 1), but in vugs and intergranular spaces it develops a clear spherulitic habit (Pl. 14, fig. 2). The phosphate mineral corkite was identified in Stairway sample LA701A, by S. Goadby (written comm.), but the identification cannot be confirmed because the sample is lost.

The movement of phosphate in the subsurface to form secondary minerals is probably a response to changes in the physico-chemical conditions; changes in pH are likely to have been particularly important in inducing mobility in a relatively insoluble mineral such as apatite (Cook, 1970b).

Previous Ideas on the Origin of Phosphorites

One of the earliest attempts to explain the origin of phosphorites was that of Murray & Renard (1891), who as a result of oceanographic observations made during the *Challenger* voyage suggested that ammoniacal solutions, derived from mass mortalities of fish and other marine creatures, were responsible for the precipitation of phosphate. Blackwelder (1916) also considered the decay of marine organisms to be a major factor in the primary precipitation of phosphate, together with some subsequent replacement of calcite, particularly in stagnant basins. Mansfield (1918) initially 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 volcanism, when considerable quantities of fluorine are available, would also be times of maximum phosphate precipitation. Pardee (1917) suggested that phosphorites were laid down under cold glacial conditions, when the seas would be unsaturated in calcium carbonate, and precipitated phosphate would not be masked by accompanying precipitation of calcium carbonate. Breger (1911) considered bacteria to be of importance in the concentration of phosphate. This was supported by Baas Becking (1957), who showed that bacteria in sea water are able to concentrate phosphate by a factor of 200. McConnell (1965) also considered that phosphates could be precipitated through a biochemical agent.

Phosphatic nodules and pellets have commonly been ascribed to the phosphatization of faecal pellets (Hayes & Ulrich, 1903; Cayeux, 1939), but Emigh (1958, 1967) suggests that most phosphatic pellets form by the phosphatization of calcium carbonate. Frondel (1943) points out that the phosphatization of coral limestones commonly occurs on 'guano islands'. Ames (1959) concludes from experimental studies that phosphorites probably form by the phosphatization of calcite.

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 & Ulrich (1903) consider that the Devonian phosphates of Tennessee have been formed by mechanical reworking of Ordovician phosphorites. Adams, Groot, & Hiller (1961) suggest that the phosphatic pellets of the Brightsea Formation of Maryland may also have been derived from older formations.

Work by Dietz, Emery, & Shepherd (1942) on phosphorites on the sea-floor off southern California has shown that topography may be a major factor in the formation of phosphatic nodules, for almost all nodules are found on topographic highs. They consider that the phosphate precipitated directly 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 Tethyan phosphorites. They found that the phosphorites, unlike those of southern California, occur in the synclines, which also formed depressions during deposition. The depositional environment was apparently strongly reducing. Youssef (1965) points out that the phosphorites of Egypt also 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.

Kazakov (1937) postulated that phosphate may precipitate out directly from sea-water as cold water ascends onto the shelf from the deep parts of the ocean, on the west side of continents. Calcium carbonate would be first precipitated as the temperature and pH of the water increases and the partial pressure of CO_2 decreases. The calcium phosphate would be precipitated at depths between 50 and 200 metres. The detailed work of the United States Geological Survey on the Phosphoria Formation of the Western United States also broadly supported the conclusions of Kazakov. McKelvey, Swanson, & Sheldon (1953), McKelvey et al. (1959), Sheldon (1963), and Cressman & Swanson (1964), all regard upwelling ocean currents as the primary source of the phosphates but conclude that the phosphate is precipitated before the calcium carbonate, at depths of 200 to 1000 m. However, Kolodny (1969) questions whether in fact phosphorites are forming at the present day in areas of upwelling, for he found that all pellets in such areas are at least older than 8×10^5 years. Such problems have led to rejection by some workers of upwelling as a mechanism for the formation of phosphorites. Bushinski (1964, 1969) regards rivers as more likely sources of phosphate and is supported by Pevear (1966), who examined phosphorites of probable estuarine formation in the Eastern United States.

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 that 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 Siltstone, 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, that is, that they were formed in one part of the basin and later transported to another part by current action.

The Origin of the Stairway Sandstone Phosphorites

There are five basic points to be considered in any discussion on the origin of the Stairway Sandstone phosphorites:

(i) Are the phosphate pellets and nodules the result of reworking of an older formation; if so, have they been reworked and transported from some other part of the Stairway Sandstone basin of deposition? Alternatively, have they formed in situ?

(ii) Were the phosphate pellets precipitated authigenically by inorganic or organic means or did they form by diagenetic phosphatization?

(iii) What was the environment of deposition?

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

(v) What was the primary source of the phosphate?

Transported or in situ?

Phosphatic pellets are found in several older formations of the Amadeus Basin: the Areyonga Formation, the Tempe Formation, the Pacoota Sandstone, and the Horn Valley Siltstone. However, as is apparent from the palaeogeological map (Fig. 3), little reworking of these formations is likely to have occurred during Stairway Sandstone time; and, in addition, there is too little phosphate in them to account for the concentration 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 are allochthonous or autochthonous is more difficult to resolve. Crook (1964) and Barrie (1964) both suggest that the phosphorites were reworked within the confines of the Stairway Sandstone basin of deposition. As I have discussed at length (Cook, 1967b) the evidence for and against the in situ formation of the pellets, the reasons for the conclusions reached need only be summarized very briefly.

The detrital grains in many phosphate pellets and nodules are identical in size and composition with the surrounding non-phosphatic sediments. In such cases an in situ formation seems most likely. There are however, numerous examples of major textural differences between the detrital grains within the pellets (average diameter of about 3ϕ) and those associated with, but outside, the pellets (average diameter of about 1ϕ). This seems to suggest that the phosphate pellets are detrital; but this is unlikely in view of the high velocities that would be necessary to move some of the larger pellets and nodules and the concentration of phosphate in the middle Stairway (in which mudstones predominate) rather than in the more arenaceous lower or upper Stairway. The rather irregular shape of many of the pellets as opposed to the rounded shape which one would expect of a detrital clast also tends to cast doubt on the detrital hypothesis. The winnowing hypothesis on the other hand is supported by four main lines of evidence. Quoting from Cook (1967b) these are:

(a) The separation of the coarse sand and phosphatic pellet fields in the kurtosis/standard deviation and mean diameter/standard deviation plots.

(b) The considerably greater increase of modal grain size compared with the increase of maximum grain size, with incoming of phosphate.

(c) The lack of increase of modal and maximum grain size with increase in the amount of phosphatic material present, and

(d) The disappearance of the 'fine tail' in the modal grain size histogram (and also change in the skewness) which occurs with increasing phosphate.

It seems reasonable to conclude that winnowing is probably the most important single mechanism for the concentration of phosphate pellets in the Stairway Sandstone. However, some pellets (those whose diameter is the same as the associated terrigenous material) have probably been moved for short distances within the basin. Conversely some have not been modified at all since deposition; such instances are suggested where the margin of the boundary grades into the surrounding sediments and also where the detrital grains within the pellets are essentially the same diameter as those outside the pellets.

Primary or Secondary Origin

There are few remains of macrofossils associated with the phosphorites to suggest that biochemical activity was important for the precipitation of phosphate. However, many of the pellets contain black organic material, and the lutites in which the phosphorites occur are black and carbonaceous; so a paucity of preserved macrofossils does not necessarily indicate a shortage of organic material. From the available evidence it is impossible to say whether precipitation was organically or inorganically controlled or both.

It is likely that at least some and perhaps most of the ovules did not form diagenetically, as their boundary with the surrounding sediment is sharp and well defined and there is little or no detrital material included in the pellet.

The appearance of the cementing phosphate and sandy pellets and nodules is more consistent with having formed diagenetically, by the post-depositional phosphatization of fine sands, silts, and muds below the sediment-water interface. This is supported by the gradational nature of the margins of some of the pellets, the irregular character of others, and in some cases the lack of compositional differences between the pellets and the adjacent non-phosphatic sediment. As mentioned previously, much of this type of phosphorite was subsequently winnowed, removing the fine non-indurated, unphosphatized material from around the pellets, and leaving a lag deposit of phosphate pellets and nodules.

Phosphatization of fossils which originally had calcitic shells is known to have taken place in the Stairway Sandstone. There is, however, no evidence whatsoever of the type of wholesale phosphatization of the calcite suggested by Emigh (1958). Similarly the phosphatization of faecal pellets may be responsible for a few of the pellets but is not an important mechanism.

It therefore appears that a majority of the phosphorites formed initially by the early diagenetic phosphatization of fine sands and muds below the sediment-water interface. Some of the phosphate (particularly that in the ovules) formed as a primary chemical or biochemical precipitate. This suggested mode of origin would appear to be similar to that suggested by Bushinski (1964) for some of the Russian 'platform phosphorites'.

The environment of deposition

It has already been concluded from several lines of evidence that the Stairway Sandstone was deposited in a shallow marine environment and there is no evidence to suggest any major environmental changes at the time of formation of the phosphorites. Depths of the order of 200-1000 m as suggested for the Phosphoria Formation (McKelvey et al., 1953) are out of the question for the Stairway Sandstone. The estimates of 50-200 m by Kazakov (1937) are more reasonable; but some of the Stairway phosphorites were probably deposited at depths as little as 20 m.

The redox potential and acidity of the environment were perhaps irrelevant to the deposition of much of the phosphate if it occurred below the sediment-water interface. The association of abundant pyrite and organic matter with phosphate suggest a reducing environment. However, Krumbein & Garrels (1952) have already shown that the precipitation of phosphate does not depend on Eh. pH does, however, have an important influence on the precipitation of phosphate, a pH in the order of 7.1 to 7.8 probably being necessary for the formation of the chemically or biochemically precipitated ovules. The conditions necessary for the diagenetic phosphatization of muds have never, to my knowledge, been investigated, and are completely unknown, although they are likely to fall outside the accepted range of 7.1 to 7.8.

Influence of topography and tectonics

Barrie (1964) considers that the Stairway Sandstone phosphorites were deposited on topographic highs. He suggests that a ridge of Upper Proterozoic sediments north of drill hole AP4 was also a submarine ridge during Stairway Sandstone time, and that the phosphorites found in AP4 were initially formed on it. There is, however, no evidence of this: the palaeocurrents measured in the Stairway Sandstone just north of AP4 flow due north, straight across the postulated ridge with no deflection whatsoever. Barrie's hypothesis must therefore be regarded as unproven.

The isopachous map of the middle Stairway Sandstone (Fig. 7) shows a marked thinning along a line through the Seymour Range, the Chandler Range, and the James Range, dividing the basin into two. In the western half the sea was more open and phosphorites are common; in the eastern half, it was more paralic. This line of thinning may merely be a line along which deposition was minimal, but it may also represent a ridge which influenced sedimentation.

If there were shallows in the Stairway Sandstone seas, they would probably have influenced the deposition of phosphorite, for phosphorites deposited there would have been more subject to winnowing (and therefore of a higher grade) than those deposited at greater depths. No such shallows have yet been proved.

Penecontemporaneous tectonics played little part in influencing sedimentation, for the Ordovician was a time of little or no tectonic activity in the Amadeus Basin. There may be numerous minor hiatuses within the Stairway Sandstone, all of which may have influenced the deposition of phosphorites, but there are certainly no major unconformities nor other evidence of earth movement during the deposition of the formation, apart from that occurring in the vicinity of the Goyder structural trend (Cook, 1971a).

Therefore, at present there is no evidence to suggest that the deposition of the Stairway Sandstone phosphorites was influenced in any way by topography or tectonics. Unconformities in no way influenced the concentration of phosphate pellets although some concentration is believed to have occurred on diastems.

The source of the phosphate

Cook (1966) estimates that there are 2.25 x 10^{11} tons of P_2O_5 in the Stairway Sandstone. This compares with the estimate of McKelvey et al. (1959) that there are 3.1 x 10^{11} tons of P_2O_5 in the oceans at the present day. It might therefore appear that the Stairway Sandstone contains a considerable amount of phosphate; but it is considerably less than the amount of P_2O_5 in major phosphorite deposits such as the Phosphoria Formation (conservatively estimated to contain 1.7 x 10^{12} tons). More important than the amount of P_2O_5 in the present oceans is the amount received into the oceans from rivers. If the oceans are saturated with phosphate, then any additions must be balanced by removal elsewhere, perhaps in the tests of organisms (although much of this in fact returns to solution after the death of the creature) or precipitated to form phosphatic sediments.

Cold upwelling oceanic currents are undoubtedly one way of precipitating phosphate, for they contain in solution considerably more P_2O_5 than do the warmer surface waters. Sheldon (1963) and other workers have good evidence for suggesting that upwelling currents were the source of the Phosphoria Formation phosphate.

The distribution of the redbeds, carbonates, and phosphatic siltstones and shales of the middle part of the Stairway Sandstone (Fig. 8) is similar to the facies distribution in the Phosphoria Formation of Western Wyoming; and also phosphatic units are best developed on the seaward side of the basin, suggesting that the source of phosphate is in the oceans. As has already been mentioned, a great deal of the phosphate is believed to have been precipitated below the sediment-water interface in the Stairway Sandstone. It is therefore likely that many of the phosphorites were able to form under water only slightly more phosphatic than normal marine concentrations. Periodically the phosphate content may have risen until ovules etc. were chemically or biochemically precipitated. It is probable that minimal terrigenous sedimentation was just as important to the formation of the phosphorites as the phosphate concentration of the seawater, for even under strongly upwelling conditions only slightly phosphatic sediments will result if there is abundant detritus.

Bushinski (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. The 2.25 x 10^{11} tons of P_2O_5 in the Stairway were deposited over a period of about 5-10 m.y. This is an average rate of deposition of about 20,000 to 40,000 tons of P_2O_5 per year: three or four large rivers could have carried sufficient phosphorus to form the Stairway Sandstone phosphorites. Such large rivers would have had to carry exceptionally little sediment, however, in view of the slow rate of sedimentation in Stairway Sandstone time.

Volcanism is perhaps the least likely source of the Stairway phosphate. There are no Ordovician volcanics whatsoever in the Amadeus Basin, and throughout Australia as a whole there was little volcanic activity except in the Lachlan Geosyncline, where calcalkaline and splitic volcanics are known to be present. Since the Lachlan volcanism is some 1500 km southeast of the Amadeus Basin it is unlikely to have influenced Stairway sedimentation in any way whatsoever.

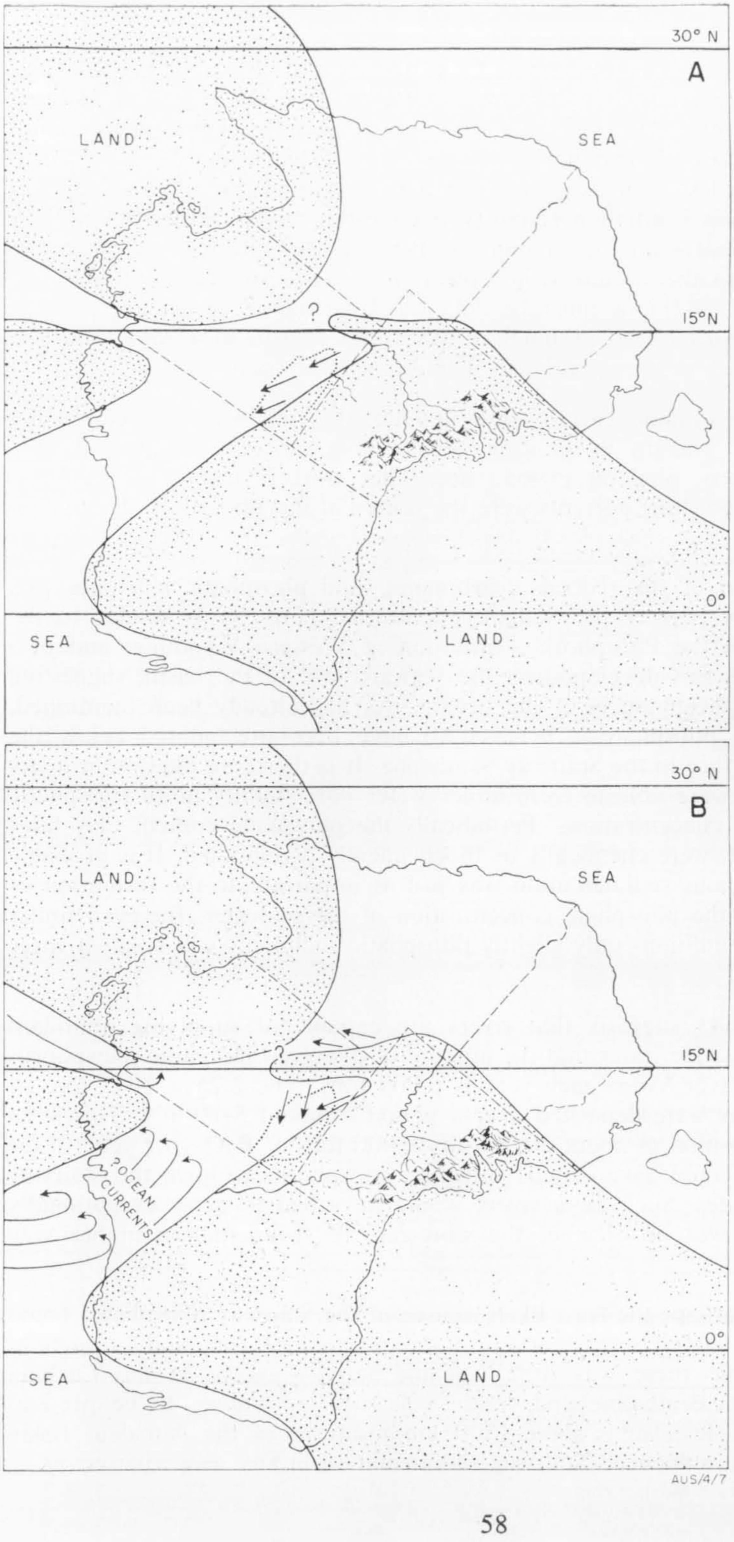

Figure 28. Palaeogeography of the Stairway Sandstone. (A) lower Stairway; (B) middle Stairway.

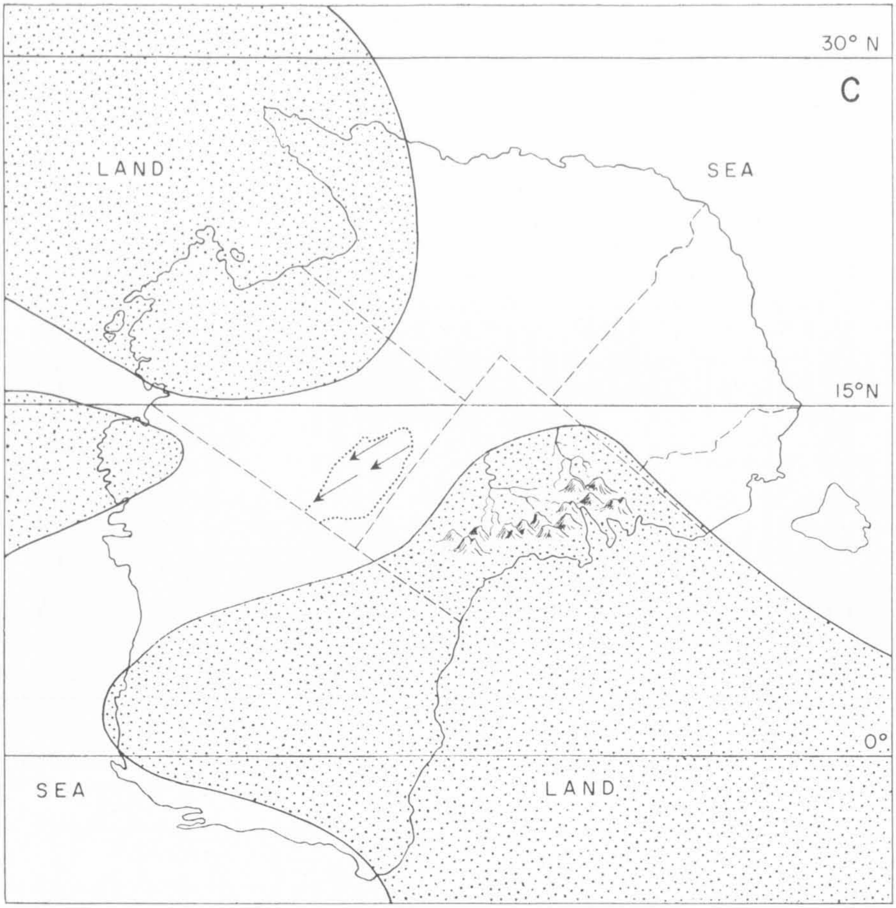

Figure. 28. Palaeogeography of the Stairway Sandstone. (C) upper Stairway.

SUMMARY AND CONCLUSIONS

Palaeoclimate

The sparse palaeomagnetic data on the Lower Palaeozoic of Australia (Irving, 1964) suggest that in the Ordovician the Amadeus Basin would have been situated at a low latitude in the northern hemisphere. A suggested picture consistent with the palaeomagnetic data is shown in Figure 28, placing the Amadeus Basin within the torrid zone. Trade winds would have reached this area for at least part of the year, and this, together with the embayment open to west, may have periodically produced minor upwelling of cold phosphate-rich ocean currents. Folk (1968) suggests that bimodal sands such as those commonly present in the Stairway Sandstone, with a mode separation of two phi units, are characteristically desert sands. Similarly, redbeds tend to form under hot desert conditions (Walker, 1967a,b). Halite pseudomorphs are present in the overlying Stokes Siltstone. All these factors support the suggestion of a hot arid climate in Stairway Sandstone time.

Provenance

The nature of the supermature orthoquartzites throughout the Stairway Sandstone, particularly the well rounded grains and the abundance of non-undulating quartz, suggests that the source area was composed predominantly of quartzose sediments. The pebble band within the lower Stairway, which is composed of well rounded clasts of metaquartzite and silicified sandstone, indicates ruditic rocks, such as the Precambrian Winnall Beds, in the source area. The simultaneous occurrence at one horizon in the middle Stairway of both well rounded and euhedral grains of zircon suggests a combination of single and multicycle material such as a source area composed of both plutonic and quartzose sedimentary rocks might supply. In upper Stairway time the provenance was again overwhelmingly arenitic, although the occurrence of chert grains may imply a minor calcareous source.

There is some suggestion from the inferred palaeocurrents that in the upper and lower Stairway, sediments were derived mainly from the southeast, whereas in the middle Stairway, a northeast component is apparent.

Palaeogeography

The Ordovician is known to be a time of major transgression, with extensive though shallow seas covering much of the continent. It is perhaps significant to note here that throughout the world, the Ordovician appears to have been a time of major inundation of the continents by the sea. The inundation may have been due to the melting of polar ice, the development of major eugeosynclinal belts with attendant volcanism (producing displacement of oceanic water and adding to the hydrosphere through volcanic exhalation), wholesale gentle downwarping of the continents, or tectono-eustatic changes.

The overall picture of the palaeogeography of the Amadeus Basin is shown in Figure 28, and it is apparent that the basin was connected to the open ocean to both east and west. In the east, eugeosynclinal sedimentation was taking place (the Tasman Geosyncline). To the west, the Bonaparte Gulf and Fitzroy Basins were somewhat shallower. Local changes in the palaeogeography were superimposed on this major picture. Lower Stairway time opened with the development of a minor embayment to the southeast, due either to the breaking of a barrier or local downwarping (Fig. 28A). There is evidence that in places on the southern margin of the lower Stairway area (e.g. the Mount Sunday Range) there were coastal cliffs up to 30 m high. At this time a broad shelf connected the Amadeus Basin to the open sea to the northwest. The connexion to the open sea to the east was rather more restricted.

The same situation persisted during the deposition of middle Stairway sediments (Fig. 28B), although lack of arenites and the abundance of phosphorites suggest a decrease in the supply of detritus. This may have been a result of factors such as the formation of a barrier or a decrease in rainfall. In addition, prolonged erosion had bv this time probablv planed down the hinterland, and consequently manv rivers would have carried little detritus.

In upper Stairway time there was a major marine transgression, and extensive shallow seas flooded over the previously peneplaned land area (Fig. 28C). There were now broad connexions to both east and west.

Depositional History

At the end of Horn Valley Siltstone time a maior change in sedimentation resulted in a large body of coarse regressive offshore bar sands being deposited over the deeper water sediments of the Horn Valley Siltstone. The area of deposition of these regressive sands was much the same as that of the Horn Valley Siltstone except for the formation of the Mount Charlotte embayment.

Lower Stairway sedimentation ended with the deposition of a thin though very extensive pebble band, which may be a reflection of some minor earth movement. The regression of the barrier island across the shelf was followed by a similar migration of a lagoon or a series of lagoons, comparable to the situation on the emergent coast of the Gulf of California described by Curray & Moore (1964). Middle Stairway deposition was marked by a decrease in the rate of sedimentation and tranquil low-energy conditions. This was a time of phosphate deposition in the northwest, where the sea was more open, but in the southeast the environment was rather more saline and restricted. With the advent of upper Stairway sedimentation, shallow marine sands (offshore bars, submarine dunes, etc.) prograded across the basin in response to a major transgression. Conditions now reverted to those existing before the Middle Stairway, with fairly high-energy conditions, predominantly arenitic sedimentation, currents mainly from the southeast (as opposed to the northeasterly component evident in the middle Stairway), and a comparatively low rate of phosphate deposition.

Phosphate Deposition

The eight morphological types of phosphatic material found in the Stairway Sandstone are similar to those found in many other phosphorites, but the relative abundance of sandy pellets suggests that the phosphorite should be regarded as a 'platform phosphate' which formed in rather shallow marine conditions. Many of the phosphate pellets are believed to have formed as an early diagenetic phase, just below the mud-water interface, although some of the ovules may be primary precipitates. The initial sediment was probably no more than a phosphatic mudstone, but winnowing produced thin higher-grade phosphatic lag deposits. Although the immediate source of the phosphate cannot be unequivocally established it is believed to be of marine origin, with upwelling currents a possible mechanism. However, as much of the phosphate is thought to have formed by early (prelithification) diagenesis, it would have only been necessary for the phosphate concentration in the water to be a little above average. A slow rate of deposition and winnowing were just as important as the phosphate concentration of the water to the development of the Stairway Sandstone phosphorites.

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APPENDIX 1

ECONOMIC CONSIDERATIONS

Hydrocarbons

Natural gas has been discovered in the Stairway Sandstone in the northern half of the Amadeus Basin. Significant amounts are present in the Mereenie and Palm Valley Anticlines; trace amounts were apparent in the Gosses Bluff No. 1 Well. In addition approximately 3 m of oil-saturated sand was intersected in the AP1 well, and fluorescence was encountered throughout much of the lower Stairway. Wells in the southern half of the Amadeus Basin (Mount Charlotte No. 1 and Erldunda No. 1) encountered no hydrocarbons.

There are several possible reasons for the apparent lack of hydrocarbons in the south:

(i) There is only a thin veneer of post-Stairway sediments, and escape of hydrocarbons was easy.

(ii) The Horn Valley Siltstone, an excellent source rock in the north, is absent in the south.

(iii) The lower unit, which is the important reservoir in the Stairway Sandstone, is absent from the southern half of the basin.

Therefore the hydrocarbon potential of the Stairway Sandstone is undoubtedly less in the south.

The high and low energy areas delineated by the isoset and iso-angle maps (Figs 11 & 12) define regions where winnowing is likely to have produced the highest intergranular porosities and therefore initially the best potential reservoir rocks. However, in the northern half of the basin the major obstacle to hydrocarbon accumulations has not been the primary porosity-permeability, but rather the present-day low permeabilities of the sandstone due to post-depositional silicification. This study did not investigate regional variations in silicification, but it did suggest that the silicification is probably due to overburden pressure or tectonism. Therefore permeabilities are likely to be least on the northern margin of the basin.

Potential stratigraphic traps are undoubtedly present in Stairway Sandstone. Perhaps the most outstanding example brought out by this study is the 'pinchout' of the lower Stairway in the vicinity of the Seymour Range. In the same area in the middle Stairway, carbonate lenses interfinger with the redbed facies of the Mount Charlotte embayment (Fig. 8); any eastward migration of oil from the phosphatic shales would have an excellent chance of being trapped within the carbonate facies.

A belt of stratigraphic thinning where 'pinchouts' are likely is postulated to run from the Seymour Range to the Chandler Range and then through the James Range area (Fig. 7). Hydrocarbons migrating from the phosphatic shale of the middle Stairway could have been trapped on the west side of this zone. The east side of the zone (and much of the Mount Charlotte embayment) is less likely to have hydrocarbon accumulations, owing to the presence of redbeds in the middle Stairway. Overall, the Stairway Sandstone offers good petroleum prospects. Both the lower and upper Stairway contain known reservoir rocks and both have an excellent capping: the lower Stairway has the middle Stairway lutites and the upper Stairway the Stokes Formation lutites as impermeable cap rocks.

The black organic-rich mudstones of the underlying Horn Valley Siltstone probably constitute good potential source rocks. Similarly black phosphatic middle Stairway mudstones are likely to be important source rocks just as phosphatic mudstones are in other parts of the world, particularly in the Wyoming and Middle East oilfields.

Phosphate Deposits

There is undoubtedly a considerable amount of phosphate in the form of carbonate fluorapatite in the Stairway Sandstone, although over its total thickness, the formation would probably only average 1% P_2O_5 or less. To date no economic concentrations of phosphatic material have been found. It has been shown that winnowing was of major importance in the enrichment of phosphorites; therefore future prospecting should, as a first step, be concentrated in areas where winnowing is likely to have occurred. Any areas which constituted submarine ridges in Stairway times would undoubtedly merit further consideration. One such area may have been the line of thinning through the Seymour, Chandler, and James Ranges. Similarly, ancient strand-lines might also constitute areas of potential pellet concentration; for this reason Barrie (1964) suggests the southern margin of the basin as being an area of possible phosphate enrichment.

In addition to phosphorites that may have been enriched by winnowing, the possibility of finding rich primary phosphorites that have not been diluted by terrigenous material must be considered. Figure 8 shows that the eastern half of the basin has poor phosphate prospects as the sediments are of the redbed or carbonate facies. Palaeocurrents flow from the southeast across the basin; therefore the area of least terrigenous sedimentation would be to the northwest. The best phosphatic areas to the northwest may have been in the region that was strongly deformed during the Alice Springs Orogeny and subsequently eroded, so that there is no trace of the high-grade phosphorites. Alternatively, the optimum area may have been situated even farther to the northwest, in the Canning or Fitzroy Basins. A closer look at the Stairway Sandstone equivalents of these basins could well bring economic-grade phosphorites to light.

In addition to primary concentrations, secondary concentrations of phosphate may be present: I have, for instance, noted the presence of high-grade secondary phosphorites in the Tertiary weathering profile of the Georgina Basin. Similarly in the Amadeus Basin, the phosphorites from the subsurface are invariably of a lower grade than those at the surface. Pellets are also mechanically concentrated in Quaternary gravels in places, such as the Johnny Creek area, and constitute an alternative way in which the relatively low grade primary ores may have been enriched.

In conclusion, the chances of finding an economic phosphate deposit in the Stairway Sandstone can only be rated as moderate to poor, particularly in view of the enormous transportation problems posed by such an isolated region. However, the use of some of the suggested geological approaches together with geophysical tools such as airborne radiometric surveys may ultimately lead to the discovery of a major deposit.

APPENDIX 2

DETAILED GRAPHIC LOGS (See Plate 15)

Several types of detailed graphic logs have been proposed in the past for the study of sedimentary sequences, the parameters incorporated in the logs depending primarily on the purpose of the investigation. The basic aim of all methods is to present, as clearly as possible, such features as lithology or sedimentary structures, so that any basic cyclicity of sedimentary environments is apparent. Bouma (1962) has used the method to good effect in his investigation of turbidite sequences of the Peira-Cava area of France. Because of the proven worth of the method, the comprehensiveness of its symbolism, and its ready availability in published form, Bouma's methods and symbols have been used wherever possible. Some adaptation was necessary because of particular features of the Stairway Sandstone, such as the phosphorites, and therefore special columns have been added to incorporate this additional information. Also, a major part of Bouma's work was concerned with sections measured in the field, whereas the detailed graphic log studies in the Stairway Sandstone are restricted to core from the continuously cored diamond drill hole AP1. This hole, which was one of four drilled to test for phosphate in the Stairway Sandstone, was drilled to a total depth of 248 m, but only the interval 15-215 m was logged in the time available. The investigation was primarily in the laboratory. The values of the various parameters were noted on a 'questionnaire sheet', and then plotted on large graphic log sheets at a scale of 1:24. However, as this gave a graphic log over 10 m long the logs were reduced photographically by half to make them more convenient to handle.

Graphic Presentation

1. *Thickness*

(a) *Apparent thickness*: This is the vertical distance in feet measured from the top of the hole. This thickness is noted on the graphic log at 2-foot (0.61 m) intervals; the metric intervals are also shown on the right hand side of the log.

(b) *True thickness*: This is the true thickness of the Stairway Sandstone measured from the top of the formation, situated at an apparent thickness of about 69 feet 10 inches (21.3 m) and with a correction factor applied for the structural dip of the beds in the core. This true thickness is noted on the left hand side of the log at 10-foot (3.04 m) intervals.

2. *Core*

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

(b) *Condition*: Most of the core was in good condition, but a little was either lost or broken up during drilling. In places, half the core was taken for P_2O_5 analysis. In the more shaly units, core has split into many fine laminae parallel to the bedding.

3. *Rock type*

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

4. *Bedding-Plane Properties*

(a) *Type*: The symbols used for bedding-plane types are identical with those used by Bouma (1962) and are divided into relative classes such as very sharp, sharp, etc.

(b) *Structures on the bedding plane*: This column was included in case any features were present in the small area available on the few bedding planes visible; but in fact no recognizable features were seen.

5. *Current direction*

This column was included so that should this type of information be available from surface outcrop or from oriented core, it could be shown on the log. In the case of the AP1 core, no such information was available.

6. *Layer Properties*

The symbols used are identical with those of Bouma (1962). The main column is in this case divided into 10 sub-columns each of which represents a layer property or sedimentary structure. Variations within the basic layer property are indicated by the position of the 'blocks' within the sub-column, so that in all, it is possible to represent a total of 31 different layer properties by the method given in Plate 15. It would have been useful to have had a single column for showing the degree of bioturbation. The lack of such a sub-column is, however, overcome by, for instance, representing very strong churning by infauna by the blocking in of the 3 columns to show 'strongly disturbed parallel lamination', 'strongly disturbed lenticular wavy lamination' and 'tracks and burrows in all directions'.

7. *Texture*

(a) *Modal Grain Size*

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

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

(b) *Maximum Grain Size*
This is given in the phi scale, the phi value being measured directly with a binocular microscope.

(c) *Calcium Carbonate*
This is estimated by means of a 10% solution of hydrochloric acid and is merely a rough indication of the calcium carbonate content of the rock.

8. *Porosity*
The intergranular and vuggy porosities are estimated visually from inspection under the binocular microscope.

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

10. *Supplementary Data*
The presence of pyrite, glauconite, free oil, or fluorescence is noted under the heading of supplementary data. In addition, the pyrite column distinguishes between oolitic and non-oolitic forms. The semi-quantitative division of pyrite and glauconite into 'rare', 'common', and 'very common' was estimated visually. 'Rare' implies that the component was visible only with the aid of a hand lens or binocular microscope. 'Common' implies that the component is easily visible to the naked eye; and 'very common' is used when the component is considered to form a significant part of the rock type.

11. *Fossils*
Only the presence of macrofossils is noted. Parts of the core have been submitted for microfossil examination but the results are not available as yet. The only fossils present are brachiopods (represented by the triangular symbol), gastropods, and bivalves (represented by the 'bomb-like' symbol). The presence of fossils in general is shown by the ammonite symbol. A diagonal line across the fossil symbol implies that the fossils are fragmentary.

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

N8—very light grey
N7—light grey
N6—medium light grey
N5—medium grey
N4—medium dark grey
N3—dark grey
10Y4/2—greyish olive
5Y8/1—yellowish grey
5Y7/2—yellowish grey
5Y6/1—light olive grey
5Y5/2—light olive grey
5Y4/1—olive grey
5G6/1—greyish green
5GY6/1—greenish grey
5GY5/2—greyish green
10YR8/2—very pale orange
10YR7/4—greyish orange
10YR4/2—dark yellowish brown

(b) Weathered

This column is not used.

13. *Properties of phosphatic material*

(a) *Approximate percentage of phosphatic pellets and grains*: This percentage was estimated visually and noted on the log as one of 4 classes: 1-5%; 5-10%; 10-20%; and 20-50%. These broad classes were used because of the difficulty of estimating accurately the percentage of phosphatic material. Quantitative chemical analysis for P_2O_5 content would have been preferable, but this information was only available for parts of the core and therefore visual estimation was used throughout the log for consistency. The analyses available suggest the following P_2O_5 contents for the 4 classes of visual estimates:

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

(b) *Textural Range*: Again, phi grain sizes were measured directly under a binocular microscope. This column could equally well be termed 'maximum grain size' as the upper limit of the textural range is also the maximum grain size.

(c) *Roundness*: The roundness was obtained from visual estimation charts in which 5 classes of roundness are distinguished.

(d) *Sphericity*: As in roundness the 5 classes of sphericity were estimated from visual estimation charts.

(e) *Colour*: The rock-colour chart distributed by the Geological Society of America was used for colour classification.

14. *Number of Layers*

This column heading is used by Bouma (1962) in a fairly broad way. Here, it means the number of individual laminae within the unit and is the smallest recognizable layer of uniform sediment. It does not represent a major change in the environment of deposition but merely a momentary small fluctuation in, for instance, the current velocity. In the graphic log of the Stairway Sandstone, because units as thin as about 6 mm (¼ inch) are considered individually, most units correspond to a single layer.

15. *Unit Number*

Because of the detailed nature of the work, the unit recognized in the Stairway Sandstone corresponds to the sedimentation unit of Otto (1938) and Pettijohn (1949). The numbering of sedimentation units starts at the first unit logged so that the numbers of the sedimentation units increase down the core. They range from unit number 14 at 50 feet (approximately 15 m) to number 842 at 700 feet (approximately 215 m).

16. *Remarks*

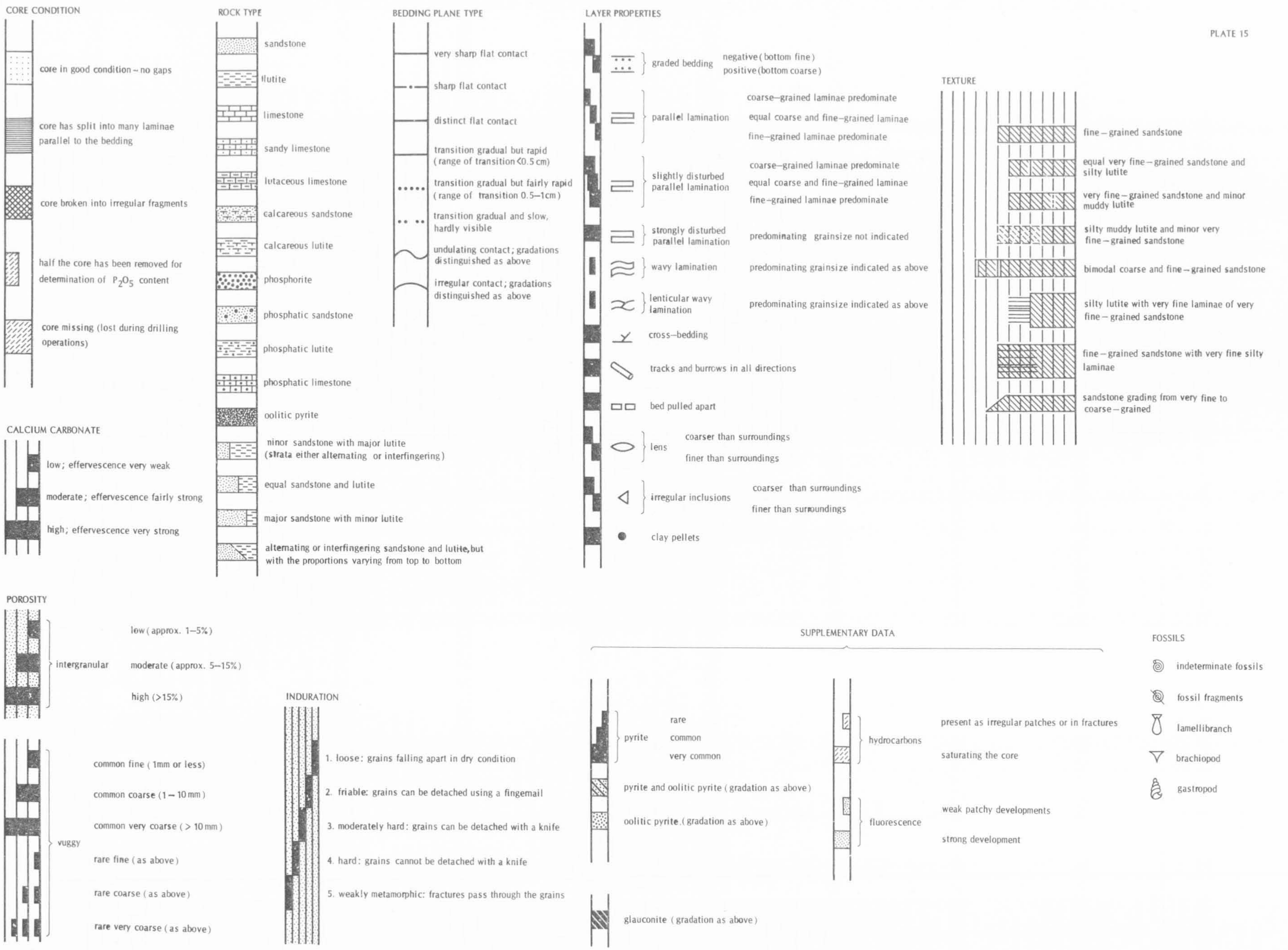
This column is used for the location of samples, the letters indicating both location and reason for the sample:

T—thin section sample
H—heavy mineral separation
S—detailed size analysis carried out on the thin section of this sample

M—sample submitted for microfossil determination
C—sample for determination of clay mineralogy
X—sample for X-ray determination of phosphate mineral present

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

PLATE 15


CORE CONDITION
core in good condition – no gaps
core has split into many laminae parallel to the bedding
core broken into irregular fragments
half the core has been removed for determination of P_2O_5 content
core missing (lost during drilling operations)
ROCK TYPE
sandstone
lutite
limestone
sandy limestone
lutaceous limestone
calcareous sandstone
calcareous lutite
phosphorite
phosphatic sandstone
phosphatic lutite
phosphatic limestone
oolitic pyrite
minor sandstone with major lutite (strata either alternating or interfingering)
equal sandstone and lutite
major sandstone with minor lutite
alternating or interfingering sandstone and lutite, but with the proportions varying from top to bottom
BEDDING PLANE TYPE
very sharp flat contact
sharp flat contact
distinct flat contact
transition gradual but rapid (range of transition <0.5 cm)
transition gradual but fairly rapid (range of transition 0.5–1cm)
transition gradual and slow, hardly visible
undulating contact; gradations distinguished as above
irregular contact; gradations distinguished as above
LAYER PROPERTIES
graded bedding
negative (bottom fine)
positive (bottom coarse)
parallel lamination
coarse–grained laminae predominate
equal coarse and fine–grained laminae
fine–grained laminae predominate
slightly disturbed parallel lamination
coarse–grained laminae predominate
equal coarse and fine–grained laminae
fine–grained laminae predominate
strongly disturbed parallel lamination
predominating grainsize not indicated
wavy lamination
predominating grainsize indicated as above
lenticular wavy lamination
predominating grainsize indicated as above
cross–bedding
tracks and burrows in all directions
bed pulled apart
lens
coarser than surroundings
finer than surroundings
irregular inclusions
coarser than surroundings
finer than surroundings
clay pellets
TEXTURE
fine – grained sandstone
equal very fine – grained sandstone and silty lutite
very fine – grained sandstone and minor muddy lutite
silty muddy lutite and minor very fine – grained sandstone
bimodal coarse and fine – grained sandstone
silty lutite with very fine laminae of very fine – grained sandstone
fine – grained sandstone with very fine silty laminae
sandstone grading from very fine to coarse – grained
CALCIUM CARBONATE
low; effervescence very weak
moderate; effervescence fairly strong
high; effervescence very strong
POROSITY
intergranular
low (approx. 1–5%)
moderate (approx. 5–15%)
high (>15%)
vuggy
common fine (1mm or less)
common coarse (1 – 10 mm)
common very coarse (> 10 mm)
rare fine (as above)
rare coarse (as above)
rare very coarse (as above)
INDURATION
1. loose: grains falling apart in dry condition
2. friable: grains can be detached using a fingernail
3. moderately hard: grains can be detached with a knife
4. hard: grains cannot be detached with a knife
5. weakly metamorphic: fractures pass through the grains
SUPPLEMENTARY DATA
pyrite
rare
common
very common
pyrite and oolitic pyrite (gradation as above)
oolitic pyrite (gradation as above)
glauconite (gradation as above)
hydrocarbons
present as irregular patches or in fractures
saturating the core
fluorescence
weak patchy developments
strong development
FOSSILS
indeterminate fossils
fossil fragments
lamellibranch
brachiopod
gastropod

HOLE AP1 SCALE 1:48 PLATE 16

FORMATION Stairway Sandstone AGE Ordovician

LOCATION Johnny Creek, N.T. MEASURED BY P.J.Cook

HOLE AP1 SCALE 1:48 PLATE 17

FORMATION Stairway Sandstone AGE Ordovician

LOCATION Johnny Creek, N.T. MEASURED BY P.J.Cook

HOLE AP1 SCALE 1:48 PLATE 18

FORMATION Stairway Sandstone AGE Ordovician

LOCATION Johnny Creek, N.T. MEASURED BY P.J.Cook

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HOLE AP1 SCALE 1:48 PLATE 19

FORMATION Stairway Sandstone AGE Ordovician

LOCATION Johnny Creek, N.T. MEASURED BY P.J.Cook

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HOLE AP1 SCALE 1:48 PLATE 20

FORMATION Stairway Sandstone AGE Ordovician

LOCATION Johnny Creek, N.T. MEASURED BY P.J.Cook

HOLE AP1 SCALE 1:48 PLATE 21

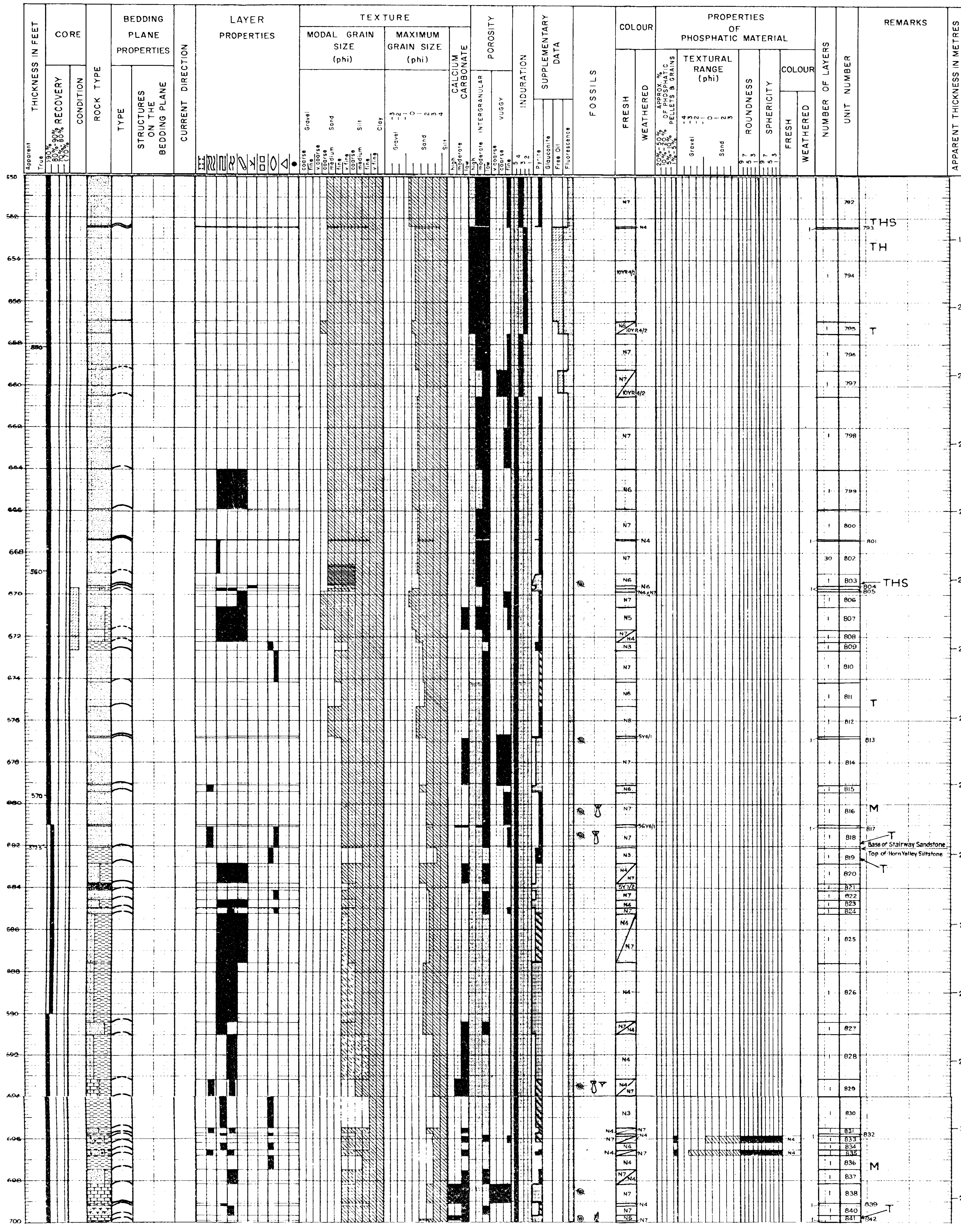
FORMATION Stairway Sandstone AGE Ordovician

LOCATION Johnny Creek, N.T. MEASURED BY P.J.Cook

HOLE AP 1 SCALE 1:48 PLATE 22

FORMATION Stairway Sandstone AGE Ordovician

LOCATION Johnny Creek, N.T. MEASURED BY P.J.Cook



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