COMMONWEALTH OF AUSTRALIA

DEPARTMENT OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

RECORDS 1965/57

Copy 4.

AN APPRAISAL OF THE PHOSPHATE PROSPECTS OF THE BOWEN BASIN

by

J.A. Kaulback

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Records 1965/57

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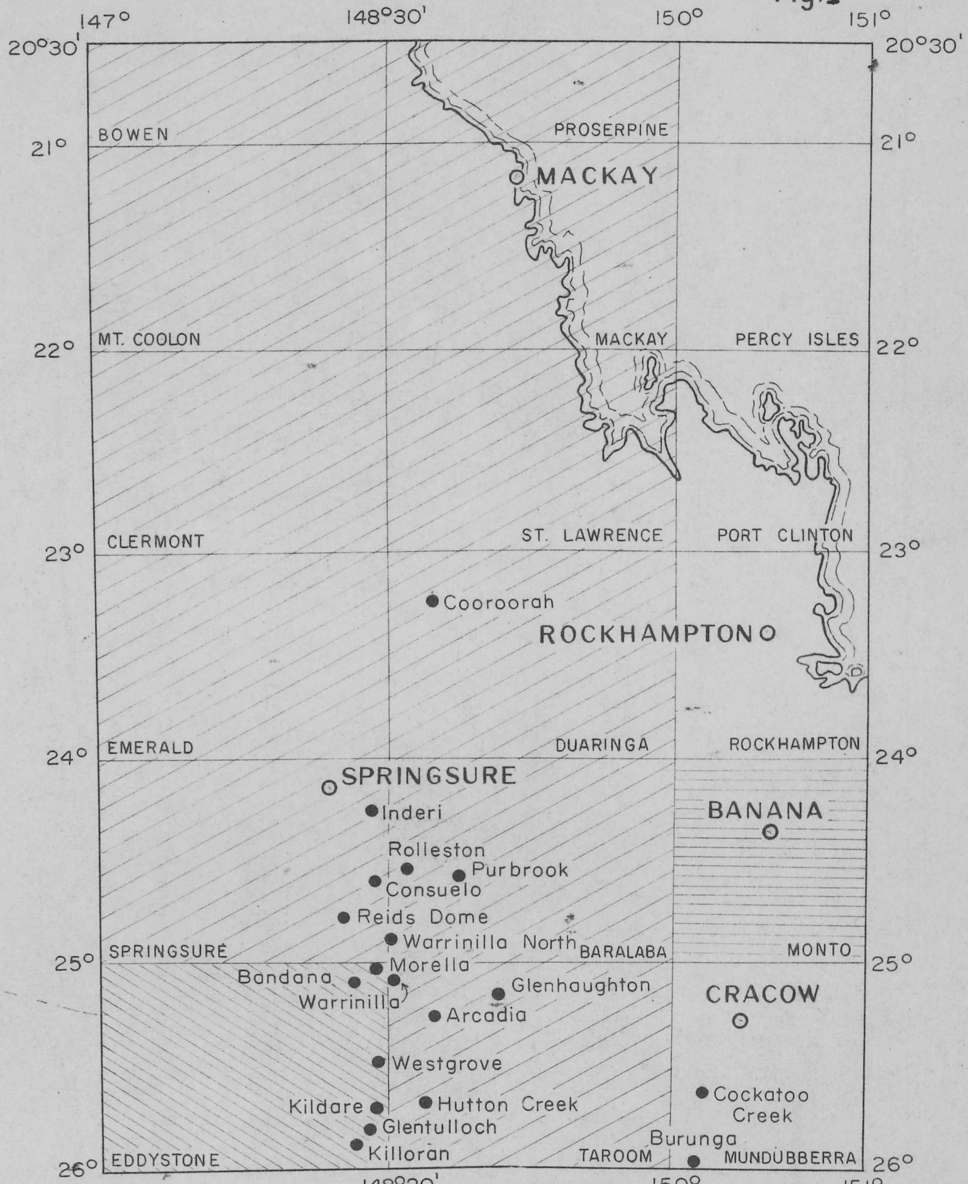


LOCALITY MAP

BOWEN BASIN

Showing 1:250,000 sheets

50 0 50 100 MILES

Mapping completed *Mapping in progress, 1964*

Mapping by Geological Survey of Queensland, in progress

Bureau of Mineral Resources, Geology & Geophysics. Sept, 1964.

To accompany Record No: 1965/57 Q-A65

AN APPRAISAL OF THE PHOSPHATE PROSPECTS

OF THE BOWEN BASIN

FOREWORD

by L.C. Noakes

Record 1965/37 "An Approach to the Search for Sedimentary Phosphate" by J.A.Kaulback suggested a pattern for the fundamental study of phosphate potential in sedimentary basins. This record by the same author seeks to apply the pattern to the Bowen Basin in Queensland as an example of the method and of the type of conclusions that can be drawn.

The Bowen Basin is not a simple or straightforward example for testing the application of this technique; sedimentation in three geographical provinces and inevitable facies changes within and between them result in complications which demand a lengthy review. But this serves to emphasise that a review needs to synthesise current knowledge of the basin and to summarise the facts on which interpretation of environment and assesment of potential can be based, if it is to be of continuing use to investigators.

It is hoped that this review will serve a useful purpose and that other organisations will addopt or improve this pattern to provide basic appraisals of other sedimentary basins so that the search for sedimentary phosphate in Australia may continue along increasingly sound lines.

SUMMARY

A brief review of the geology of the Bowen Basin is given, including a description of areas of deposition, stratigraphy, structure, and summary of geological history. Following lines suggested in Record 1965/37, the phosphate potential of the basin is discussed under two headings: Preliminary Analysis, where formations most suitable for phosphorite deposition are selected, and Detailed Analysis, in which are selected those lithological sevtions from these formations, which are likely to contain phosphorite.

The lithostratigraphy of the Bowen Basin is complicated by the subdivision of the basin into three separate depositional provinces - the western, central, and eastern provinces. Between these provinces there are great variations in depositional environment within the same time units, so that the phosphate potential of rocks deposited within the same unit can only be analysed in a general way. Detailed analysis must be restricted to formations only, and these are almost invariably confined to one of the major depositional provinces.

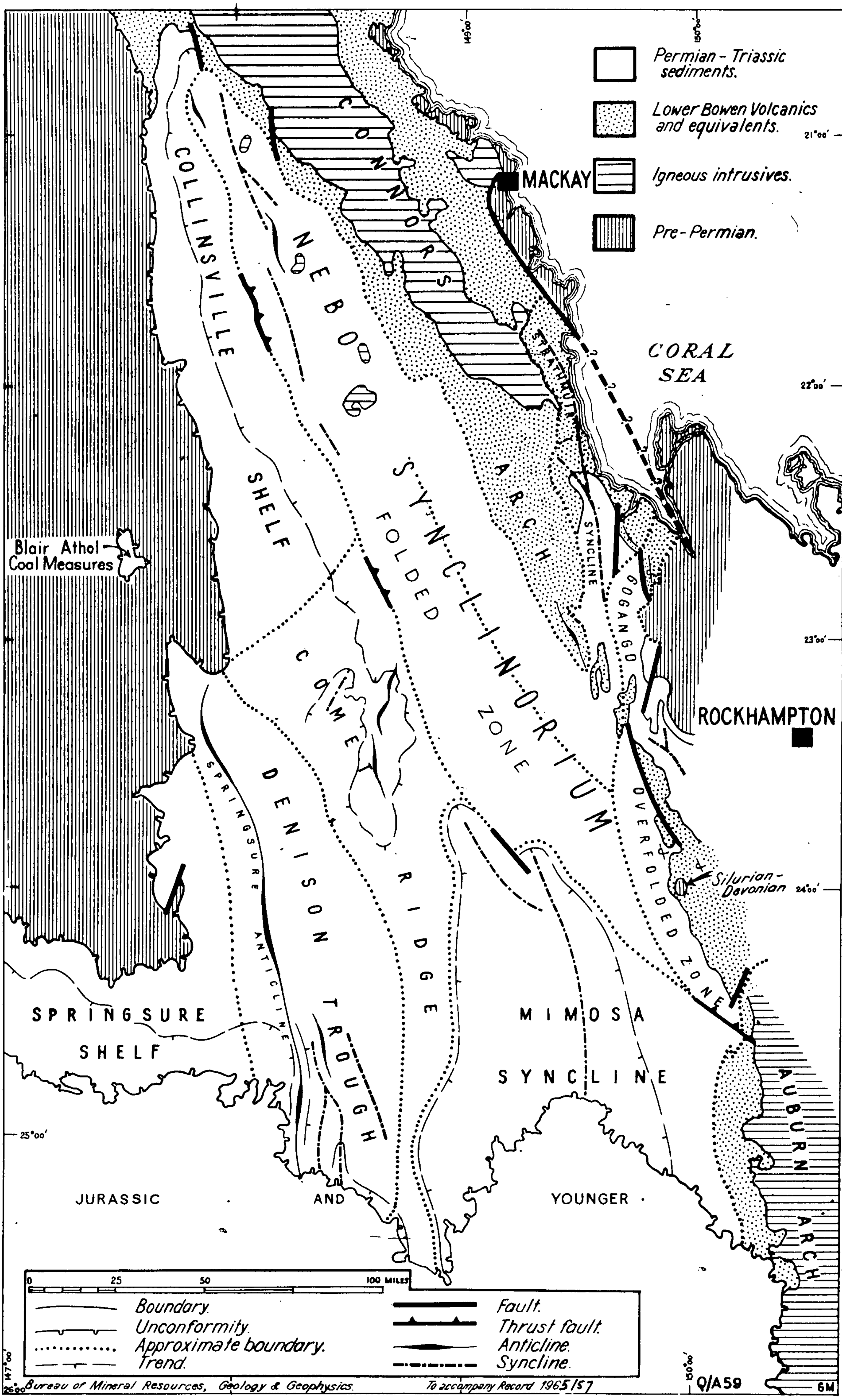
The Permian Middle Bowen Beds are the only rocks deposited in one period of continuous marine sedimentation, and, as all known economic deposits of sedimentary phosphate are in rocks of marine origin, all non-Permian units (which are predominantly non-marine) are eliminated as unlikely to contain economic phosphate depposts.

From the Permian Middle Bowen Beds, detailed analysis indicates three major and three less important lithostratigraphic groups with high phosphate potential. This indicated potential is broadly endorsed by the few assays available from the sequence. The groups selected are (in order of importance):

(1) Barfield and Flat Top Formations and equivalent formations in the Back Creek Group.
(2) Cattle Creek Formation.
(3) Mantuan Productus Beds.
(4) B uffel Formation.
(5) Ingelara Formation.
(6) Sirius and Stanleigh Formation.

Fig 2.

STRUCTURAL ELEMENTS OF THE BOWEN BASIN



INTRODUCTION

LOCALITY

The locality of the Bowen Basin is shown in Fig.1 and Plate 1. Rockhampton and Mackay are the principal ports. The area is crossed by north-south and east-west railways, and by a good road network.

SOURCES

Information for this review was gathered from both published and unpublished B.M.R. Records and reports (see References), from which extensive portions are quoted verbatim. Valuable help was received from Dr. J. M. Dickins and Mr. E. J. Malone.

REVIEW OF GEOLOGY

AREAS OF DEPOSITION

The Bowen Basin is a northerly trending synclinorium, 600 miles long and 100-200 miles wide, filled with 30,000 feet of mainly Permian and Triassic rocks which in the south are transgressively covered by several thousand feet of the continental Jurassic and marine Cretaceous of the Surat Basin. To the east, the basin is bordered by the Middle Palaeozoic Yarrol Basin sequence mainly, and in part by Lower Palaeozoic metamorphics and intrusives of the coastal cordillera, and to the west by similar rocks in and around the Anakie Uplift.

The Bowen Basin may be divided broadly into three depositional provinces: a western province, which consists of the Denison Trough, flanked by the Springsure Shelf to the west and the Comet Ridge to the east (Fig.2); a central province consisting of the northern trough flanked by the Collinsville Shelf to the west, a south-eastern shelf which became a trough in the Upper Permian, and the Mimosa Syncline trough; and the eastern province consisting of troughs flanking both sides of the Connors and Auburn Arches and extending eastwards between them. These provinces are characterised by distinct facies.

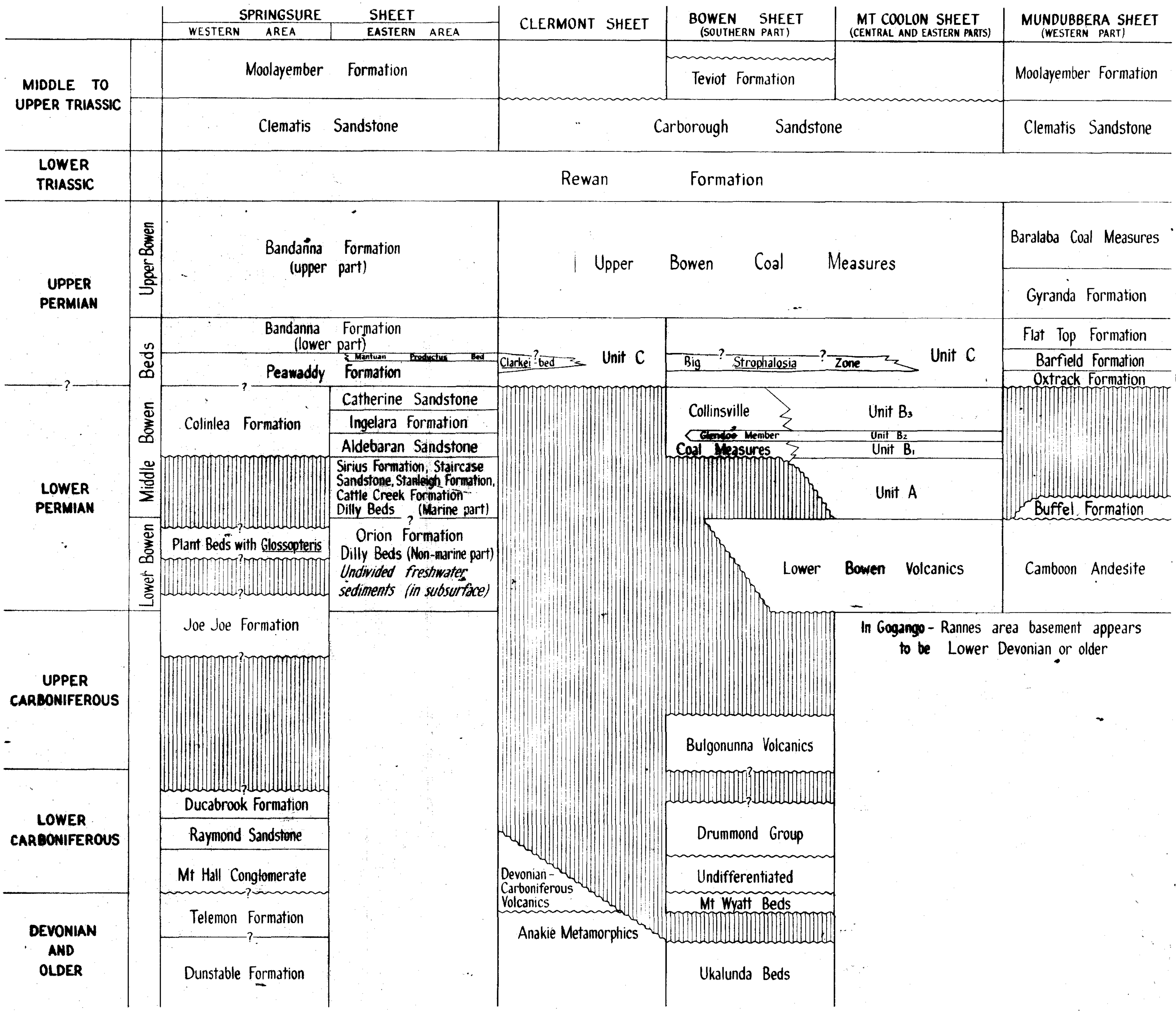
The Bowen Basin can be further divided into a number of structural elements (Fig.2), which are closely related to the three main depositional provinces of the Basin as well as to the depositional areas of individual rock units. The axis of the central trough migrated from one unit to another and the trough shrank in size, so that the youngest sediments (middle to upper Triassic) were deposited in the most restricted downwarp.

STRATIGRAPHY

The stratigraphical succession of the western and central provinces of the Bowen Basin is summarised in Table 1 and Fig.4. Stratigraphic information on the eastern province is not yet available. The depositional areas of the major regional rock units are shown in isopach maps in Fig.3 which are based on present thicknesses of the rock units (estimated or measured in outcrop, by seismic survey or in oil wells - Table 2). Outcrop geology is shown in Plate 1.

Each of the regional rock units consists of one or more formations recognised in the three main outcrop areas of the Bowen Basin. The stratigraphical relationships between the rock units of the three areas are shown in Fig.4. Rocks older than the Permian are considered as a part of the Drummond Basin, to the west of the

Fig. 4



Bureau of Mineral Resources, Geology and Geophysics.
June 1964.

To Accompany Record No. 1965/57

TABLE 1. STRATIGRAPHY OF PERMIAN AND TRIASSIC ROCKS

PERIOD	REGIONAL ROCK UNIT	FACIES AND MAXIMUM THICKNESS	WEST SPRINGSURE	AREA	NORTH CENTRAL PROVINCE NORTHERN	BOWEN BASIN	SOUTH EAST CENTRAL PROVINCE BANANA	CRACOW AREA	DESCRIPTION OF EVENTS
	Middle to Upper Triassic	Deltaic 2750'	Moolayember Formatiinn Clematis Sandstone	Shale Quartz sandstone	Carborough Sandstone and Teviot Formation	Quartz and feldspathic sandstone Lithic sandstone and micaceous siltstone	Moolayember Formation Clematis Sandstone	Mudstone with sandstone interbeds, conglomerate, shale, tuff. Lithic sandstone.	Main period of uplift and erosion Main Bowen folding and intrusive episode.
Lower Trias.	Rewan Formation	Terrestrial 3450'	Rewan Formation	F.claystone with quartz sandstone lenses	Rewan Formation		Rewan Formation	Sandstone, pebbly sandstones, mudstone, conglomerate.	Reduction in size of basin and change to restricted marine or brackish environments, followed by terrestrial deposition as a result of uplift of Lower Bowen Volcanics/Urannah Complex block. The latter eroded.
Upper Permian to Trias.	Upper Bowen Coal Measure	Freshwater 2420'	Bandanna Formation Upper Part	F.coal, overlying shale with tuffaceous siltstone, sandstone and thin limestone interbeds	Upper Bowen coal measures	F.Lithic sandstone, carbonaceous shale, conglomerate siltstone and coal.	Baralaba coal measures. Syranda Formation	Lithic sandstone, mudstone, coal. F.mudstone, lithic sandstone, tuff, minor conglomerate.	
Upper Permian	Unit C	Marine 5725'	Bandanna Formation Lower part	Ms.Shale mudstone and clay	Unit C, containing big Strophalosia	Md.Siltstone, greywacke	Flat Top Formation	Md.Mudstone, argillite and sandy siltstone	
	MIDDLE BOWEN BEDS		Mantuan Productus Bed	Ms.Coquinitic feldspathic lithic sandstone	Zone and Clarkei Bed	Mit.Calcareous quartz greywacke and siltstone with scattered, cobbles, pebbles and angular boulders.	Barfield Formation	Md.Massive mudstone with calcareous concretions, calcareous lithic sandstone, tuff, agglomerate.	Major extension of basin as a shallow marine transgression. Deep in east and centre.
			Peawaddy Formation	Mrb.Lithic sandstone and siltstone			Oxtrack Formation	Ms+d. Fossiliferous limestone, calcareous siltstone and mudstone and coquinite	
Lower Permian	Unit B	Deltaic and Marine 1600'	Catherine Sandstone	Mp.Micaceous and tuffaceous sandstone		FD.Coal measures, marginal			
	MIDDLE BOWEN BEDS		Ingelara Formation	SrM. Sandy siltstone, silty sandstone and shale.	Unit B Collinsville Coal Measures, containing Glendoo Member		Not represented		Basin extends to east and north, and shallows. Deltaic in margins and in places, e.g. where Collinsville Coal Measures deposited. Elsewhere marine environment, at times shallow.
			Aldebaran Sandstone	FDf. Quartz sandstone w. quartz conglomerate bands.		Ms. Quartz and feldspathic sandstone.			
			Colinlea Formation	FDf. Quartz sandstone and pebble conglomerate					
Lower Permian	Unit A MIDDLE BOWEN BEDS	Marine 2820'	Cattle Creek Formation	rM.Conglomeratic silty sandstone w. lithic quartz sandstone and Eurydesma limestone					
			Sirius Formation	SrM. Shale, siltstone and lithic quartz sandstone	Unit A	Md.fine tuffaceous sandstones with plant debris and feldspathic sandstone above	Not represented		
			Staircase Sandstone	FD1. Quartz sandstone				Ms.Fossiliferous limestone, silicified with volcanic pebble conglomerate at base, grad-into chert.	Island arc activity ceases. Moderately deep marine basin. Lower Bowen Volcanics not a source of sediment
			Stanleigh Formation	SrM. Shale w. sandstone interbeds.			Buffel Formation		
Lower Permian	Lower Bowen Volcanics	Volcanic 12,000'+	No outcrop		Lower Bowen Volcanics and equivalents	Md. Volcanic flows, tuffs; thin marine sediments.	Camboon Andesite Rannes Beds	Volcanics	Development of Bowen Basin begins. Island arc activity: volcanics (east) and island arc derived sediments (west) with multiple contemporaneous intrusions at base of island arc.
Eastern Province	Undivided freshwater sediments	Freshwater 8,500'+	Orion Formation Undivided freshwater sediments in subsurface	F. Silty shales, sandstones, shale, and coal.	Not present	Not present			

Key:

F:	freshwater	D:	deltaic
s:	shallow	l:	lacustrine
b:	brackish	t:	turbidity-current deposit
M:	marine	d:	deep
r:	restricted	p:	peralic
f:	fluviatile		

Bowen Basin, and are not discussed in this paper; nor are post-Triassic rocks, belonging to the Surat Basin, which overlaps the Bowen Basin in the south.

The Permian is the only System represented which contains rocks of marine origin (Middle Bowen Beds, Fig.4). All known economic deposits of sedimentary phosphate are in rocks of marine origin and therefore for the purposes of this report it is reasonable to eliminate all non-Permian rocks as unlikely to contain economic deposits of phosphate. A brief description of the lithology of rock units in the predominantly marine Permian follows, to which is added, for the sake of completeness, a description of Triassic rock units.

PERMIAN

The Permian rock units listed below are described in order, from oldest to youngest.

1. Undivided Freshwater Sediments and Lower Bowen Volcanics.

11. Middle Bowen Beds (Units A. B. and C.)

UNIT A.

SPRINGSURE AREA:

Stanleigh Formation

Staircase Sandstone

Sirius Formation

Cattle Creek Formation

NORTHERN BOWEN BASIN:

Unit A.

BANANA-CRACOW AREA:

Buffel Formation

UNIT B.

SPRINGSURE AREA:

Colinlea Sandstone

Aldebaran Sandstone

Ingelara Formation

Catherine Sandstone

NORTHERN BOWEN BASIN:

Collinsville Coal Measures

UNIT C.

SPRINGSURE AREA:

Peawaddy Formation

Bandanna Formation

NORTHERN BOWEN BASIN:

Unit C.

BANANA-CRACOW AREA:

Oxtrack Formation

Barfield Formation

Flat Top Formation

Undifferentiated Back Creek Group

111. Upper Bowen Beds.

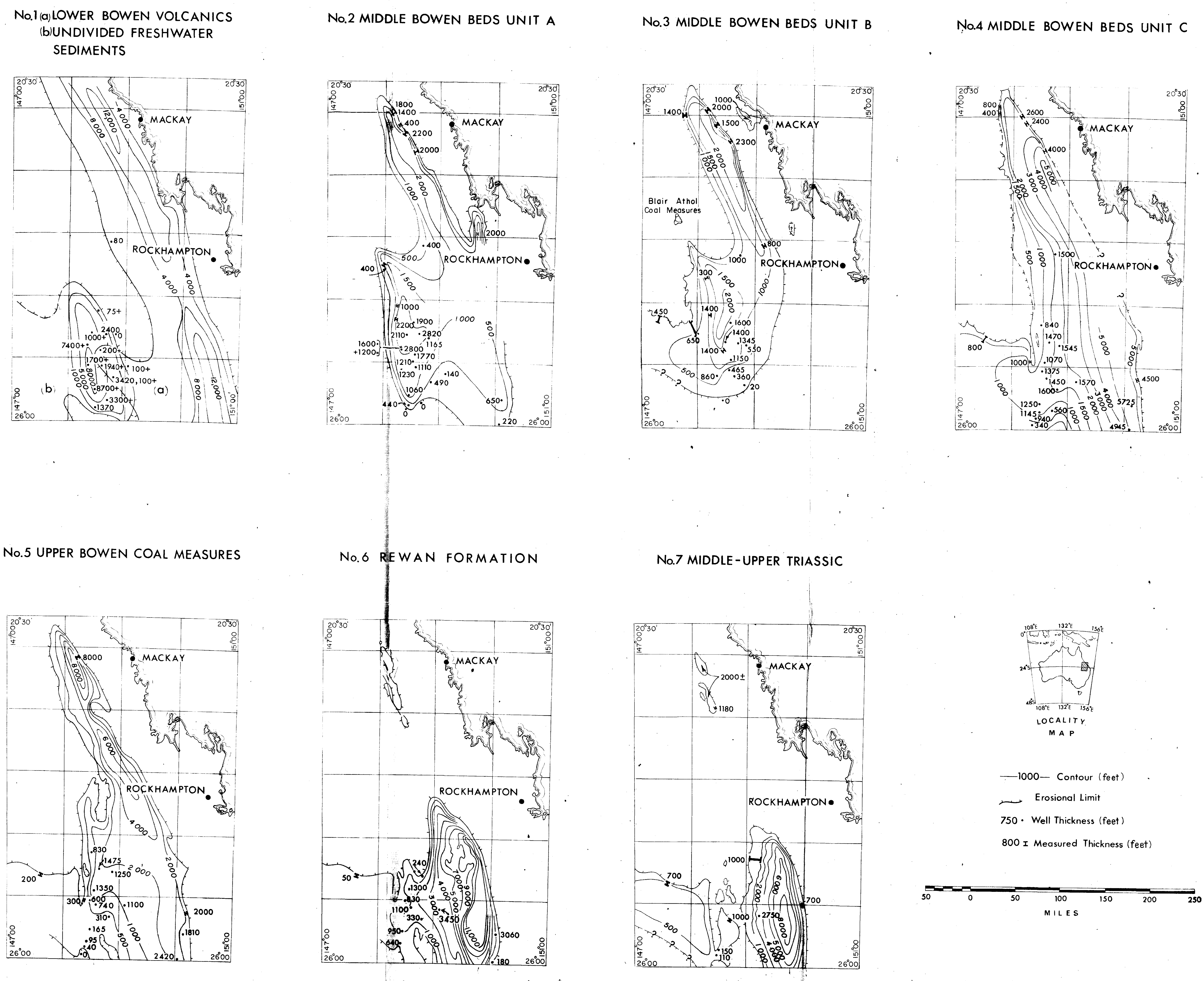
TABLE 2

THICKNESSES OF REGIONAL ROCK UNITS INTERSECTED IN OIL WELLS

	Middle-Upper Triassic	Rewan Formation	Upper Bowen Coal Measures and equivalents	Middle Bowen Beds Unit C	Middle Bowen Beds Unit B	Middle Bowen Beds Unit A	Undivided Fresh water Sediments and equivalents.	Lower Bowen Volcanics and equivalents.
A.F.O. Cooroorah No. 1	-	-	-	1500'	1000'	400'	-	80'(?)
A.F.O. Inderi No. 1	-	-	830'	840'	1600'	1900'	75'+	-
A.O.E. Consuele No. 1	-	-	-	-	1400'	2110'	1000'	-
A.F.O. Rolleston No. 1	-	-	1475'	1470'	1345	2820'	2400'	-
A.F.O. Purbrook No. 1	-	240'	1250'	1545'	550'	1165'	0'	-
A.O.E. Reids Dome No. 1	-	-	-	-	-	1600'	7400'+	-
Planet Warrinnilla North No. 1	-	1300'	1350'	1070'	1150'	1770'	200'+	-
Arcadia O.S.L. 3 and A.A.O. 7	-	300'	310'	1600'	20'	490'	3420'	100'+
A.A.O. Westgrove No. 1	-	950'	165'	1250'	0'	1060'	8700'+	-
A.A.O. Kildare No. 1	150'	640'	95'	1145'	0'	440'	-	-
O.S.L. Hutton Creek No. 1	-	-	-	560'	-	-	3300'+	-
A.A.O. Glentulloch No. 1	110'	-	40'	940'	-	-	1370'	-
A.A.O. Killoran No. 1	-	-	-	340'	-	-	-	-
U.K.A. Burunga No. 1	-	180'	2420'	4945'	-	220'	-	-
U.K.A. Cockatoo Creek No. 1	-	3060'	1810'	5725'	-	650'	-	-
Marathon Glenhaughton No. 1	2750'	3450'	1100'	1570'	-	140'	-	100'+
S.Q.D. Morella No. 1	-	830'	600'	1375'	465'	1210'	-	200'+
A.F.O. Bandanna No. 1	-	-	-	-	860'	1230'	1700'	-
Planet Warrinilla No. 1	-	1100'	740'	1450'	360'	1110'	1940'	-

Fig 3.

ISOPACH MAPS OF REGIONAL ROCK UNITS, BOWEN BASIN, QUEENSLAND



Bureau of Mineral Resources, Geology and Geophysics. June 1964.

Q-A-64

1. Undivided Freshwater Sediments and Lower Bowen Volcanics

(Fig.3, Isopach 1)

The earliest deposition in the Bowen Basin took place in two almost separate downwarps. The larger is an elongate trough occupying the eastern margin of the Basin. This trough received dominantly andesitic volcanics and sediments derived from volcanics, and, near its eastern margin, spilitic pillow lavas. The volcanics wedge out rapidly to the west, where, in the north of the area, they are unconformable on Upper Carboniferous volcanics and intrusives. To the east, they overlie Carboniferous sediments of the Yarrol Basin without obvious angular discordance. The youngest sediments in the Lower Bowen Volcanics trough are marine fossiliferous tuffs, which indicate that the entire pile subsided below sea level. Some of the sediments are thought to have been deposited in deep water. The thickness of 12,000 feet shown in the centre of the trough is probably conservative, but indicates the order of magnitude of the subsidence.

At about this time, a dominantly freshwater sequence was deposited in a deeply subsiding, slightly elongated depression in the south-west of the Basin. This downwarp is the oldest recognisable expression of the Denison Trough. Generally, a ridge of Devonian-Carboniferous volcanics and sediments, the Comet Ridge, separates these two depositional areas.

These two units are at least partly contemporaneous, as both pass upwards with little or no break into fossiliferous marine sediments of the same age. The two units represent the initial sedimentation within the Basin, though their bases are rarely exposed. Their upper limits are marked by the beginning of widespread marine sedimentation and the end of vulcanism in most areas.

11. The Middle Bowen Beds

Units A, B, and C of the Middle Bowen Beds were each deposited in a generally uniform area and environment; the units are separated by important and basin-wide changes of environment which are reflected in the sedimentation and palaeontology.

Unit A represents the earliest marine sedimentation in the northern trough; Unit B was deposited during a period of expansion and shallowing of the sea with coal measures developed around the north-western margin; Unit C is a much more widespread transgressive unit than Unit B and was deposited during general subsidence.

UNIT A.

(Fig.3, Isopach2)

Unit A is the oldest dominantly marine sedimentary sequence in the Bowen Basin. The change of environment from non-marine to marine (which took place during deposition of the Lower Bowen Volcanics in the northern Bowen Basin) and the more widespread sedimentation indicate general subsidence of most of the Bowen Basin. The main loci of deposition of Unit A are the Denison Trough, which continued to subside, and a northern trough situated parallel to and west of the centre of the Lower Bowen Volcanics trough. The present eastern limits of Unit A are mainly structural, and its original extent to the east was much greater, as indicated by the thickness of Unit A in the Strathmuir Syncline. The fairly straight western boundary of the Denison Trough follows a fault zone stretching from Reid's Dome to the southern Springsure Shelf, which is apparently associated with a marked reduction in thickness to the west. This fault zone was probably active during deposition. Outside the two main depositional downwarps, Unit A

Figure 5.

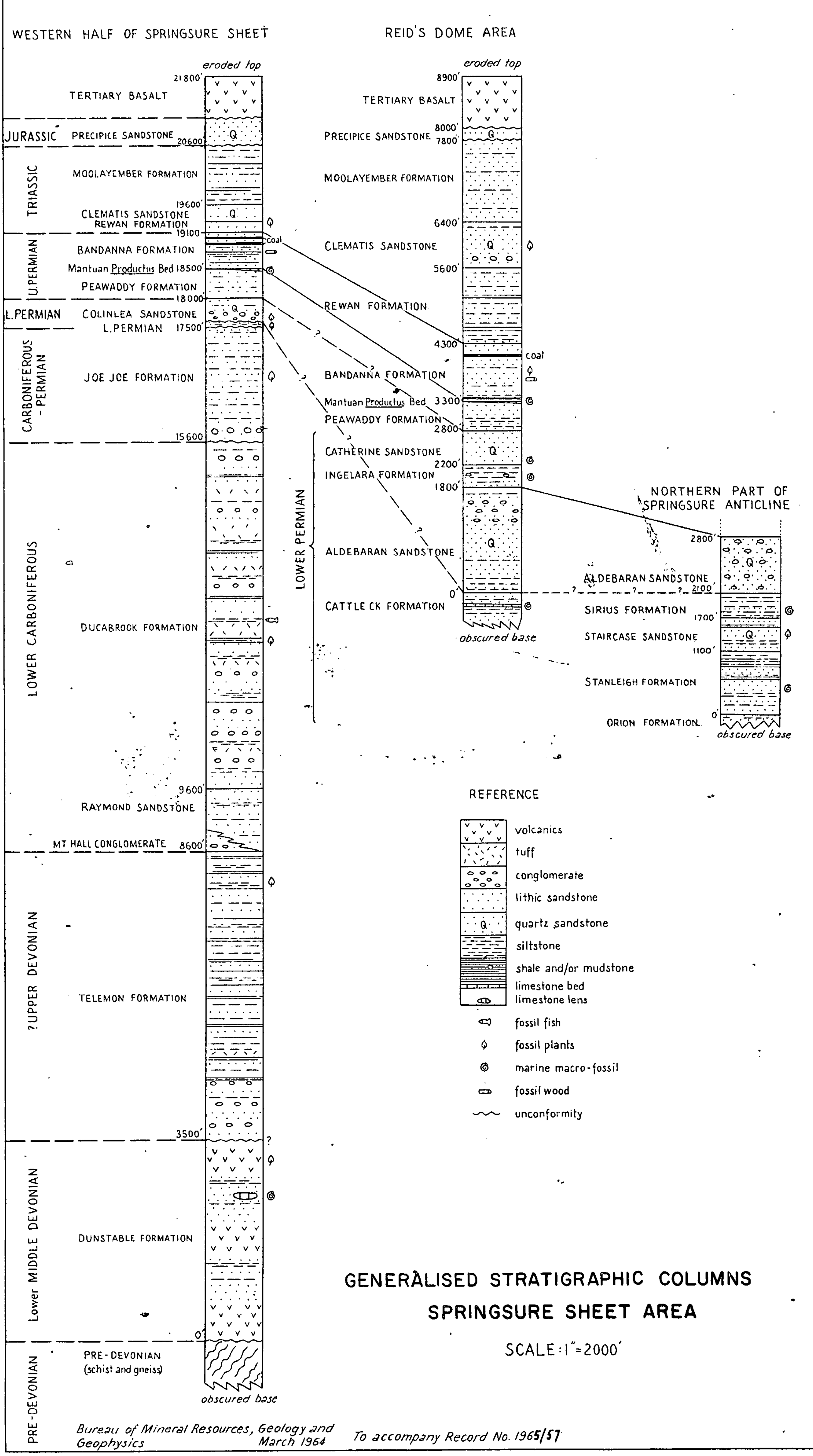
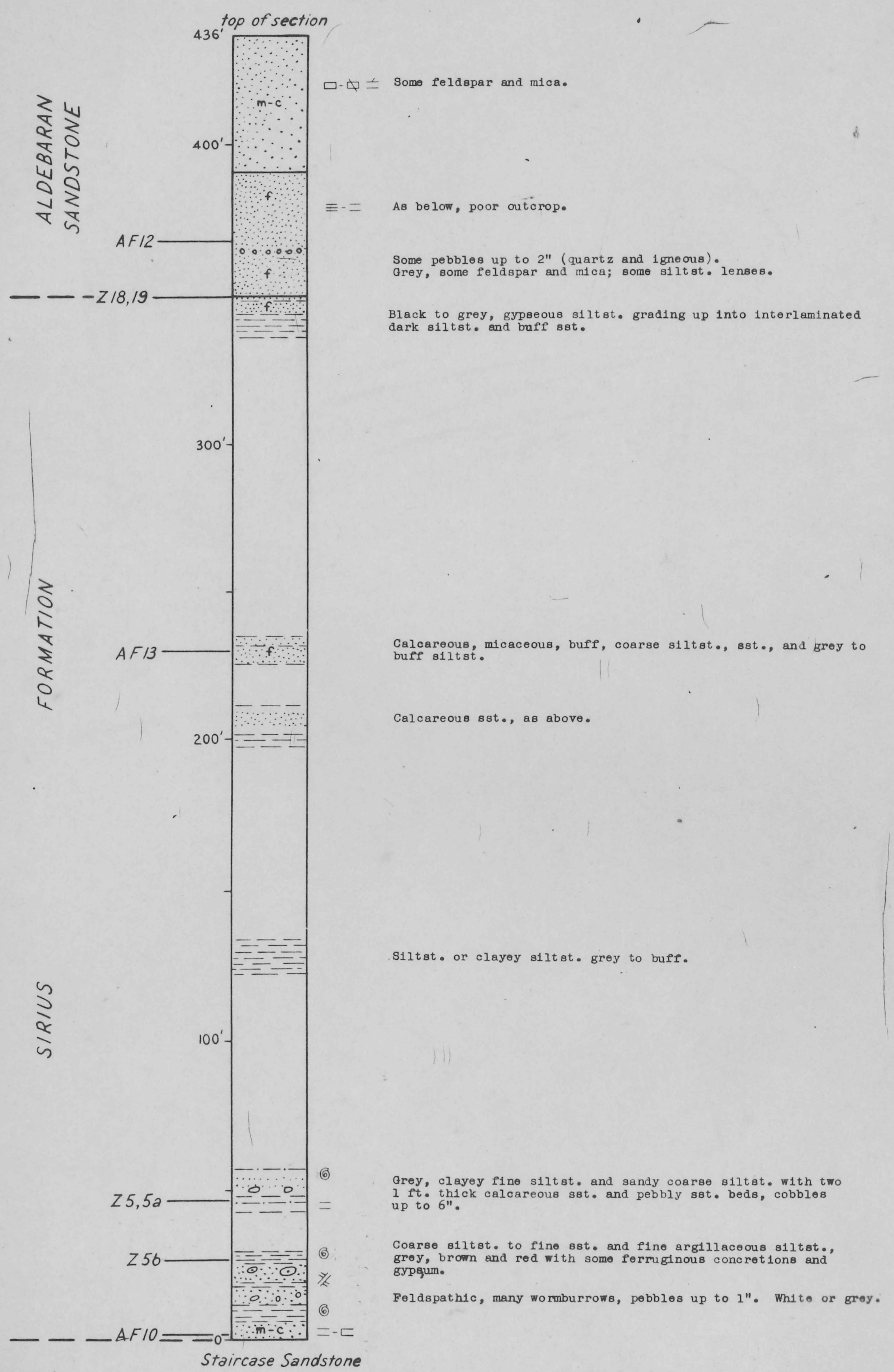

WESTERN HALF OF SPRINGSURE SHEET
eroded top
21800'
TERTIARY BASALT
JURASSIC
PRECIPICE SANDSTONE
20600'
TRIASSIC
MOOLAYEMBER FORMATION
19600'
CLEMATIS SANDSTONE
REWAN FORMATION
19100'
coal
U. PERMIAN
BANDANNA FORMATION
Mantuan Productus Bed 18500'
PEAWADDY FORMATION
18000'
L. PERMIAN
COLINLEA SANDSTONE
L. PERMIAN 17500'
CARBONIFEROUS - PERMIAN
JOE JOE FORMATION
15600'
LOWER CARBONIFEROUS
DUCABROOK FORMATION
9600'
RAYMOND SANDSTONE
MT HALL CONGLOMERATE 8600'
?UPPER DEVONIAN
TELEMON FORMATION
3500'
Lower MIDDLE DEVONIAN
DUNSTABLE FORMATION
0'
PRE-DEVONIAN
PRE-DEVONIAN
(schist and gneiss)
obscured base
REID'S DOME AREA
eroded top
8900'
TERTIARY BASALT
8000'
PRECIPICE SANDSTONE 7800'
MOOLAYEMBER FORMATION
6400'
CLEMATIS SANDSTONE
5600'
REWAN FORMATION
4300'
coal
BANDANNA FORMATION
Mantuan Productus Bed 3300'
PEAWADDY FORMATION
2800'
LOWER PERMIAN
CATHERINE SANDSTONE
2200'
INGELARA FORMATION
1800'
ALDEBARAN SANDSTONE
0'
CATTLE CK FORMATION
obscured base
NORTHERN PART OF SPRINGSURE ANTICLINE
2800'
ALDEBARAN SANDSTONE
2100'
SIRIUS FORMATION
1700'
STAIRCASE SANDSTONE
1100'
STANLEIGH FORMATION
0'
ORION FORMATION
obscured base
REFERENCE
volcanics
tuff
conglomerate
lithic sandstone
quartz sandstone
siltstone
shale and/or mudstone
limestone bed
limestone lens
fossil fish
fossil plants
marine macro-fossil
fossil wood
unconformity
GENERALISED STRATIGRAPHIC COLUMNS
SPRINGSURE SHEET AREA
SCALE: 1"=2000'
Bureau of Mineral Resources, Geology and Geophysics
March 1964
To accompany Record No. 1965/57

Figure 6.

MEASURED SECTION OF SIRIUS FORMATION (S12)

Measured in Staircase Creek at foot of Staircase Range (Springsure North Run 2, Photo 5011)
(Measured by J.M. Dickins, P.R.Evans, and A. Fehr using dip and paced distance across strike. Distances checked on aerial photographs. Basal part of Aldebaran Sandstone measured by Abney Level, overall dip taken as 15°)



Bureau of Mineral Resources, Geology and Geophysics, March 1964 To accompany Record No 1965/67

Figure 7

GENERALIZED MEASURED SECTION IN STANLEIGH FORMATION AND STAIRCASE SANDSTONE (S9)

Measured in Orion Creek (Springsure North Run 2, Photo 5011)
(Measured by E. J. Malone, B. Sell (Minad) and R.W. Stephens (Minad) using dip and pace and compass)

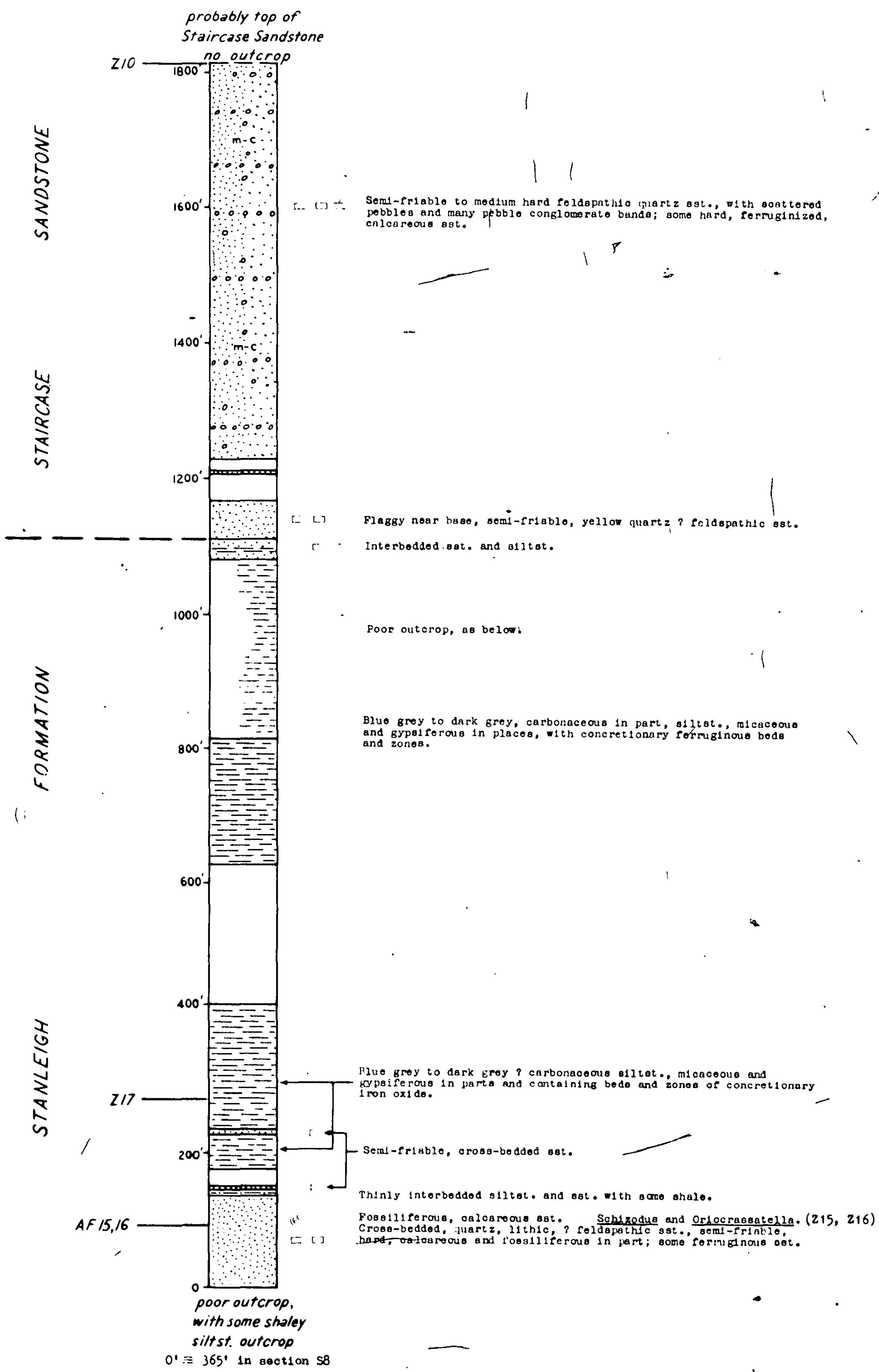


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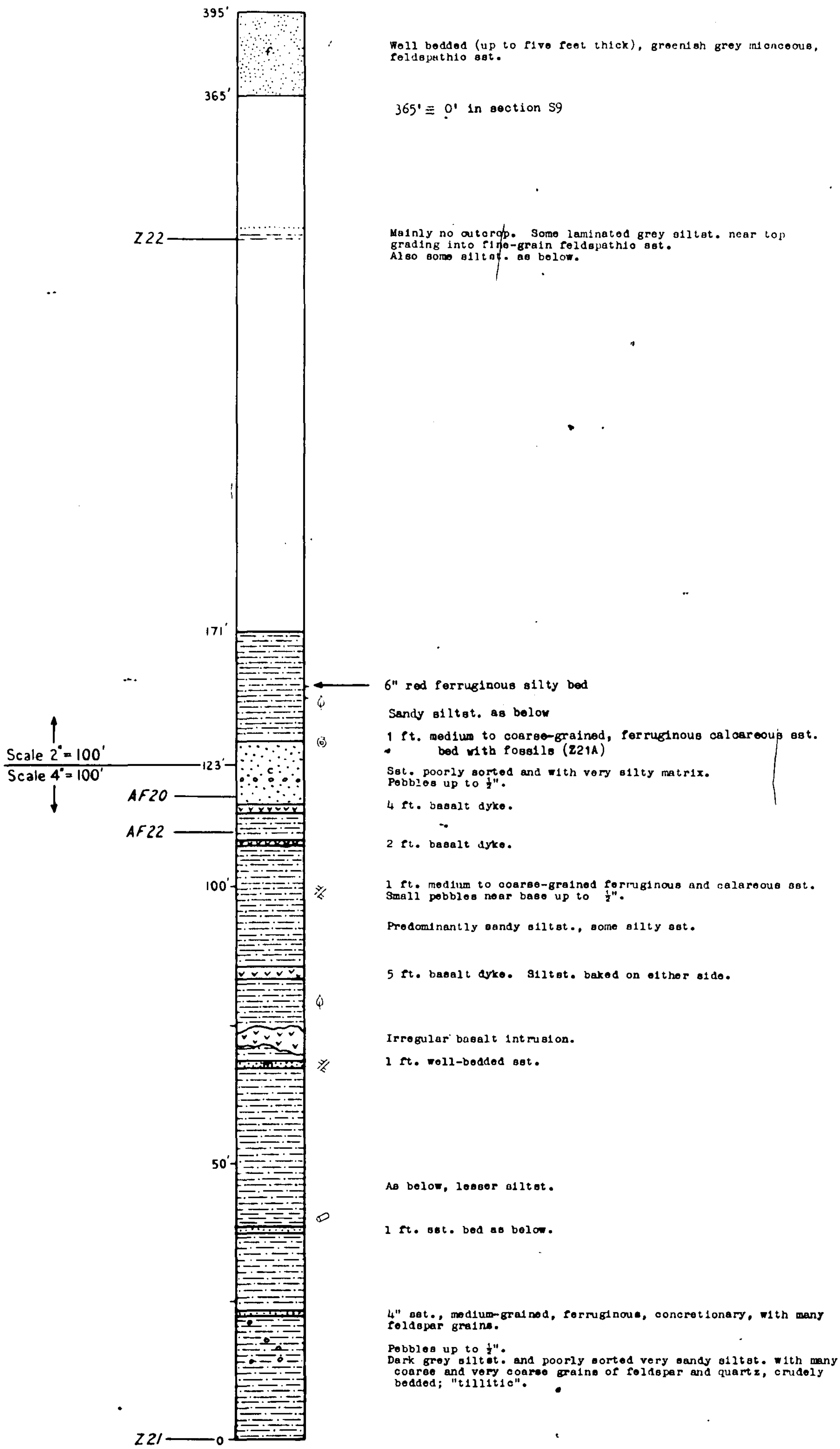
Figure 8

MEASURED SECTION IN LOWER PART OF STANLEIGH FORMATION (S8)

Measured in a south branch of Orion Creek (Springsure North, Run 2, Photo 5011)
(Measured by J. M. Dickins, P. R. Evans and A. Fehr using chain, pace, and Abney Level)

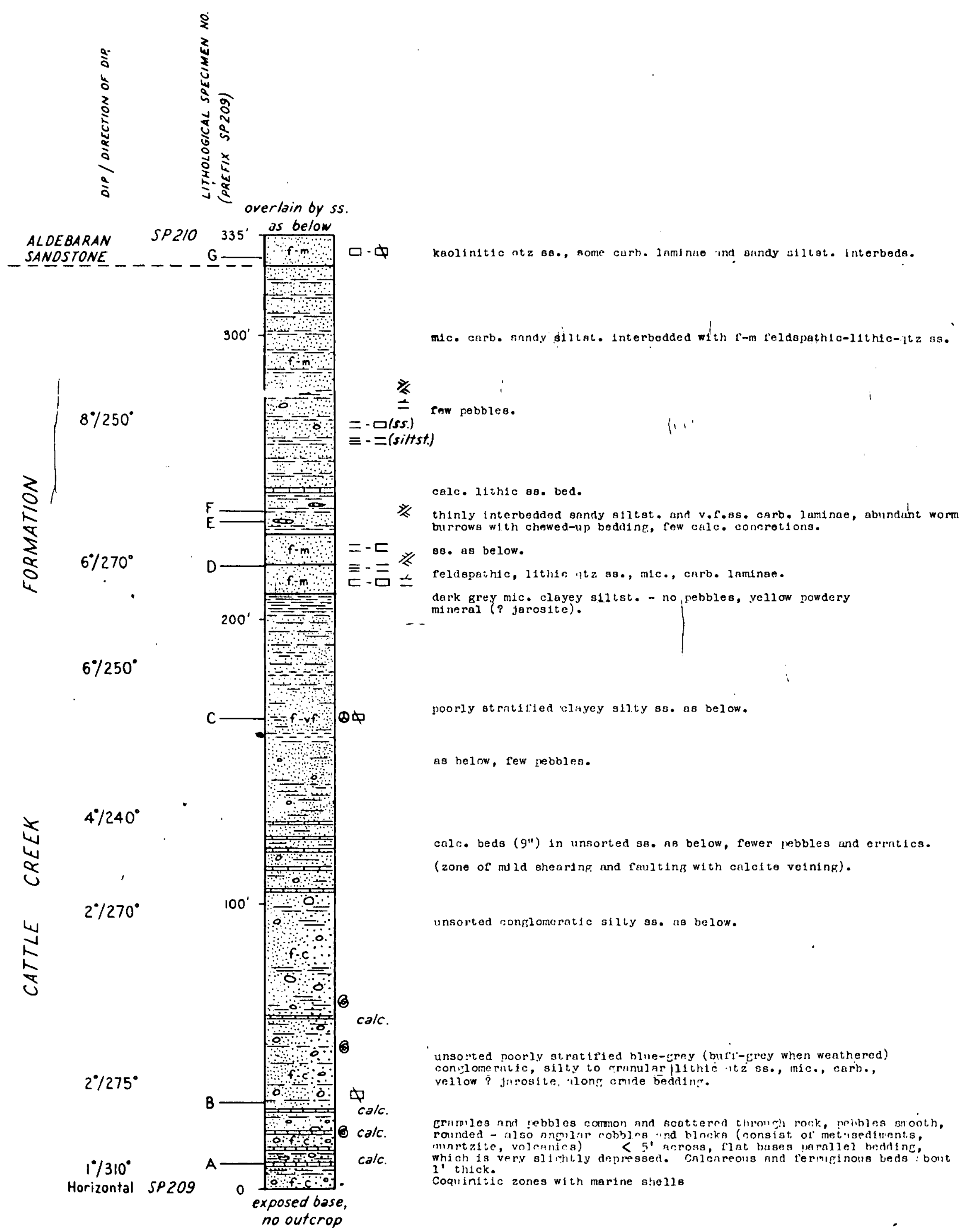


Bureau of Mineral Resources, Geology and Geophysics. March 1964 To accompany Record No 1965/57

Figure 9

MEASURED SECTION IN CATTLE CREEK FORMATION (S13)

Upper part of Cattle Creek on the west flank of Reid's Dome
between points SP 209 & SP 210 (Springsure, Run 4, Photo 5231)
(Measured with Abney Level by R.G. Mollan & E.J. Malone)



extends as a fairly thin sheet over the ridge between them and as a widespread, thin fossiliferous limestone in the south-east.

Correlation of the Stanleigh Formation, Cattle Creek Formation, Staircase Sandstone, and Sirius Formation of the Springsure area with Unit A of the northern Bowen Basin is based on faunal evidence and regional stratigraphic evidence. The Buffel Formation below the Oxtrack Formation in the Banana-Cracow area is included in Unit A; it is similar in lithology and fauna to the Yatton Limestone, which is at the base of Unit A in the northern Bowen Basin.

SPRINGSURE AREA

Stanleigh Formation 1100' (Figs. 7 and 8)

The Stanleigh Formation consists predominantly of blue silty carbonaceous shale, with interbeds of yellow/brown cross-bedded lithic sandstone, of which some are calcareous at the base and middle of the sequence. Locally the Formation contains zoned clay ironstone concretions (up to 50 cm long) including fossils or pebbles, some dark gypsiferous shale, and one coquinitic limestone bed, the "Eurydesma Limestone". It was probably deposited in a marine environment which gradually replaced the freshwater conditions indicated by underlying strata. The occurrence of gypsiferous shale suggests restricted circulation, and cross-bedded sandstone would be consistent with shallow deltas subject to marine incursions. The Formation grades upward into Staircase Sandstone.

The unit is underlain, with a gradational contact, by the Orion Formation (300'), which consists of interbedded granular lithic quartz sandstone with scattered pebbles, siltstone, and shale with plants. The base of the Orion Formation is not seen: it is thought to be equivalent to the Undivided Freshwater Sediments (4600 max.) and to have freshwater or swampy origin.

Staircase Sandstone 700' (Fig.7)

This sandstone is a jointed, cross-bedded, fine to medium grained, well cemented quartz sandstone, with conglomerate and pebble interbeds. Kaolinite cement may indicate lacustrine or deltaic deposition. The unit is overlain conformably by the Sirius Formation.

Sirius Formation 350' (thinning southward) (Fig.6)

This Formation consists of fossiliferous interbedded shale, ailtstone, and fine-grained lithic-quartz sandstone with argillaceous laminae. Grey and buff siltstone beds commonly contain gypsum and jarosite; some are calcareous. Pebbles and cobbles are scattered in basal beds. Angular blocks of epimetamorphic phyllite up to 3' long occur in the sandstone beds. Sorting is poor and disseminated pebbles may have a glacial origin, or may have been carried from a nearby landmass by dense, sediment-laden currents. Apatite is a significant accessory mineral. The Formation was probably deposited in a restricted shallow, marine basin; it is conformably overlain by the Aldebaran Sandstone.

Cattle Creek Formation 1625' (Fig.9)

Cattle Creek Formation is a fossiliferous, dark grey, poorly sorted, conglomeratic, silty sandstone with thin calcareous beds. The sandstone contains mica, carbonaceous material, and lenses and bands of gypsum with associated jarosite along bedding planes. Pebbles cobbles and boulders of metamorphic rocks occur throughout the section; cobbles and pebbles are rounded but boulders are angular. There are fine to medium grained lithic-quartz sandstone interbeds (30') with slump-structures. Some are calcareous. Fossiliferous limestones up to 10' thick occur (pebbly, shelly, coquinitic or bryozoan), including the 10' Eurydesma Limestone. This Formation has poorer sorting than the Sirius Formation, and is characterised, as is the Sirius Formation, by the absence of feldspar and the presence of 30'-50' of tuff. Apatite is a significant accessory mineral. The unit is marine, and was probably deposited in a restricted basin. Its origin is probably similar to that of the Sirius Formation. Its base is not exposed. It is overlain conformably and gradationally by the Aldebaran Sandstone. Possible relationships to other formations are shown in Fig.5. A sample from a nodular sandstone interbed at Reid's Dome contained 12% P_2O_5 (see Appendix 1).

NORTHERN BOWEN BASIN

Unit A.

Unit A in the Northern Bowen Basin was deposited on an uneven basement of Lower Bowen Volcanics, and thicknesses vary from 400' to 2800' (Fig.3). Predominantly it consists of fine-grained tuffaceous quartz greywackes, silt and quartz sandstone with minor limestone interbeds, and to the west cross-bedded quartz sandstone with pebble conglomerate. In the east (Mackay) it crops out poorly as brown ferruginous greywacke with brown calcareous siltstone. It has a marine origin probably moderately deep, with a western shelf facies and eastern marginal facies.

BANANA-CRACOW AREA

Buffel Formation 640'

The Buffel Formation consists of fossiliferous calcarenite and coquinite with some chert interbeds, grading laterally (to the north) and vertically to hard white aphanitic chert or silicified limestone. A volcanic pebble conglomerate with fossiliferous limestone matrix occurs at its base. It is of marine origin, probably neritic, and was deposited in a cold climate, in depressions in the volcanic surface, where it was protected from subsequent erosion. The Buffel Formation is the only representative of Unit A in the Banana-Cracow area, and is separated from the overlying Oxtrack Formation of Unit B by a time break, without angular disconformity.

UNIT B

(Fig.3, isopach 3)

Unit B is less extensive in the south-east than Unit A but has spread beyond Unit A to the west. The Denison Trough is still recognisable as a distinct downwarp, though for the last time. Unit B includes extensive sand sheets, probably fluviatile in part, which extend beyond the Denison Trough to the west (the Colinlea Sandstone) and to the north-east across the Comet Ridge. In the northern trough, Unit B transgressed beyond Unit A to the north and west, with the development of the Collinsville Coal Measures around the northern margin. The Blair Athol Coal Measures occupy a position relative to the Denison Trough similar to that occupied by the Collinsville Coal Measures relative to the northern trough.

The Calen Coal Measures, cropping out north-west of Mackay, are tentatively included in Unit B. The coal measures include thick quartz sandstone units and are lithologically similar to Unit B in the Collinsville area.

Unit B is of generally similar lithology in both the northern Bowen Basin and the Springsure area. In both areas, it contains thick, cross-bedded lenticular sandstone beds and evidence of at times non-marine sedimentation. The marine Ingelara Formation is possibly equivalent to the Glendoo Sandstone Member, a widespread marine

Figure 10

MEASURED SECTION FROM ALDEBARAN SANDSTONE TO PEAWADDY FORMATION (S20).

Measured in creek 4 miles west of Rewan H.S. from SP 750/1 to SP 750/4. (Springsure, Run 4, Photo 5231)

(Measured by A.G. Kirkegaard using Abney Level)

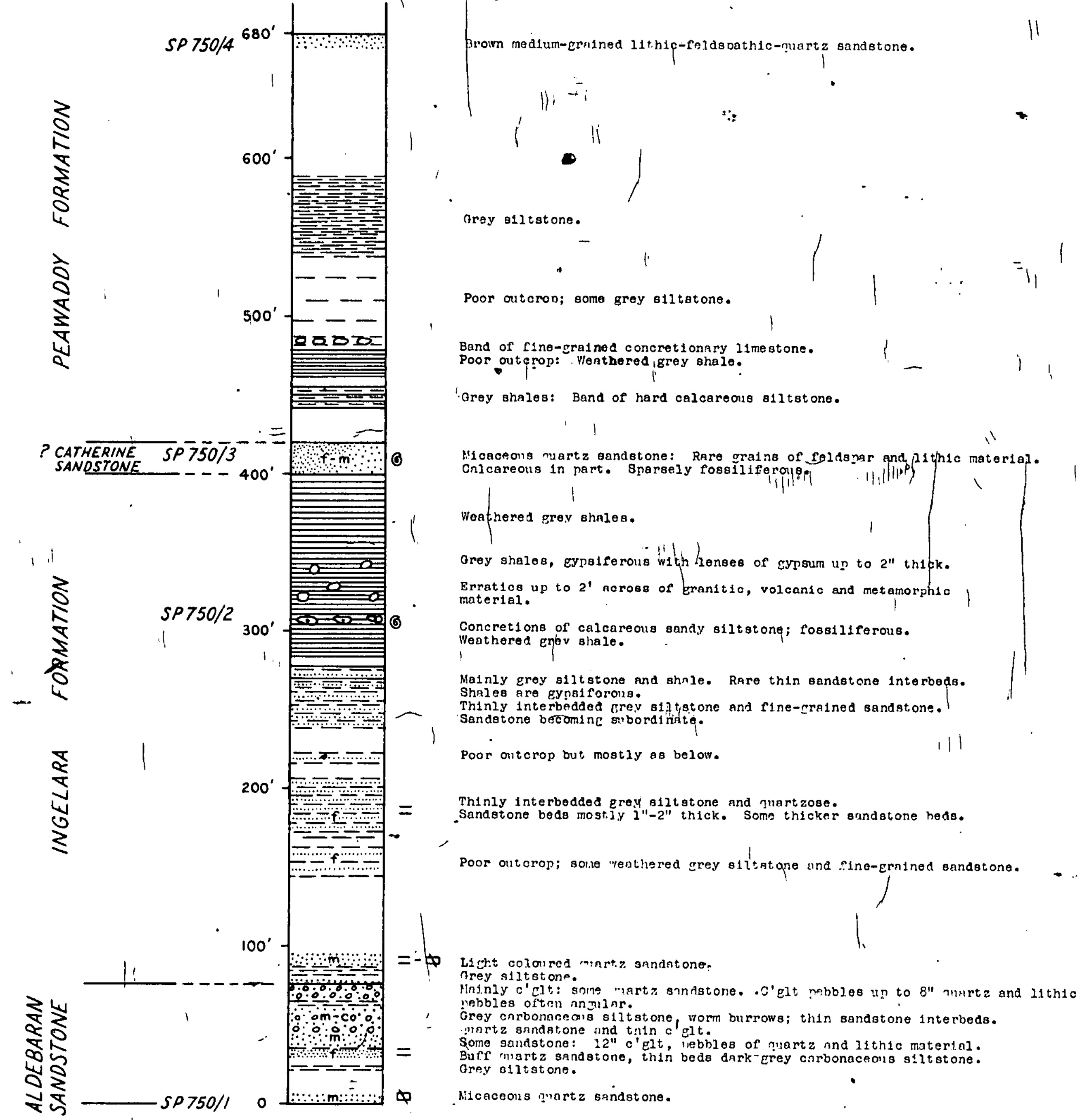
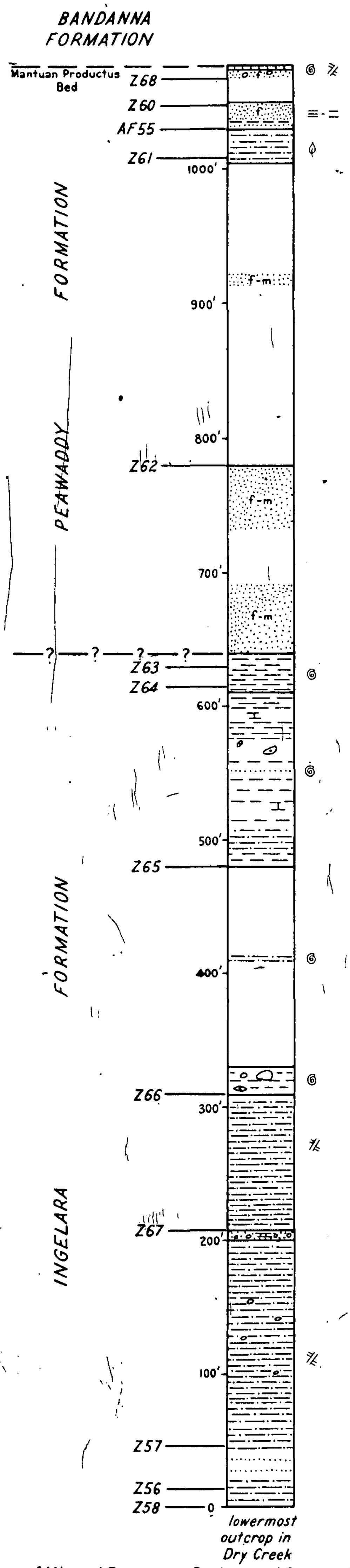


Figure 11

MEASURED SECTION OF INGELARA AND PEAWADDY FORMATIONS (S19)

Measured in Dry Creek (Springsure 1:50,000, 1955, Run 8, Photo 5011)
(Measured by J. M. Dickins, B. Sell (Minad) and R.W. Stephens (Minad), based on pace and photo distance). Upper part of section in Eddystone Sheet area.



Grey-green, f. sst. micaceous, feldspathic, ? glauconitic, ? with rock fragments, rather unsorted pebbles up to 1". 2 ft. hard calcareous bed with many worm burrowings at top, overlain by 2 ft. greenish-yellow puggy clay and calcareous whitish lithic sst.
Mainly sandstone with much feldspar and mica. 2 ft. bed of fine to medium-grained calcareous sst. and some grey sst.

Siltst., grey, micaceous, sandier towards top.

With feldspar and mica, calcareous.

Khaki or buff, soft weathering, mainly quartz with some feldspar and mica and possibly rock fragments. Some massive weathering; incompletely exposed especially in middle part.

Siltst.; 2 calcareous beds, one with corals and crinoids.

Predominantly claystone or shale, some sandy and with fine sandy interbeds.
A few concretionary calcareous beds and some cobbles and boulders up to 2 ft.
Macrofossils sparse.

Poor outcrop as below. Calcareous, fossiliferous beds and only a few cobbles and boulders.
Macrofossils sparse.

Claystone or shale and sandy siltst. In places sand predominates. Poorly sorted, crudely bedded; cobbles and boulders up to 2 ft. Very fossiliferous concretionary lens up to 2 ft. thick.

Mainly grey siltst. and sandy siltst. with some fine sand. Very micaceous.

Sst., calcareous, ferruginous, with pebbles. Pebbles and cobbles up to 4" across, mainly quartz, many of fine sand and some chert and volcanics.

Interlaminated black carbonaceous siltst., grey sandy siltst. and very fine white sst. Micaceous, scattered pebbles up to 1".

Estimated height above Aldebaran Sst. not more than 50 ft.

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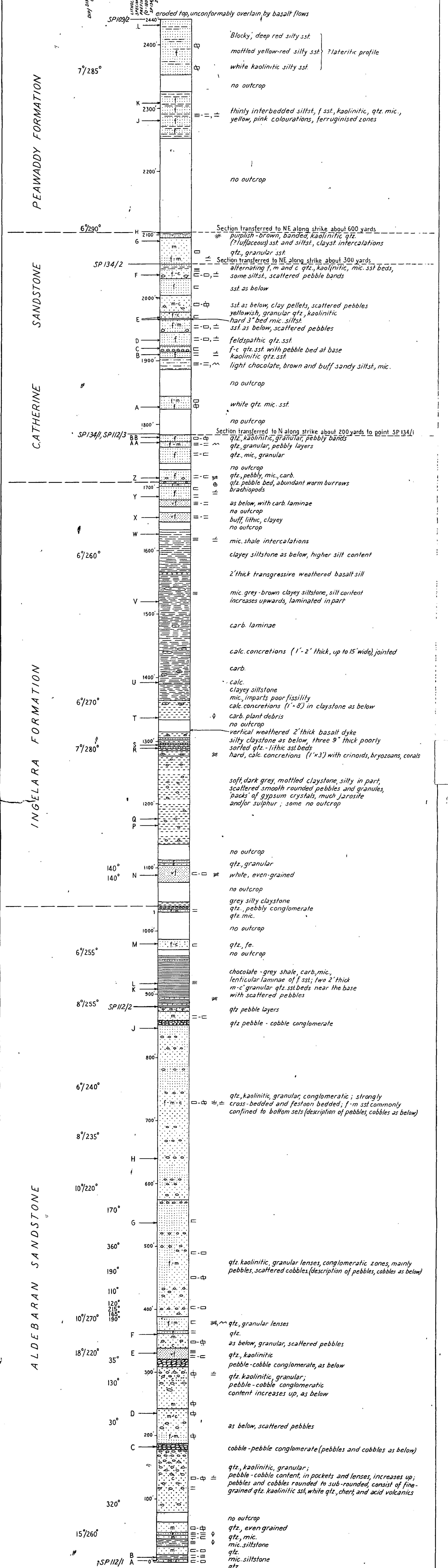
Figure 12 **MEASURED SECTION IN PERMIAN FORMATIONS IN THE WEST LIMB OF THE SPRINGSURE ANTICLINE (S(5))**



Measured in Aldebaran Creek (south branch), a small tributary, and small escarpment to the north of the tributary, south of Mt. Catherine between points SP109/2 (Springsure Nth. Run 4/Photo 5068) (Measured with Abney Level by R.G. Mollan, A. Fehr, R.L.V. Bastian)

Bureau of Mineral Resources, Geology and Geophysics, March 1964. To accompany Record No. 1965/57 transgressive unit in the middle of the Collinsville Coal Measures, that is in the middle of Unit B.

Unit B is not present in the Banana-Cracow area. Uplift in this area during Unit B time is compatible with general shallowing of water in the depositional area which expanded westward as a partly non-marine environment.

SPRINGSURE AREA

Colinlea Sandstone 620'

The Colinlea Sandstone consists of quartz sandstones and conglomerates deposited as fluvial and deltaic sands in fresh water. It overlaps pre-Permian rocks unconformably to the south and south-west and is overlain by the Peawaddy Formation (Unit C) conformably.

Aldebaran Sandstone 2000' (Fig.12)

This is a conglomeratic quartz sandstone, with siltstone and shale interbeds and very minor coal seams. It was deposited in freshwater deltaic and fluviatile conditions, similar to those of Staircase Sandstone but with stronger currents.

The Aldebaran Sandstone is conformable on the Sirius Formation in the Springsure Anticline; in Reid's Dome it grades downwards into the Cattle Creek Formation. To the south it overlies the Sirius Formation unconformably and is transitionally overlain by the Ingelara Formation.

Ingelara Formation 690' (Figs.10, 11 and 12)

A poorly sorted sandy siltstone, with silty claystone and fossiliferous shales, with lenses of pebbles, this Formation is carbonaceous and pyritic in places, with gypsum and jarosite bands, calcareous concretions and boulder erratics of igneous rocks. It represents a restricted marine incursion, and is conformably overlain by the Catherine Sandstone, and in the southern part of Reid's Dome by the Peawaddy Formation, where the Catherine Sandstone has wedged out.

Catherine Sandstone 500' (Figs.10 and 12)

This unit consists of fine grained, white-grey, micaceous quartz sandstone, some pebbly, with glauconite and tuff grains at the top, and minor shale. It is marine, with evidence of paralic depositional conditions in the north. It thins to the east, and is absent in the south, where it has wedged out. It is overlain conformably by the Peawaddy Formation.

NORTHERN BOWEN BASIN

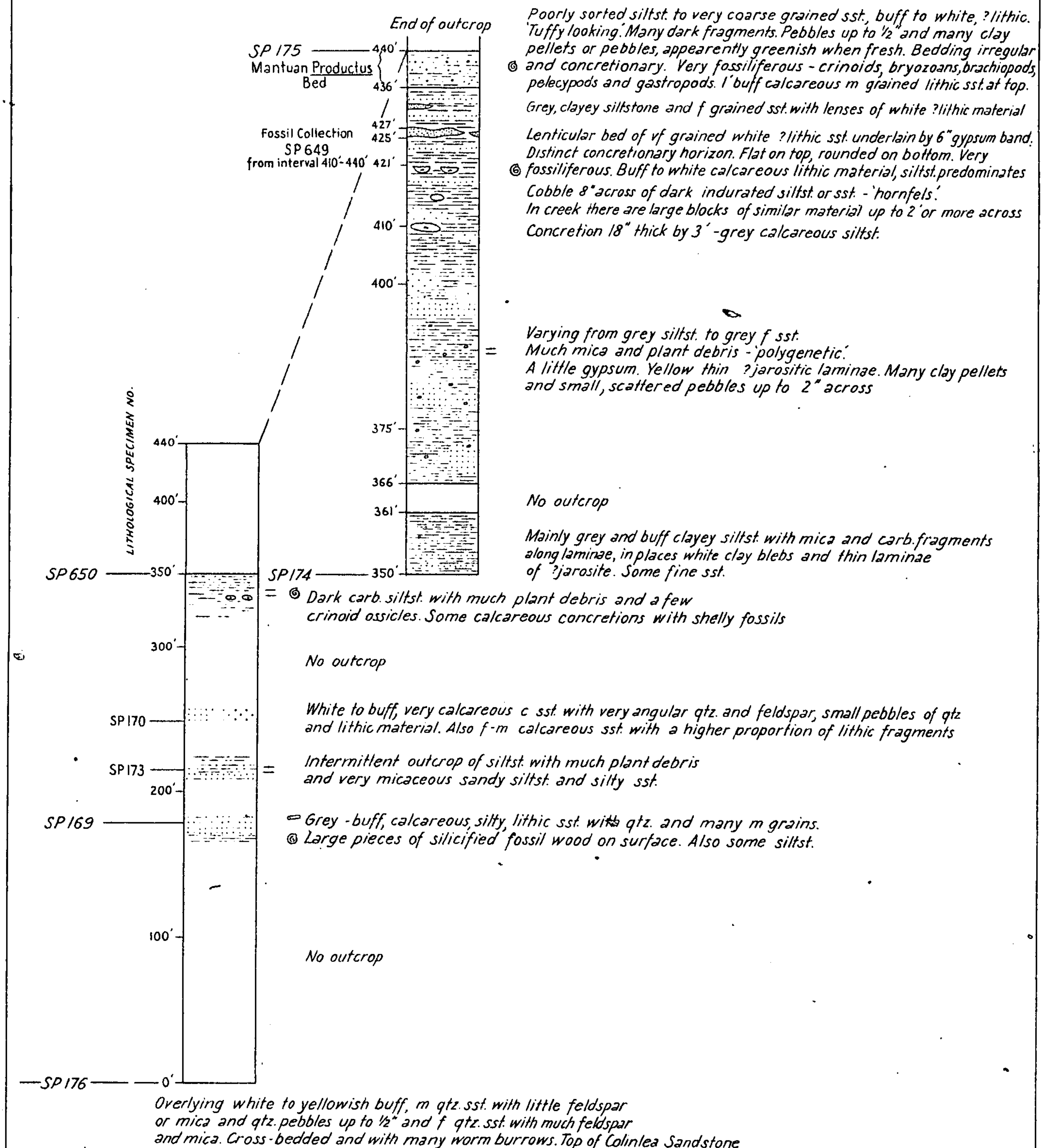
Collinsville Coal Measures

The Collinsville Coal Measures consist of coal seams, quartz sandstone and interbedded carbonaceous shale and siltstone, with conglomerate or pebble sandstone at its base, overlying the Carboniferous Bulgonunna Volcanics. The middle marine Glendoo Member consists of fossiliferous quartz greywacke. The Collinsville Coal Measures are conformably overlain by Unit C. They pass southwards into an equivalent <u>Unit B</u> facies consisting of an arenite-siltstone sequence with interbedded pebble and conglomerate beds. They were deposited in deltaic or swamp conditions marginal to a shallow marine environment.

Figure 13

MEASURED SECTION OF THE PEAWADDY FORMATION (S 26)

Section beginning 3¾ miles north-east of Tanderra Homestead and ending 2 miles south-south-east of the homestead (Springsure, Run 1, Photo 5114) (Measured by J.M. Dickins and R.G. Mollan, using Abney Level for the top 90' and calculation with the aid of Abney Level and aerial photos for the bottom 350')



Dip taken as 1° to the south, based on measurements of bedding and dip slopes. Checked from field and aerial photo identification of beds.

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.Figure 14

MEASURED SECTION OF THE PEAWADDY FORMATION (S 24)

In Sandy Creek, 1⅓ miles south-west of junction with Consuelo Creek (Springsure, Run 4, Photo 5231)
(Measured by J.M. Dickins and N.F. Exon, using dip and photo distance and Abney Level)

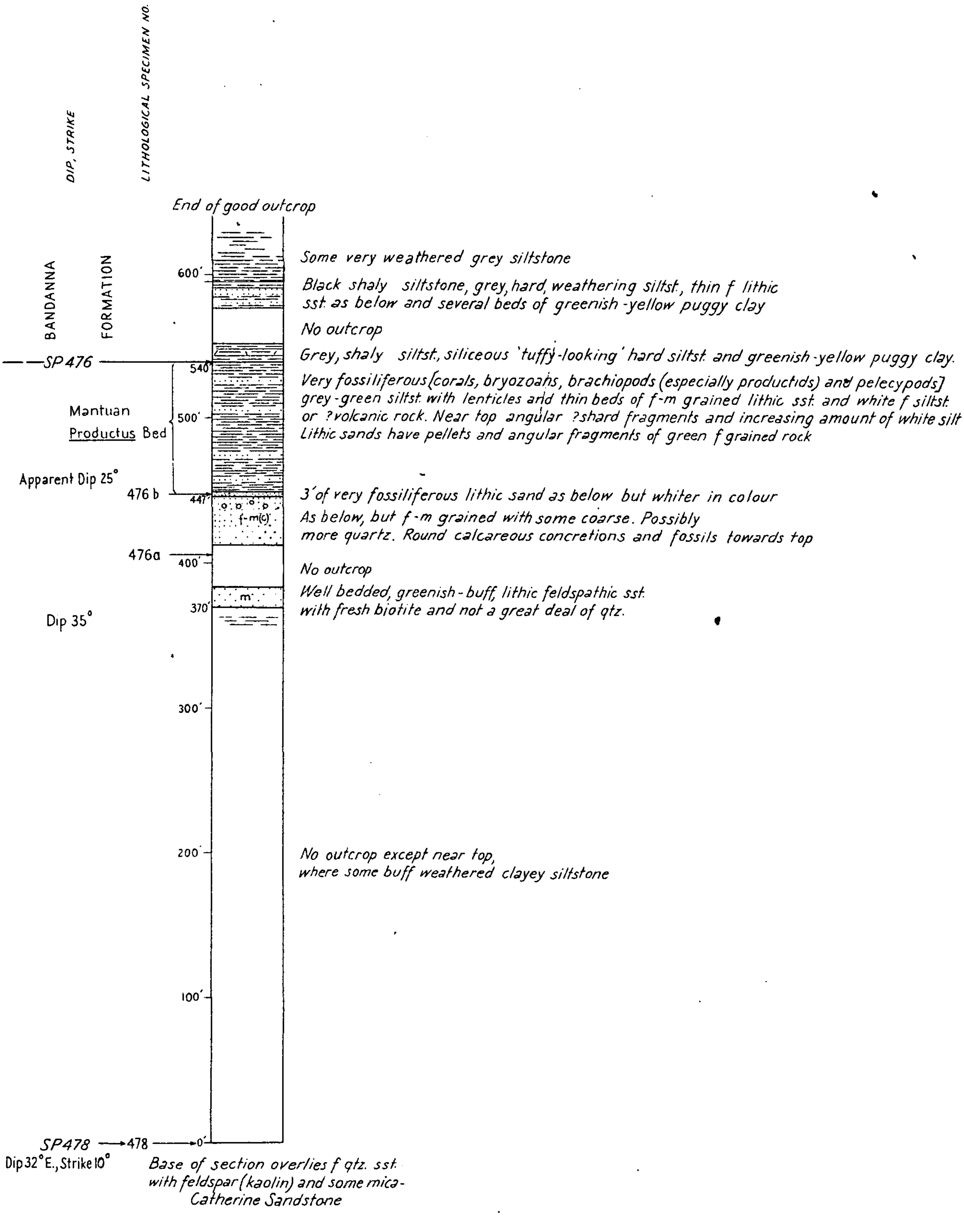


Figure 15

MEASURED SECTION IN THE PEAWADDY FORMATION (S22)

Peawaddy Creek on the west flank of the Consuelo Anticline between points SP 440/3 and SP440/1 (Springsure, Run 2, Photo 5131)

(measured with Abney Level by R.G. Mollan)

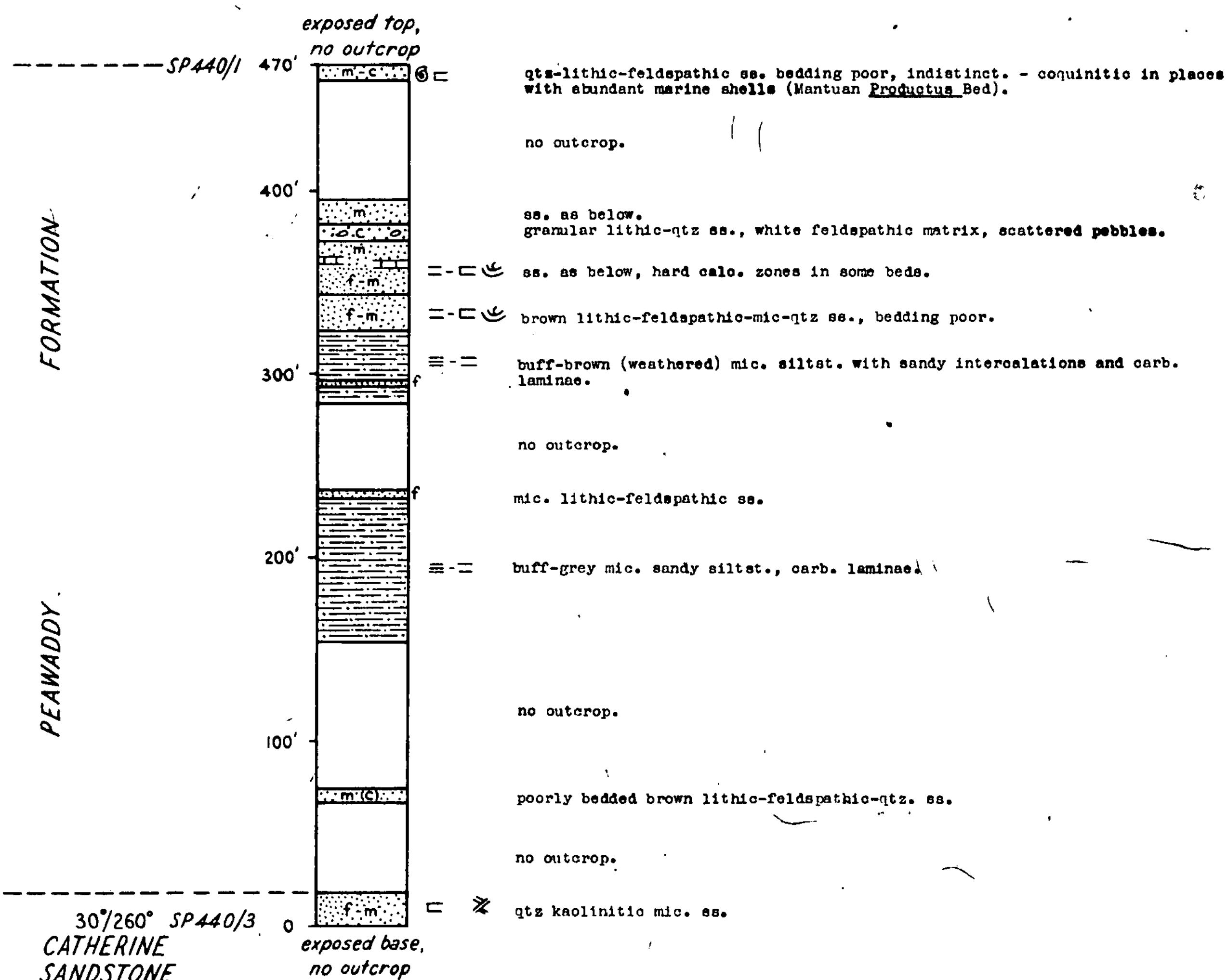
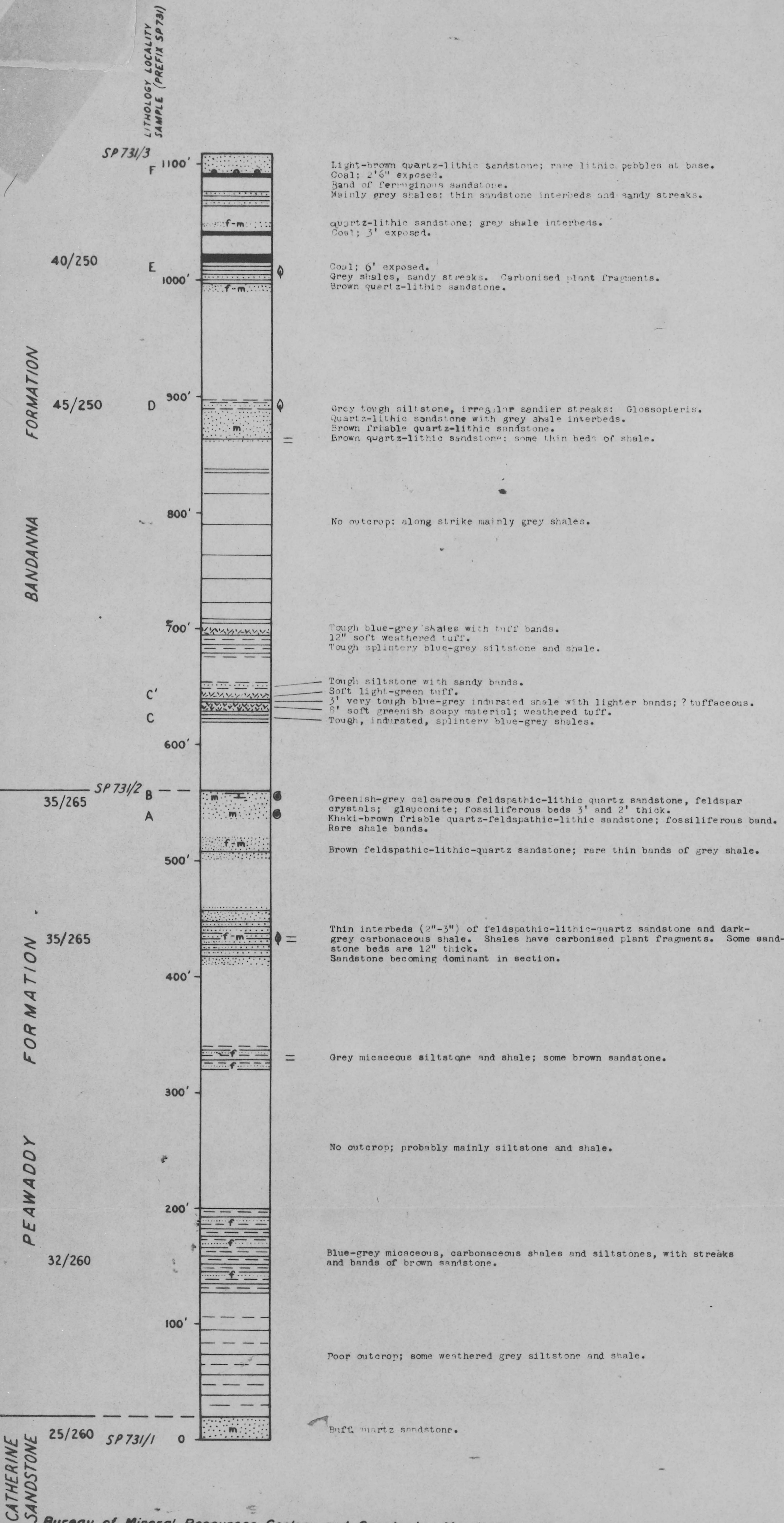


Figure 16

MEASURED SECTION IN THE PEAWADDY AND BANDANNA FORMATIONS (S27)

Measured west of Mt. Serocold in small tributary of Serocold Creek from SP 731/1 to SP 731/3 (Springsure, Run 3, Photo 5149)
(measured by A.G. Kirkegaard using pace and compass)



UNIT C

(Fig.3, isopach 4)

Unit C is a widespread marine transgressive unit, first recognised in the northern Bowen Basin (Dickins et al., 1964). It is recognised on faunal evidence in the Banana-Cracow area, where it is represented by the thick Oxtrack, Barfield and Flat Top Formations.

Unit C in the Banana-Cracow area disconformably overlies either the thin representative of Unit A (Buffel Formation) or the Camboon Andesite, a relationship that confirms the unit's transgressive nature in the north (Fig.4). The lower Bandanna Formation is correlated with the Flat Top Formation and the two may be continuous (Malone, 1964). Lithologically, they have much in common.

The top of Unit C throughout the Bowen Basin is the base of the dominantly non-marine Upper Bowen Coal Measures and equivalents. The base of the Upper Bowen Coal Measures is obvious in the north of the Bowen Basin. It is not so obvious in the Springsure and Banana-Cracow areas, or in the Clermont and Duaringa Sheet areas, where there is apparently a transition from marine to non-marine sediments.

Unit C was deposited during general subsidence with extensive thin sedimentation transgressing to the west and with thick, deeper-water sedimentation in an eastern trough. This trough is parallel to and west of the old Lower Bowen Volcanics trough. Its extension to the south implies renewed subsidence in the south-east, where there was little or no subsidence during Unit A and Unit B times. This subsidence may be accompanied by uplift and vulcanism to the east, as Unit C in the south-east contains some volcanic detritus. In the south-west, there is no sign of the Denison Trough as a distinct downwarp.

A gap is left in the isopachs west of Rockhampton on isopach 4 and also on isopach 2 (Fig.3). This area is included in the eastern province, where the sediments are complexly folded, faulted, and cleaved, and have undergone some regional metamorphism. No fossils of any importance in correlation have been found in them. The lithologies of the sediments are sufficiently unlike those of sediments in other parts of the Basin to make lithological correlation impossible in such a structurally deformed area, and at present the stratigraphy is little known. The Lower Bowen Volcanics and equivalents, as well as older volcanics, are present in a number of anticlines in the area. Unit A and Unit C are almost certainly present, but the thicknesses of each cannot be determined. Unit B may be entirely absent, though the recognition of a Unit B fauna in the Strathmuir Syncline suggests it is present at least in the north of this area.

SPRINGSURE AREA

Peawaddy Formation 500' (Figs.13, 14, 15 and 16)

This formation includes lithic sandstone, commonly calcareous, siltstone and carbonaceous shale with gypsum and jarosite along bedding planes. Towards the west of the Springsure area, siltstones contain cobbles, boulders and calcareous concretions. It contains, at the top, fossiliferous coquinitic sandstone and siltstone lenses, some glauconitic, collectively known as the Mantuan *Productus* Bed. The Peawaddy Formation transgresses the Catherine Sandstone and the Ingelara Formation to the east and south. It is overlain disconformably by the Bandanna Formation.

Figure 17

GENERALISED SECTION OF BANDANNA FORMATION (S28)

On Carnarvon Gorge road, beginning 1⅙ mile west-north-west of junction with Bandanna road. (Eddystone, Run 1, Photo 5011), in Eddystone Sheet area. (Measured by J. M. Dickins and N. F. Exon, using dip and photo distance)

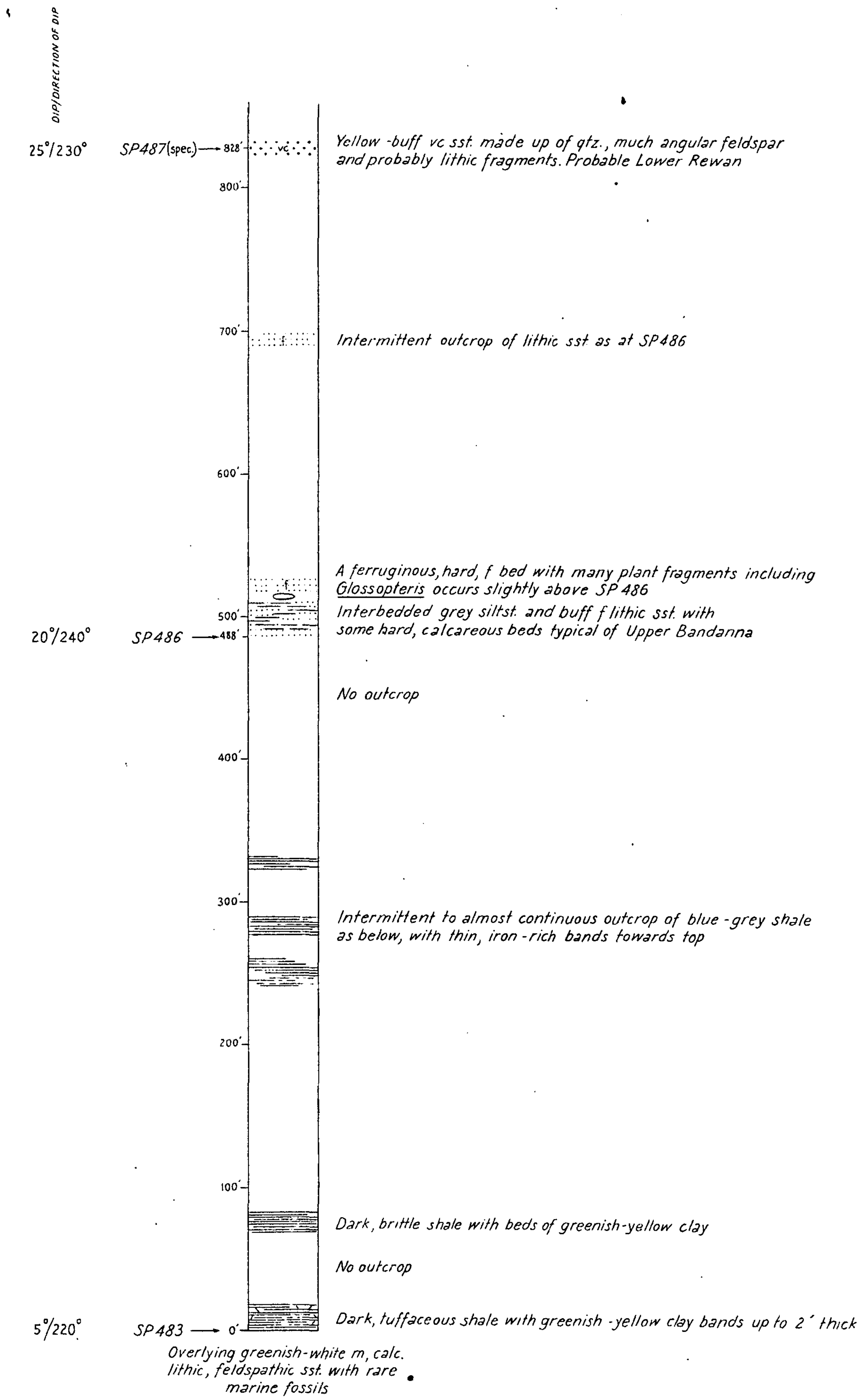


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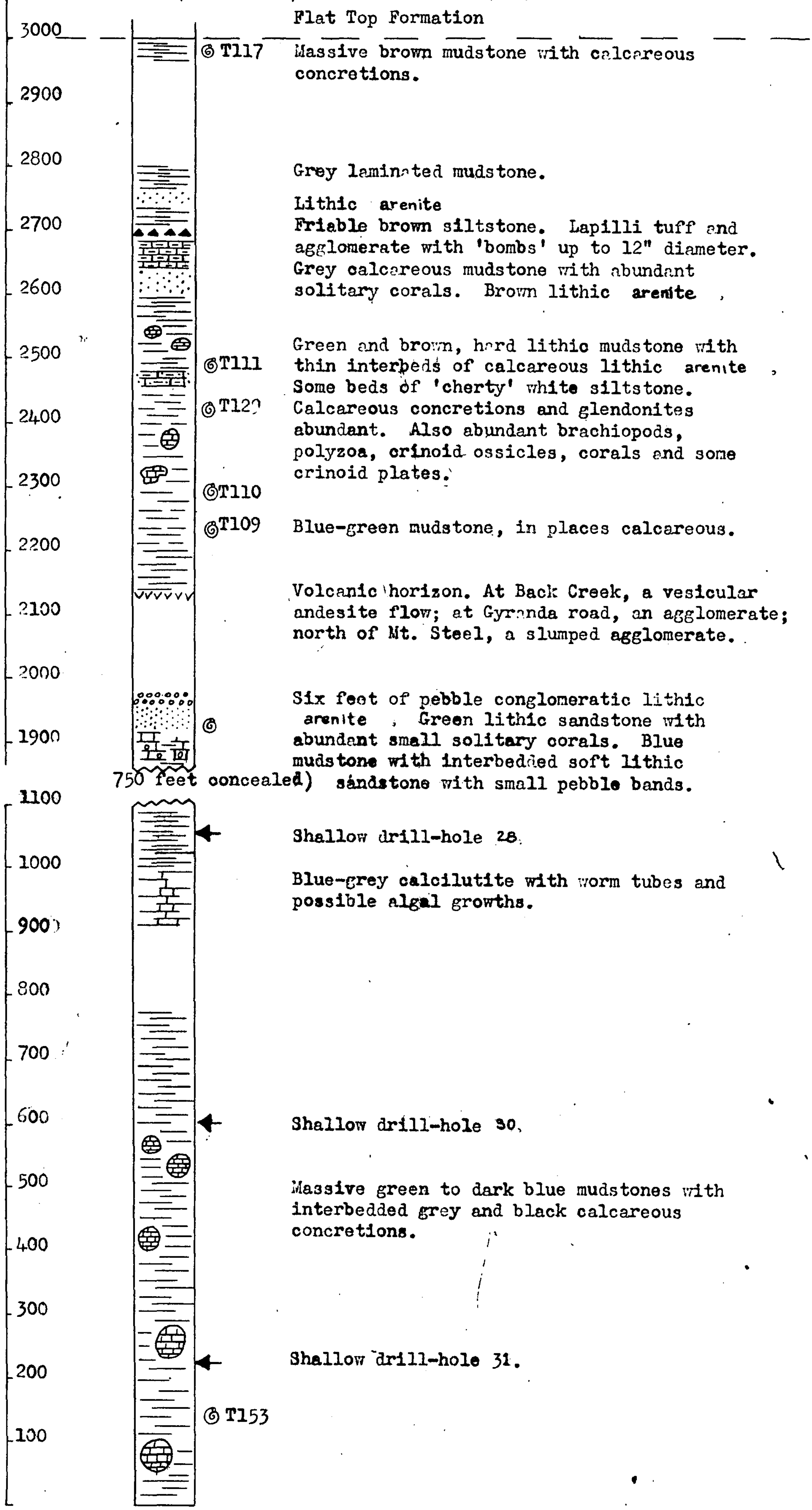
Fig. 18

BARFIELD FORMATION

Composite section from observations in the field, Cracow area



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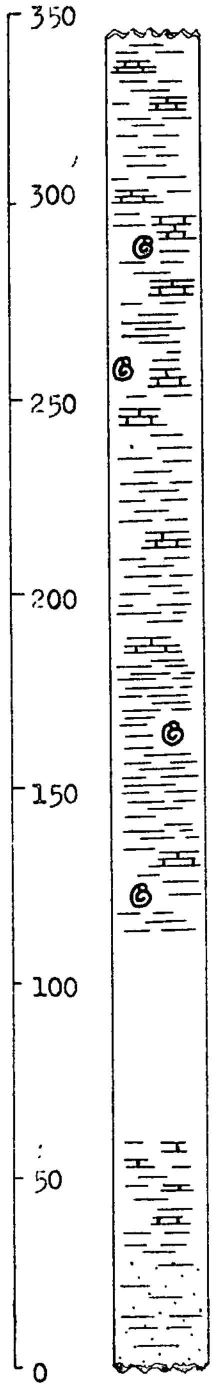
OXTRACK FORMATION



Calcareous fossiliferous mudstone grading into coquinite in places. Thin to medium bedded.

Hard light blue mudstone with abundant marine fossils. Some small lenses of coquinite. Medium bedded.

No outcrop.

Hard brown mudstone interbedded with blue siltstone. Calcareous in part.

Hard white lithic sandstone and siltstone, medium to thin bedded.

Section measured three miles south-west of Cracow Homestead.

Scale 2"=100'.

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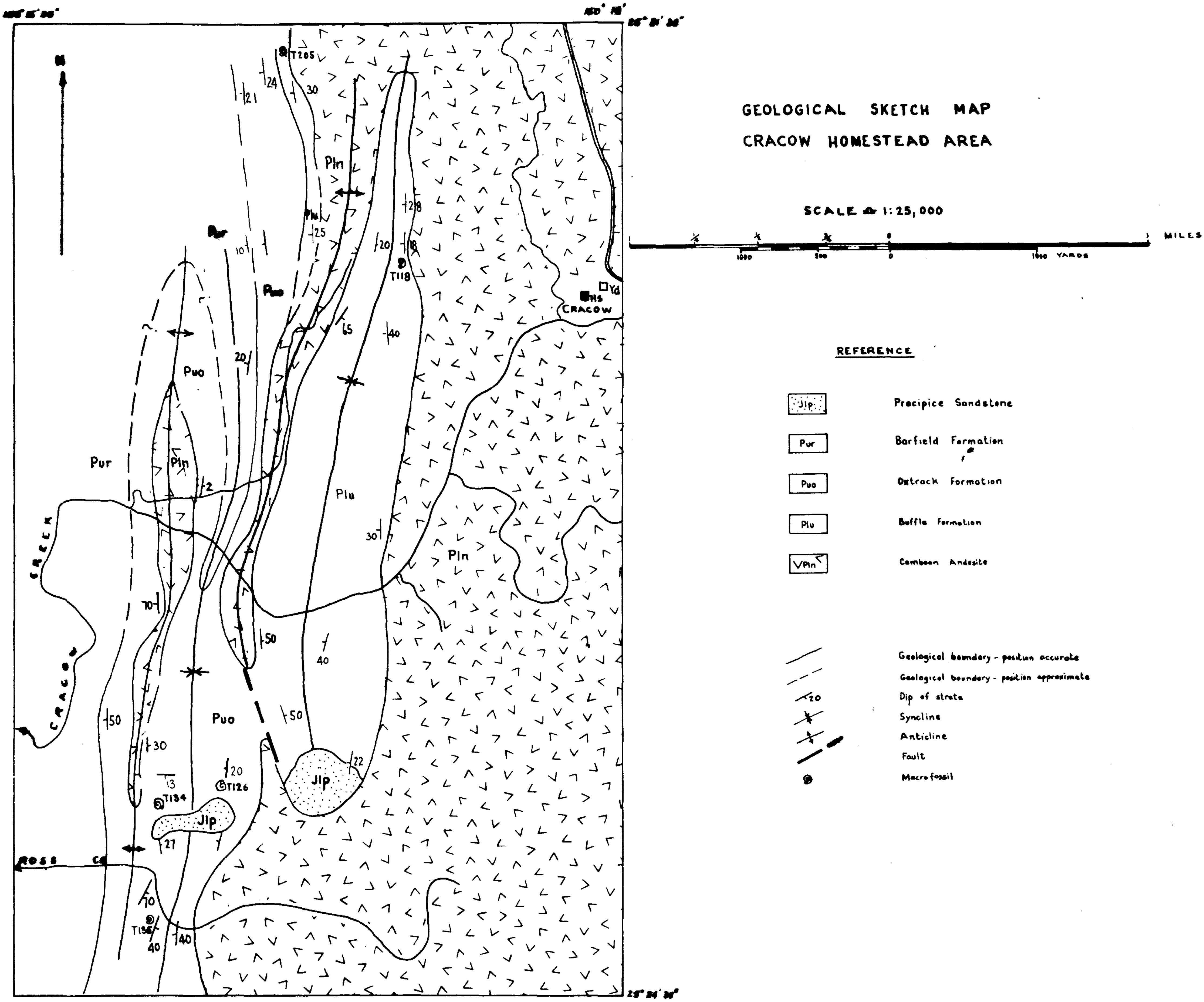
May, 1964. To accompany Record 1965/57

Fig. 20

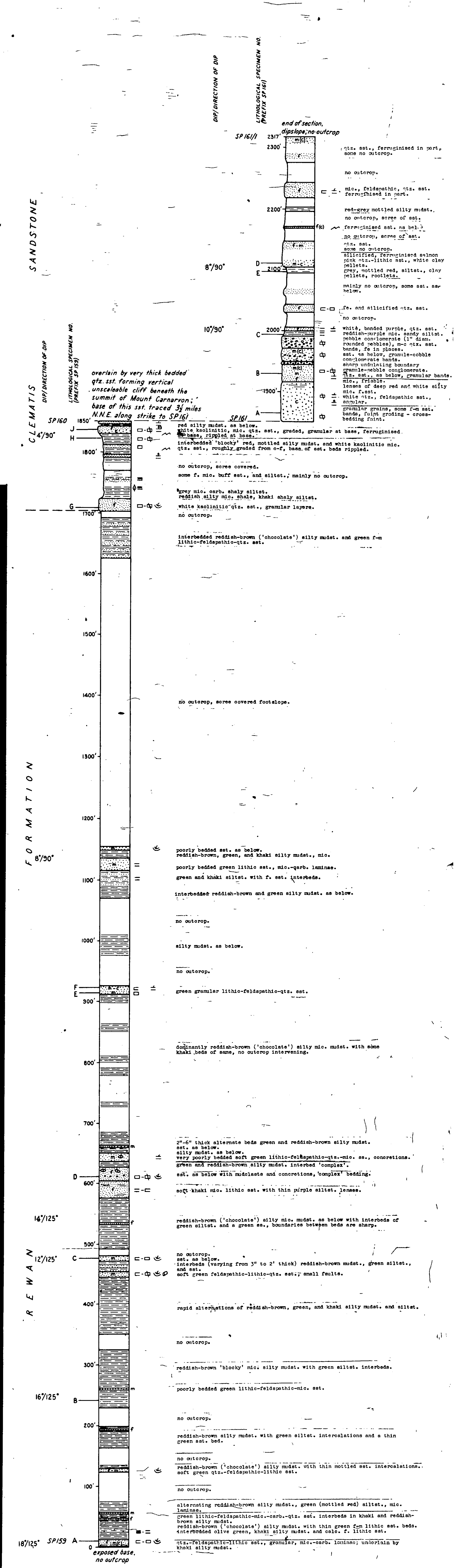


Bureau of Mineral Resources, Geology & Geophysics, May 1964. To accompany Record 1965/57

Figure 21

MEASURED SECTION IN THE REWAN FORMATION AND CLEMATIS SANDSTONE (S29)

Measured in a small creek from its junction with Consuelo Creek (SP 159) to its head at the base of Mount Carnarvon (SP 160) and in cuestas immediately east of Serotold Homestead between SP 161 & SP 161/1 (Springsure, Run 4, Photo 5231)
(Measured with Abney Level by R.G. Molian)



Marine deposition occurred at least at its later stages, with some deposition in a shallow, brackish, restricted invironment.

Bandanna Formation 1500' (Figs.14, 16 and 17)

The lower part of this formation is of shale and mudstone with montmorillonitic clay interbeds and minor lithic sandstone beds; the shales are commonly cherty, with high ash and glass shard content. The upper part of the formation consists of lithic sandstone and subgreywacke, calcareous sandstone, limestone, and siltstone, and is characterised by coal seams up to 15' thick. The presence of microplankton swarms (Evans, 1964) suggests marine conditions during deposition of the lower part of the formation (Fig.22). There was also some contemporaneous volcanic activity, as evidenced by tuffs. The lower part of the formation was probably deposited in a gently subsiding basin; the upper part was deposited in a shallow freshwater (swampy) basin with recurrent periods of subsidence (glauconite). Only the lower part is included in the "Middle Bowen Beds"; the upper part is Upper Permian to Lower Triassic.

The Bandanna Formation lies conformably on the Peawaddy Formation and is overlain conformably and transitionally by the Triassic Rewan Formation.

Note. The microplankton swarms are present in a 30'-40' bed in the lower part of the Lower Bandanna Formation immediately above the Mantuan Productus Bed. There are a few thin layers containing microplankton above the main bed. Their known and presumed extent is shown in Fig.22.

NORTHERN BOWEN BASIN

Unit C 2600'

This unit consists of pebble conglomerate, overlain by carbonaceous quartz greywacke with conglomerate bands containing the Big Strophalosia Zone, overlain by siltstone interbedded with minor quartz greywacke. It is fossiliferous. The Big Strophalosia Zone consists of fossiliferous calcareous pebbly greywacke with angular boulders, which is probably a widespread density current deposit. Unit C as a whole was deposited in deep marine conditions with a shelf to the west. It overlies beds of Unit B of various lithologies conformably, and is conformably overlain by the non-marine Upper Bowen Coal Measures. The Big Strophalosia Zone is time-equivalent to the Clarkei-bed, a shelly quartz greywacke with erratics which crops out to the south, in the Clermont area.

BANANA-CRACOW AREA (Fig.20)

Oxtrack Formation 350' (Fig.19)

This unit is a fossiliferous limestone grading upward into calcareous fossiliferous siltstone. Brachypods, pelecypods, bryozoa, corals and crinoids are abundant. To the north of the Banana-Cracow area, the Formation crops out as chert, probably silicified limestone, and to the south the limestone is again strongly silicified. Further north, in the Gogango Range, the formation consists of fossiliferous calcareous siltstone and calcarenite. In the south-west, fossiliferous calcareous mudstone grades laterally into coquinite and overlies lithic sandstone with interbedded siltstone. Marine, mostly neritic, but deep-water in some places, this formation was deposited during rapid subsidence and in a warm climate. It overlies the Buffel Formation (UnitA) with no apparent angular discordance, and in some places the Camboon Andesite; it is overlain conformably by the Barfield Formation.

Barfield Formation 3000' (Fig.18)

The Barfield Formation consists of mudstones, some pyritic, with calcareous concretion bands, in places interbedded with lithic arenites, limestone lenses, pebble bands and calcilutite. Spilites, breccias and evidence of slumping occur, and, at the top, volcanic lithic arenite and lapilli tuff. The formation is fossiliferous, and was deposited in a marine, deep and possibly reducing environment, which was, however, shallow in part. It conformably overlies the Oxtrack Formation, and is conformably overlain by the Flat Top Formation.

Flat Top Formation 1800'

This unit consists of mudstone, argillite and sandy siltstone, and contains small and large scale slump structures. Wood-fragment impressions increase, and marine fossils decrease in abundance from north to south. In the south (Cockatoo Creek No.1) coal seams occur. In the north (Baralaba Sheet) the formation consists of calcilutite locally silicified, coquinite, and chert. A deep marine environment is indicated in part.

Undifferentiated Back Creek Group ?1500'

In the Don River area and to the north of it, the Oxtrack, Barfield and Flat Top Formations are not easily distinguishable, due to intense deformation and poor outcrop, and the rocks have been mapped as undifferentiated Back Creek Group. This group consists of subgreywacke, shale and minor conglomerate. It has a shallow, near-shore marine origin. Farther to the north and north-east, flysch-type sediments, probably equivalent to the Barfield and Flat Top Formations, indicate rapid subsidence. The Group unconformably overlies rocks of various ages from the Camboon Andesite to the Oxtrack Formation. A nodule from an exposure of a sheared siltstone and shale sequence, on the Rockhampton-Duaringa road, contained 27% P_2O_5; the sequence is thought to be in part equivalent to the Barfield Formation.

111. Upper Bowen Beds.

(Fig.3, Isopach 5)

In the Banana-Cracow area, the base of the Upper Bowen Coal Measures is placed at the base of the freshwater Gyranda Formation. The upper part of the underlying Flat Top Formation is rarely fossiliferous and may be non-marine in part.

The Upper Bowen Coal Measures is a continuous rock unit. Seismic surveys indicate the continuity of the unit under the Mimosa Syncline from the Banana-Cracow area to the Springsure area. From there, they can be traced into the northern Bowen Basin.

The upper Bowen Coal Measures occupy an area generally similar to that occupied by Unit C. The eastern trough is still apparent, though the thickest sedimentation is at the northern end. The change of environment from marine in Unit C to lacustrine, paludal, and fluvial in the Upper Bowen Coal Measures is possibly associated with uplift along the axis of the Lower Bowen Volcanics trough.

TRIASSIC

The Rewan Formation (Fig.3, Isopach 6, and Fig.21)

The Rewan Formation is a continuous rock unit throughout the southern part of the Bowen Basin. It is present in the trough of the Nebo Synclinorium, in the north of the Basin. The boundary between the Rewan Formation and the Upper Bowen Coal Measures is fairly sharp in the Banana-Cracow area; the base of the Rewan Formation is commonly marked by a volcanic conglomerate bed overlain by the characteristic red-brown mudstone of the Rewan Formation. In outcrop in the Springsure area, it directly overlies coal beds of the Bandanna Formation. The boundary is associated with a marked spore break and is probably disconformable. Farther north, in the Duaringa Sheet area, the Rewan Formation and the Upper Bowen Coal Measures interfinger at their contact.

The depositional area of the Rewan Formation was considerably less than that of the previous unit. The main locus of sedimentation was a pronounced downwarp in the south-east, the first stage in the development of the Mimosa Syncline. The distribution of the Rewan Formation relative to the Mimosa Syncline is markedly asymmetrical, as the thickest section of Rewan Formation is east of the axis of the Syncline. This is particularly noticeable in the north-east of the Syncline, where it is affected by later uplift.

The Middle to Upper Triassic (Fig.3, Isopach 7 and Fig.21)

The youngest rock sequence considered in this paper comprises the Clematis Sandstone and the Moolayember Formation in the south of the Bowen Basin, and the Carborough Sandstone and Teviot Formation in the north.

The boundary between the Clematis or Carborough Sandstones and the underlying Rewan Formation is generally sharp; it is transitional in the Banana-Cracow area. The marked change in lithology from the Rewan Formation represents a significant change in environment. The two sandstone units are transitional to the overlying formations.

Most of the Middle to Upper Triassic sediments were deposited in the Mimosa Syncline. The Clematis Sandstone at the base is of fairly uniform thickness throughout; about 1000 feet thick on the western margin and thinning to about 700 feet thick on the eastern margin. The Moolayember Formation, on the other hand, thickens to about 7000 feet in the trough of the Mimosa Syncline. The uniform blanket of the Clematis Sandstone possibly accumulated in a fluviatile environment, during a period of slow, widespread subsidence which followed the rapid, localized downwarping of Rewan Formation time. Local subsidence was renewed vigorously in the Mimosa Syncline during deposition of the Moolayember Formation. The maximum thickness of the Moolayember Formation is west of the maximum Thickness of the Rewan Formation, indicating a shift in the locus of maximum subsidence.

About 2000 feet of Carborough Sandstone and Teviot Formation are preserved in the centre of the northern Bowen Basin. The Carborough Sandstone is thicker and more coarse-grained than the Clematis Sandstone. The depositional areas of the two may have been continuous; they were possibly deposited in a large river valley trending down the axis of the Bowen Basin. Fluviatile material was also supplied by a broad river valley trending mainly east across the Springsure Shelf.

STRUCTURE

The following extract is quoted directly from B.M.R. Record 1964/81: "Depositional Evolution of the Bowen Basin", by E.J. Malone, where it is entitled "Relationships of Depositional Areas and Structural Elements".

> The present structural elements of the Bowen Basin are illustrated in Fig.2. Many of the structural elements are obviously related to the depositional areas, and these relationships are discussed below.
>
> All the isopachs indicate that the Springsure Shelf acted as a moderately unstable shelf throughout the Permian and Triassic, receiving uniformly thin sediments at most times. The much slower rate of subsidence of the Springsure Shelf relative to the Denison Trough is shown by the fact that the Colinlea Sandstone, less than 600 feet thick, is a lateral equivalent on the Shelf of the 2000 feet of Unit B within the Trough. The suggested absence of many of the units from the south-west corner, owing to erosion or non-deposition, is conjectural. The subsequent structural history of the Springsure Shelf is also that of a moderately unstable shelf. Some gentle anticlines have developed over the axes of pre-existing structures, such as the Nogoa Anticline. Generally, dips are at low angles to the south and south-west.
>
> The Denison Trough, as a structural element, is characterized by the type of folding it contains. The folds consist of prominent anticlines and less prominent synclines, generally with fairly obvious, slightly curved axes which can be traced for many miles. The most important fold is the Springsure Anticline, a major structure with a number of culminations on an axis which can be traced for over 100 miles. The amplitude of this anticline is greater than 5000 feet in places. Dips of 25^{o} or more are common; the dips are generally steeper on the western flank. East of and approximately parallel to the Springsure Anticline are a number of smaller folds. Of these folds, the anticlines are similar in shape to the Springsure Anticline though of less amplitude; the synclines are much less well developed, generally have broad flat troughs, and are of very low amplitude. Towards the north-east, this type of folding is replaced by the domes and basins formed on the Comet Ridge. The Denison Trough folding, particularly the Springsure Anticline, is possibly the result of uplift of this originally deeply downwarped zone.
>
> The Comet Ridge, first apparent on Isopach 1, separating the Denison Trough from the Lower Bowen Volcanics trough, persists into the Triassic as a zone of thin sedimentation. The southern end of the Comet Ridge was involved in the Mimosa Syncline subsidence. Structurally the Ridge is characterized by low amplitude folds, mainly domes and basins with sinuous axes. The boundary with the Denison trough is gradational but that with the Mimosa Syncline is fairly sharp. Seismic structure contour maps (Planet, 1962; Marathon, 1962) show clearly the change from the uniformly east-dipping west limb of the Mimosa Syncline to the sinuous folds of the Comet Ridge. Seismic evidence of the type of folding is the reason for extending the Comet Ridge to the south between the Mimosa Syncline and the Denison Trough.
>
> The Collinsville Shelf extends north from the Comet Ridge. Depositionally, it represents the zone of overlap of

Unit B and Unit C relative to Unit A in the northern Bowen Basin. Structurally, it is a zone of low dips to the north-east with a few small anticlines, probably drape structures over basement highs. This area has acted as a moderately unstable shelf throughout the depositional and subsequent history of the Bowen Basin.

The Mimosa Syncline is a depositional downwarp only slightly modified by subsequent folding. Apparently, despite the magnitude of downwarping, it has not been uplifted to any extent. The eastern limb of the structure includes the whole Permian-Triassic sequence down to and including the Camboon Andesite, though the depositional areas of the units below the Rewan Formation are not related to the Mimosa Syncline - the Syncline was superimposed on pre-existing downwarps and, as the youngest, is at present the most obvious structure.

The Nebo Synclinorium is a moderately to tightly folded zone, intruded in places and including the Folded Zone in the south. The Synclinorium approximately occupies the position of the northern trough, which received a maximum of about 20,000 feet of sediments. The western boundary of the Synclinorium against the Collinsville Shelf and the Comet Ridge is thrust-faulted in places; elsewhere, it is marked by a narrow transition zone from the tight structures of the Folded Zone to the gentle folds of the Comet Ridge. This western boundary appears to be associated with the western limit of thick sedimentation.

The Connors Arch in the north and the Auburn Arch in the south-east are on the axis of the Lower Bowen Volcanics trough. This trough was the zone of maximum depositional subsidence; now, the two arches represent the highest structural uplift in the Bowen Basin. Igneous rocks exposed in the core of the Connors and Auburn Arches include some rocks older than the Lower Bowen Volcanics. Uplift of the Connors Arch is probably responsible for the development of the Bowen Synclinorium; uplift of the Auburn Arch has probably produced the asymmetry of the Mimosa Syncline.

The Strathmuir Syncline is occupied by the upper part of the Lower Bowen Volcanics and by Unit A, Middle Bowen Beds. During deposition of Unit A, this area was probably linked with the northern trough, across what is now the Connors Arch. However, the volcanics and sediments suggest that this was a locally more deeply subsiding area. The depositional downwarp became a syncline during subsequent folding; the east limb is steeply dipping and tightly folded in the transition to the Gogango Overfolded Zone.

The Gogango Overfolded Zone is a sinuous structural zone which extends from east of the Strathmuir Syncline to the northern end of the Auburn Arch. Lower Bowen Volcanics, Camboon Andesite, Rannes Beds, and Middle Bowen Beds are all involved in the overfolding, faulting, and mild regional metamorphism of this area though the effects of the deformation, particularly cleavage, are more obvious in the finer sediments. In this zone, the Bowen Basin sequence overlaps the western edge of the Yarrol Basin sequence. In the only contacts seen, equivalents of the Lower Bowen Volcanics are apparently concordant on Carboniferous sediments though there is some evidence of considerable disconformities. The limited extent of the Yarrol Basin sequence to the west is indicated by the presence of Silurian-Devonian sediments overlain directly by Camboon Andesite.

Development of the Overfolded Zone is possibly the result of overlapping of the Bowen Basin depositional area on to the main geosynclinal trough, occupied by the Yarrol Basin sequence. The overfolding is away from the Yarrol Basin and may be related to uplift in the main geosynclinal trough. Farther north, the Overfolded Zone is faulted against metamorphic and ultrabasic rocks which are possibly older than the Yarrol Basin sequence.

The Bowen Basin sequence is most intensely folded and deformed in the Gogango Overfolded Zone, adjacent to the main geosynclinal trough. The degree of deformation decreases away from the main geosyncline. This is displayed best by the distribution of cleavage. Axial plane cleavage is ubiquitous in the Gogango Overfolded Zone and the Strathmuir Syncline. It is generally common and well developed in the south-eastern end of the Nebo Synclinorium, but is very rare farther west in the Folded Zone. Cleavage is generally absent west of the Connors and Auburn Arches; this may be partly due to the present of these competent blocks of volcanics and igneous rocks which began to rise, probably during the Upper Permian, and to some extent protected the sediments to the west from deformation.

SUMMARY OF GEOLOGICAL HISTORY

The Bowen Basin sequence was deposited in a series of downwarps and on adjacent, less rapidly subsiding unstable shelves. The downwarps were mainly elongated north to north-west. Two distinct downwarps separated by a ridge existed during deposition of the Lower Permian units; of these the Denison Trough ceased to exist about the end of the Lower Permian and only the eastern trough persisted into the Upper Permian and the Triassic. The locus of maximum sedimentation in this eastern trough migrated from one unit to the next but, overall, the trough shrank in size so that the youngest sediments, the Middle-Upper Triassic units, were deposited in the downwarp of smallest area.

The deepest downwarps were those along the eastern margin of the Basin which received the Lower Permian volcanics. This eastern province has since undergone more structural uplift than any other part of the Basin. The Denison Trough, a Lower Permian downwarp in the south-west of the Basin, received about 15,000 feet of sediments and has been considerably uplifted to produce the Springsure Anticline and associated smaller folds. The northern trough received about 20,000 feet of Lower Permian to Triassic sediments and is complexly folded in part. The Mimosa Syncline, in the south-east, received about 20,000 feet of mainly Triassic sediments and is little folded.

The development of the Bowen Basin began in the Lower Permian with the deposition of deepwater marine sediments and volcanics in the east, together with possible island-arc activity and multiple contemporaneous intrusions; at the same time a freshwater sequence was deposited in the south-west.

In Unit A times volcanic activity ceased except in the eastern province, and marine transgression was more extensive. Sedimentation in the western province was controlled by a fault zone, which divided a shallow, restricted shelf facies to its west (Springsure shelf) from a deeper basin to the east. This fault ceased to exist at the end of Unit A time, and in Unit B the transgression was more extensive towards the west and north, though it was more restricted in the east and south.

In Unit B deltaic and freshwater conditions prevailed, during which the Ingelara Formation represents a widespread shallow marine transgression. At this time connections with the ocean were probably to the north-east or east, with a southern and western shoreline.

During Unit C the marine transgression was considerably extended. The sea was shallow over the western shelf and deep in the central and eastern areas. There was vulcanism and uplift, with rapid sedimentation, to the north-east. Connections with the open ocean were to the south.

The Bowen Basin sequence overlaps the Yarrol Basin sequence, and the two probably represent two stages of deposition in the one geosynclinal sequence. The change from deposition in the Yarrol Basin to deposition in the Bowen Basin represents a major shift in the locus of sedimentation and is associated with a vigorous renewal of vulcanism.

PHOSPHATE POTENTIAL

INTRODUCTION

The guiding principles of the method used here for determining the phosphate potential of an area are described in B.M.R. Record 1965/37 "An approach to the search for sedimentary phosphate" by J.A. Kaulback. This record indicates an approach to phosphate exploration which involves the systematic study of the sediments according to the broad principles of a universal genetic formula. This formula summarises the principal factors in the formation of phosphorite as: (1) Source, (2) Separation, (3) Trap, (4) Accumulation-and-Concentration.

Analysis of the Bowen Basin is divided into two parts: (1) a Preliminary Analysis, which in a broad way eliminates non-productive areas and sections of the stratigraphic column, such as non-marine rocks and thick detrital sequences, as well as delineates formations, lithofacies and areas favourable for phosphorite occurrence in terms of the four principal factors; (2) Detailed analysis, which selects particular lithological sequences or beds within these chosen areas, in which phosphorite is most likely to occur.

As has already been stated (on page 3), the Basin sequence as a whole shows only one period of continuous marine sedimentation, - the Permian Middle Bowen Beds - and for the purposes of this Analysis all earlier or later units (all of which are predominantly non-marine) can confidently be eliminated as potential sedimentary phosphate deposits. The following Analysis is therefore restricted to the Middle Bowen Beds.

A. PRELIMINARY ANALYSIS

1. Source

Access to ocean

It is evident from the sediments of the Middle Bowen Beds that marine conditions prevailed throughout the period of deposition, commonly over the entire basin, but always at least over part of it. Even in Unit B, where the Ingelara Formation represents the only widespread marine transgression, there is evidence of continuous marine sedimentation in the north and north-east (Mackay). Access to the open sea was therefore always present to the north and north-east in Unit B, and to the south and south-east in Units A and C. During the time in which the Middle Bowen Beds were deposited, conditions favourable for the existence and accumulation of a marine phosphate reserve were probably present at all times because the basin had direct connections with the sea.

Bathymetry

The relation between basin and phosphate reserve was probably much closer; each successive unit included, in several, a shallow-water platform component and a synchronous deep-water geosynclinal component; the deep trough, where the geosynclinal sediments were deposited, would have been a favourable region for the accumulation of phosphate reserves within the basin itself rather than merely in the ocean adjacent to it. If analogy with present-day island-arcs can be made, the island-arc or active ridge system which was intermittently present to the east of the main depositional basin throughout Middle Bowen Beds time may have had a genetically associated deep trough along its margine, which would have accumulated phosphate in solution, in the same way as do the present-day troughs associated with island-arcs.

Climate

Glacial sedimentation in Unit A shows that the climate was cold at least until the beginning of Unit B, after which the marked faunal change might have been due to a more moderate or even warm climate (Dickins, pers.comm.). A combination of cold water and depth is ideal for the retention and accumulation of phosphate solution in marine waters and even if these conditions had occurred only during Unit A times, the phosphate reserve thus formed would still have been available as a source for phosphate abstraction and redistribution at a later time although the reserve might have ceased to grow.

Time

Though it is difficult to estimate the duration in millions of years of the Middle Bowen Beds, the estimates of B.M.R. geologists exceed a minimum of 10-15 million years. McKelvey et al (1953) state that at 'normal' rates of sedimentation and with 'normal' amounts of land exposed, at least seven times the total tonnage of phosphate in the Phorphoria Formation would be available in the oceans in 15 million years. It is possible therefore for a large enough oceanic phosphate reserve for the nourishment of a significant phosphate deposit to have accumulated during the deposition of the Middle Bowen Beds, and probably during the time-span of any single Unit.

Sedimentary Cycle

The sediments of the Middle Bowen Beds (mudstones, argillites, shales, limestone, chert) are predominantly of a type produced by a "Biochemical" or "fine-Residual" rather than a "Detrital" phase of erosion. During sedimentation of this sort, phosphate is contributed to the oceanic phosphate reserve through chemical solutions so that the general character of the sediments at this time is an additional factor pointing to the accumulation of phosphate in a marine reserve. Phosphatogenic currents (or other mechanisms encouraging extraction of phosphate from solution in the marine reserve and its deposition in sediment) could have had their effect at any point during the deposition of the Middle Bowen Beds, but their greatest effect would normally have been at the end of a period of "Biochemical" sedimentation, when the greatest accumulation of phosphate coincided with least dilution by phosphate barren sedimentation.

In this connection there are several formations in which lithology suggests intervals of time when phosphate was probably contributed to the marine phosphate reserve:

Unit C: Flat Top Formation, Lower Bandanna Formation
Barfield Formation, Mantuan Productus Beds
Oxtrack Formation

Unit B: Part of the Ingelara Formation

Unit A: Cattle Creek Formation
Stanleigh Formation
Sirius Formation

The precise horizons within these formations at which phosphate is most likely to be deposited in sediments rather than contributed to the ocean is discussed later. This is a complex prediction involving palaeogeography, palaeobathymetry and sedimentation.

2. Separation Mechanism

It is difficult to find direct evidence of currents or marine circulation which might have brought phosphate from reserve to areas suitable for precipitation and deposition. No significant current directions have been measured in the Middle Bowen Beds; indeed, any present are not likely to result from currents carrying cold water from the deeps, because these normally travel upwards and along the surface, to leave no trace on the sea-floor.

Indirect evidence: plankton and chert

Indirect evidence of upwelling currents is indicated by the occurrence of chert in the Buffel Formation in Unit A and by the occurrence of microplankton swarms in the Lower Bandanna Formation in Unit C. The 40 ft. thick microplankton bed, just above the Mantuan Productus Bed, in the Lower Bandanna Formation, must have been supported by phosphate-rich water, as the presence of plankton is controlled by the availability of phosphate and nitrate in the sea, and as phosphate production is greatest in present-day oceans in areas of upwelling cold phosphatic waters. This comparatively thick horizon of abundant plankton proves only the availability of nutrients, which may either have been accumulating nearby during the deposition of the older Formations listed above, or have been introduced from the oceanic reserve; the plankton has no direct relationship with the precipitation and deposition of phosphate. Naturally, plankton growth need not have been most luxuriant in the waters directly above the areas in which it is now found, and indeed its present distribution (Fig.22) over the Springsure Shelf suggests that the same nutrient-rich current, (upwelling from the deep axial trough of the basin) which nourished the plankton, either carried it at the same time onto and across the shelf, where the plankton were deposited, or only reached the surface at the shelf where it gave rise to prolific plankton production.

Change of physico-chemical environment

When the nutrient-rich currents flowed onto the Shelf, they were afforded plenty of opportunity for changes in physico-chemical environment (in temperature, pH or hydrostatic pressure) which would cause precipitation of phosphate

The chert of the Buffel Formation is primary and composed largely of organic spicules from organisms which were probably nourished by a luxuriant growth of plankton, supported by phosphate-rich water. Chert is closely associated with phosphate in the Phosphoria Formation.

Basinal Circulation

In the absence of other indications of palaeo-current movements, the marine circulation of the Middle Bowen basin may be assumed to have been normal. The deep nutrient-rich waters, after upwelling into the basin, were largely depleted of phosphorous by chemical precipitation and plankton assimilation; these waters, circulating back in the upper levels of the sea, yielded no phosphate on their return, either to the open sea or to another side of the basin.

Restricted Basins

It is probable that a restricted basin retains a greater proportion of the phosphate from the incoming waters before they are recirculated (Krumbein and Garrels, 1952). Restricted sedimentation occurred in the Stanleigh, Sirius, Cattle Creek, Ingelara and Peawaddy Formations, and possibly the Lower Bandanna Formation (vide gypsum).

Restricted Area

Though an adequate mechanism for the precipitation of phosphate is provided by the upwelling of phosphate-rich water from the ocean deep in the course of normal oceanic circulation, a constriction of the area in which the upwelling waters rise, such as a steep slope, a gulf or a channel, would provide a desirable concentration of precipitated phosphate. This may be in part the reason for the association of ancient and modern phosphorites with steep shelf slopes, bathymetric highs and the isobath separating platform from geosynclinal facies.

Such constrictions or slopes would have been formed in Unit A by the fault-line which divided the Denison Trough from the Springsure Shelf, and probably by the steep margin of the eastern island arc; in Unit C by the sides of the rapidly subsiding basin, by the topography of the uneven basement and probably by the margin of the eastern ridge. Throughout the Middle Bowen Beds there was probably a break of slope between shelf and trough (though its location moved from Unit to Unit), and isopachs also show a promounced embayment in the south-west in all the Units.

3. Phosphate Trap

Unless the phosphate precipitated from its source is trapped into sediment, it may be recirculated to the ocean deeps or returned to the water through the organic cycle. The free phosphate in the Middle Bowen Beds at different times may have been assimilated by plankton, which then acted in much the same way as finer sediments and were deposited; it may have been assimilated by organic (shells) processes when it was drawn over carbonate provinces; it may have formed aggregations and sunk to the sea floor; or it may have been adsorbed by suspended clay or silt materials and then have been deposited (Jitts, 1959). These possibilities again direct attention to specific lithologies within the finer and biochemical sediments which are to be found in the formations already listed under 'Source'.

4. Accumulation and Concentration

At this stage, when the probable existence of a phosphate source, of a mechanism for separating the phosphate from its source, and of a means of trapping it into sediment have been established, it is necessary to find a time and a place favourable for the accumulation and concentration of phosphate. The general requirements for an economic concentration of phosphate, once source, separation mechanism and trapping mechanism exist, are:

1. No concurrent deposition of phosphate-sterile sediments.
   (a) Time: at end of long period of biochemical sedimentation with low hinterland relief.
   (b) Place: margin of basin, or elevated regions away from shore, back-reef areas, areas of strong current or turbulence.

2. Long period of time.

3. Restricted area.

4. Possibly warm or temperate palaeolatitudes. (Sheldon 1964).

It will be seen from Table 3 that the following formations fulfil at least three, if not all, of these requirements: Unit C as a whole, and every Formation in it; Catherine Sandstone, Glendoo Member and Ingelara Formation in Unit B; and Cattle Creek, Sirius, Stanleigh and Buffel Formations in Unit A.

TABLE 3

Requirements for Time or Place favourable for trapping Phosphate into Sediment.

Formations, Members and Zones (Only Marine Rocks Listed)	1a. At end of long period with biochemical sedimentation.	1b. Margin of basin, or elevated regions away from shore, etc.	2. Long period of time.	3. Restricted area.	4. ?Warm or temperate
Unit C	X	X	X		?X
Lower Bandanna	X	X	X		?X
Flat Top	X	X	X		
Mantuan Productus	X	X	X		
Barfield	X	X	X		
Big Strophalosia	X				
Oxtrack	X	X	X		
Peawaddy	X	X	X	X	
Catherine	X	X	X		
Glendoo	X	X			
Ingelara	X	X	X	X	
UNIT A		X	X		
Cattle Creek		X	X	X	COLD
Sirius		X	X	X	
Stanleigh		X	X	X	
Buffel		X	X	X	

These formations, selected for their suitability for phosphate deposition, compare closely to those selected (under 'Source') for their suitability for phosphatogenesis. The Peawaddy Formation and the Catherine Sandstone, both apparently unsuitable for phosphatogenesis, should in any case also be eliminated from the group suitable for phosphate deposition because of predominance of detrital material. The Glendoo Member should be discounted because of its coarse detrital sediment and comparatively short time of deposition. Similarly unit A in the Northern Bowen Basin is predominantly coarse-detrital.

In Unit A, phosphate which accumulated in deeper parts of the basin could have been precipitated if it were carried by currents over the restricted shallow-water environment of the Cattle Creek Formation or its probable equivalents, the Sirius and Stanleigh Formations. However, only immediately to the west of the Cattle Creek Formation has the presence of an active fault-zone been demonstrated, which provided a steep slope to activate and concentrate precipitation of dissolved phosphate. A sandstone from a nodular calcareous sandstone in the Cattle Creek Formation contained 12% P_2O_5.

The Sirius and Stanleigh Formations are both lithologically similar to the Cattle Creek Formation, and are suitable for phosphatogenesis; however, the Stanleigh Formation contains fewer erratics and was possibly less influenced by nearby fault slopes than the Cattle Creek Formation, making it less suitable for concentrated phosphate deposition.

The Buffel Formation has a marginal limestone/chert facies, but would be expected to contribute phosphate in solutions to the basin (which would be perhaps precipitated by circulation reaching the other side of the basin in Cattle Creek time) rather than attract phosphorite deposition. However, it is possible that at the top of the Formation (at the end of this period of biochemical sedimentation) a lithology may be found which indicates an environment suitable for phosphorite deposition. The chert/limestone facies is certainly a pointer.

In Unit B the Ingelara Formation, representing a restricted marine transgression in a dominantly freshwater sequence, may have been suitable for phosphorite deposition; its lithology is similar to that of the Cattle Creek. Access to the open sea was farther from the basin during Unit B than at any other time in the Middle Bowen Beds, and it is doubtful whether nutrient-rich waters could have reached as far as this without losing their salts en route due to evaporation, organic assimilation, dilution or recirculation; however, despite this reservation, the Ingelara must still be regarded as a possible phosphorite horizon.

Unit C, and in particular its upper and middle beds, appears to be the most favourable for phosphatogenesis and phosphorite formation. By this time, the periods of biochemical sedimentation of the previous Units would have contributed significantly to the marine phosphate reserve. Phosphate in solution in the deeper central and eastern parts of the basin would have been carried by normal circulation to be precipitated over shallower regions, on the western shelf or the eastern ridge, or both. In the Peawaddy Formation it would have been diluted by detrital material. In the marginal, shallow water Mantuan Productus Bed it could have been precipitated and retained, though it may have been diluted by the quantity of detrital matter. In the Lower Bandanna Formation the microplankton swarm proves the existence of phosphate-rich upwelling waters, but indicates rather that the phosphate in the area may have been assimilated by the plankton and then, after the death of the organisms, released into circulation again by bacteria, leading to a depletion of phosphate available for deposition. At the same time in other parts of the basin, (top of the Barfield and base of the Flat Top Formations), the uneven slopes of the eastern ridge may have induced rapid physico-chemical changes in upwelling phosphate-rich waters, causing rapid and heavy phosphate precipitation. Phosphate deposition would have been swamped by calcium carbonate precipitation in the rapidly subsiding, partly neritic Oxtrack Formation (Fig.19), but its less calcareous members - fine siltstones and mudstones - were suitable for adsorption of phosphate (which could later be concentrated by nodule-formation and winnowing), as were those of the Barfield and Flat Top Formations. Evidence of this is the 27% P_2O_5 content of a nodule from sheared siltstone and shale in the Back Creek Group (from the Rockhampton-Duaringa road), which is thought at this horizon to be probably equivalent to the Barfield Formation.

In summary, this general appraisal indicates a number of formations with phosphate potential within the Middle Bowen Beds; this indicated potential is broadly endorsed by the few assays available from the sequence. The most promising Formations are (in order of promise):

1. Barfield Formation (and Flat Top Formation) and equivalent formations in the Back Creek Group.

2. Cattle Creek Formation

3. Mantuan Productus Bed

(4. Buffel Formation)

(5. Ingelara Formation)

(6. Sirius and Stanleigh Formations)

In the next section the lithology of these formations will be discussed in further detail, to select the particular beds which may prove most likely to contain phosphate. It is stressed that as the oceanic phosphate reserve is permanent, and as sedimentary phosphate is a facies, a phosphorite deposit may be diachronous, and that, once a suitable, broad period of time has been found to exist, environment is the most important factor.

B. DETAILED ANALYSIS

Introduction

Assuming that a preliminary analysis has indicated that a certain formation was deposited in a region and at a time suitable in general terms for phosphatogenesis and for phosphate deposition, an attempt can be made to select specific beds within that formation at which phosphate would be expected to be concentrated. Such beds would contain lithologies which indicate a phosphate-favourable environment, viz:

(1) Source: Evidence of chemical supersaturation, precipitation and aggragation: nodules, concretions, pellets, ooliths, etc.

(2) Separation: Evidence of sub-marine topography, elevated regions, marginal slopes or offshore submarine highs which would cause changes in physico-chemical environment, giving rise to phosphate precipitation.

(3) Trap: Evidence of sediments capable of adsorbing and localising phosphate in the sea: silts, oolites, shelly sediments.

(4) Accumulation and Concentration: Evidence of sparse concurrent phosphate-barren sedimentation, giving rise to higher phosphate concentration: condensed sections; current-bedding or sandstone lenses in siltstone, indicating winnowing; still or stagnant waters; elevated sea-floor regions.

The formations which have been selected for their high probable phosphate potential are discussed below, with particular reference to these four groups of favourable criteria.

The Formations

1. a. Barfield Formation

The lithology of the Barfield Formation has been previously described, and a columnar section is shown in Fig.18.

(1) Chemical precipitation:- Black and grey calcareous concretions occur in the lower 600 ft. In the interval 900-1000 ft. carbonate precipitation reached a climax and deposited limestone. The interval 2300-2550 ft. contains calcareous concretions, which are again followed by a climax of carbonate precipitation in the limestone at 2600-2700 ft.

(2) Submarine topography:- The formation consists of two lithological cycles (0-1950 ft. and 1950-3000 ft.), each broadly beginning with mudstone (some pyritic), in which calcareous concretions become more numerous upwards and culminate in limestone deposition, and ending in siltstone, pebbly sandstone and conglomerate. The increasing coarseness of terrigenous sediments and the upward increase in chemical sediment together indicate shallowing. Deposition began with deep water sediments (slumped pyritic mudstones with volcanics). As the sea floor became shallower, the environment became more suitable for precipitation of soluble salts (warmer, less hydrostatic pressure), and within the bottom muds an increasing amount of calcareous material was precipitated and disseminated, which at some later stage was concentrated in nodules and concretions. Siltstone bands appeared in the mudstone. The relative sea level continued to drop, and intense precipitation in the much shallower waters deposited limestone and chert; the shallow (?warm), oxidising environment nourished an abundant coral and shell growth. The character of the sediment changed with further shallowing, and terrigenous influence became stronger - sandstone, pebbly sandstone and finally conglomerate was deposited.

These two cycles indicate that twice during the Formation there was a general shallowing and probably an associated marginal slope which created suitable conditions for phosphate precipitation. Coal and wood impressions show a southern shore.

(3) Adsorbing and localising sediments:- About 1500 ft. of mudstone and siltstone occur in the Barfield Formation, which would have been capable of adsorbing phosphate. In the upper part of the formation brachiopods and other fossils were capable of forming small local concentrations of phosphate.

(4) Little concurrent sedimentation:- In the uppermost level of each cycle, the currents which formed the sandstone and pebbly beds would probably have eliminated much terrigenous material by winnowing. Pelletal phosphate would probably have a higher concentration here than in the mudstone lower in the cycle.

Conclusions

Phosphate could have been adsorbed in the mudstones where it may have formed concretions, but it is probable that the highest

Phosphate precipitation must have occurred during the formation of the limestone member. At this time, however, phosphate precipitation may have been swamped by other carbonate precipitation. The highest concentration of phosphate would probably be found in the sandstone and pebbly sandstone beds above the limestone; at this horizon pellets and concretions (which may have been formed from phosphate precipitated during formation of the limestone) would have been concentrated by current action and winnowing into lag deposits. The top of the upper cycle seems perhaps more favourable than that of the lower cycle, because of its association with chert in some beds (cf. Phosphoria), and because of the volcanic activity, during which time (according to some authors) more fluorite would have been available for "fixing" the phosphate.

1. b. Flat Top Formation

The lithology of the Flat Top Formation has been previously described; due to the difficulty of correlating sections in different areas, a composite lithological section has not been made.

The Flat Top Formation is similar in lithology to the Barfield Formation. Coal seams and fossilised wood impressions indicate a southern shore, and siltstone, sandstone, calcilutite and coquinite suggest shallower levels, in which factors controlling phosphate distribution should be the same as in similar lithologies of the Barfield Formation. However, primary chert (in the form of organic spicules) in the northern outcrops suggests a preponderance of organic matter which would have assimilated available phosphate, inhibiting its sedimentation. Carbonate sedimentation is more prevalent here than in the Barfield Formation, and precipitated phosphate would be expected to be diluted by other carbonate precipitation. Sandstone interbeds, which indicate currents which could concentrate pelletal phosphate, are few. At about this time, on the other side of the basin (to the west in the Lower Bandanna Formation), currents carrying phosphate-rich waters from the deeper parts of the basin were depleted of phosphate by plankton and precipitation, and may have returned along the surface to the eastern side of the basin (Flat Top Formation) barren of phosphate. Despite these reservations however, the possibility of phosphorite in the Flat Top should not be overlooked.

1. c. Back Creek Group

The only phosphate found by B.M.R. parties in the eastern area up to the time of writing is the sample containing 27% P_2O_5 from the Back Creek Group. This is thought to be from a horizon equivalent to the Barfield Formation, which has been shown to have a high phosphate potential. Phosphorite in the Back Creek Group would be more likely to occur in the shallow, near-shore facies of shale, subgreywacke and minor conglomerate than in the thick flysch-type facies farther to the north and north-east.

2. Cattle Creek Formation

The lithology of the Cattle Creek Formation has been previously described, and columnar sections are shown in Figs.5 and 9.

(1) Chemical precipitation:- Calcareous horizons with concretions occur in the interval 0-130 ft. in Fig.9, with coquinitic zones at the very base of the measured section. There is a minor calcareous bed at about 240 ft., which is underlain by sandy siltstone with calcareous concretions. Gypsum and jarosite indicate evaporitic sedimentation in a restricted environment.

(2) Submarine topography:- the loose cobbles, pebbles and erratic boulders, coupled with seismic evidence and thickness variations,

show a nearby fault zone probably expressed as a slope. Generally, the lithology shows an upward transition from finer calcareous sediment to coarser non-calcareous sediment. This reflects increase of supply of sediment by currents, possibly caused by shallowing and the gradual extension of a marginal environment. It is similar to the cycle of sediments in the Barfield Formation, though in general the sediments are coarser.

(3) Adsorbing and localising sediments:- Fine clayey siltstone occurs in the lower two thirds of the measured section (Fig.9), and sandy siltstone occurs in the upper third.

(4) Little concurrent sedimentation:- Terrigenous sedimentation is coarser in the upper third of the measured section (Fig.9). The multi-sized erratics of the lower 150 ft. are thought to be due to the adjacent, fault-controlled cliff - or slope - line, and are alien to the normal, rather weak sedimentation of this part of the section.

Conclusions

The horizon at which phosphorite is expected to be most concentrated would be 0-130 ft. in the measured section (Fig.9). A sample of sandstone containing 12% P_2O_5 was collected from this horizon. Here the influence of the fault was greatest, as was carbonate precipitation, which may have been caused by the flow of water over the fault-induced slope. Precipitated phosphate at this time could have been trapped by adsorption into the finer sediments and later concentrated by concretion and pellet formation. These concretions or pellets would have been further concentrated by currents which deposited interbeds of coarser sediment; there is little evidence of such interbeds below 210 ft., above which the coarser sediment becomes predominant to an extent which would probably dilute any phosphatic content to very low proportions. in the bore at Reid's Dome, the Cattle Creek Formation below the exposed section of Fig.9 consists of sediments similar to the lower 100 ft. of the exposed section, and has therefore a high phosphate potential.

3. Mantuan Productus Bed (Figs.5, 11, 13, 14 and 15)

The lithology of the Mantuan Productus Bed has been described previously. This very fossiliferous horizon and the 100 ft. of sediments below it contain calcareous and glauconitic sandstones, fine clay beds, siltstone, scattered unsorted pebbles, calcareous and clay concretions, gypsum and jarosite; these characteristics all indicate an evaporitic, shallow environment, with available nutrients being chemically concentrated, precipitated and trapped into sediment and organic material. It is probable that sandstone interbeds in siltstone (current-derived) would contain the highest concentration of pelletal phosphate.

4. Buffel Formation

The lithology of the Buffel Formation (page 6) is similar in some aspects to the limestone-chert facies of the phosphoria Formation. Reasons for its being suitable for phosphorite formation have already been discussed, but other direct lithological evidence is lacking; it may be that the critical part of the sedimentary cycle - that which follows a period of biochemical sedimentation - has been eroded away. However, towards the eastern margin of the Basin, a lithology may be found which is more conducive to phosphorite deposition than that of the 'normal' Buffel Formation, in which phosphate would probably have been contributed to the ocean rather than deposited.

5. Ingelara Formation

The formation (Figs.5, 10, 11, and 12) contains in its lower half sandstone/sandstone/shale alternations; in its upper half gypsiferous shales with calcareous concretions. For reasons discussed previously, either lithology could indicate a phosphorite environment.

6. Sirius and Stanleigh Formations (Figs.5, 6, 7 and 8)

Again, sandy interbeds in shale or siltstone, common in both formations, are the most promising horizons, as are concretionary beds (cf. Cattle Creek Formation).

C. CONCLUSIONS

The information on which this report is based was collected in the course of geological mapping of large areas, and any direct evidence related to phosphate occurrence is more the result of accidents of sampling than of a directed systematic search for phosphate. In these circumstances the conclusions of this report must be based on general principles of sedimentation and oceanography applied to the history of the basin, as far as the present state of knowledge allows. In view of this, the reasoning behind many aspects of this appraisal must be highly speculative, and this should not be regarded as more than an interim report.

With this proviso, primary goals for further investigation in the Bowen Basin should be the six groups which have been selected, viz. (in order of importance)

(1) Barfield and Flat Top Formations, and equivalent formations in the Back Creek Group.

(2) Cattle Creek Formation

(3) Mantuan Productus Bed

(4) Buffel Formation

(5) Ingelara Formation

(6) Sirius and Stanleigh Formations

It should be remembered that the possibility of phosphorite occurence in any of the other marine formations of the Bowen Basin has not been disproved.

SUGGESTIONS FOR FURTHER INVESTIGATION

1. Additional information should be acquired from existing sources: available cuttings and cores from shallow and deep bores through the Middle Bowen Beds should be examined for phosphate content. Radiometric logs of boreholes should be examined for possible indications of phosphatic beds.

2. Field traverses, should be made across selected exposures of the Middle Bowen Beds, and samples collected at set intervals for quantitative P_2O_5 analysis, in order to test the conclusions of this report, and to determine promising horizons. Field tests by scintillometer should be included to determine the relationship between radioactivity and phosphatic beds.

3. If promising high-grade horizons are found, laboratory tests should be made to determine further the relationship (if any)

between radioactive minerals and phosphate.

4. If any high-grade phosphate accumulation is found in the sequence, detailed investigations by mapping, shallow drilling, and possibly radiometric survey should be programmed to seek near-surface occurrence of the favourable horizon.

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APPENDIX I

B.M.R. PHOSPHATE ANALYSES

A. Analyses of samples from black shale samples from Baralaba area:

Field No.	Percent P_2O_5
BA 898	less than 1.0
BA 858/3	less than 1.0
BA 750	less than 1.0
BA 914	less than 1.0
BA 889	less than 1.0
BA 888 (nodule) Back Creek Group	27.0

Serial No.1384, 1385.

B. Analyses of samples submitted by J.M. Dickins.

Field No.	Formation	Percent P_2O_5
Z46	Cattle Creek	6.0
Z66	Ingelara	0.3
CL122	Clermont map:basal Unit C	2.3
B270a	Bowen area: Unit C above base	0.25
M414	Mackay area: Upper Unit A	0.45
SL603	St. Lawrence: Unit A	1.6
MC802Z	Mt. Coolon	0.55
MC1065	Unit A	2.9
MC957a	Unit C. Big Strophalosia Zone	0.20

C. Analysis of sample from Reid's Dome, submitted by A. Fehr.

AF49	Cattle Creek	12.0

D. Analysis of samples from Mundubbera area.

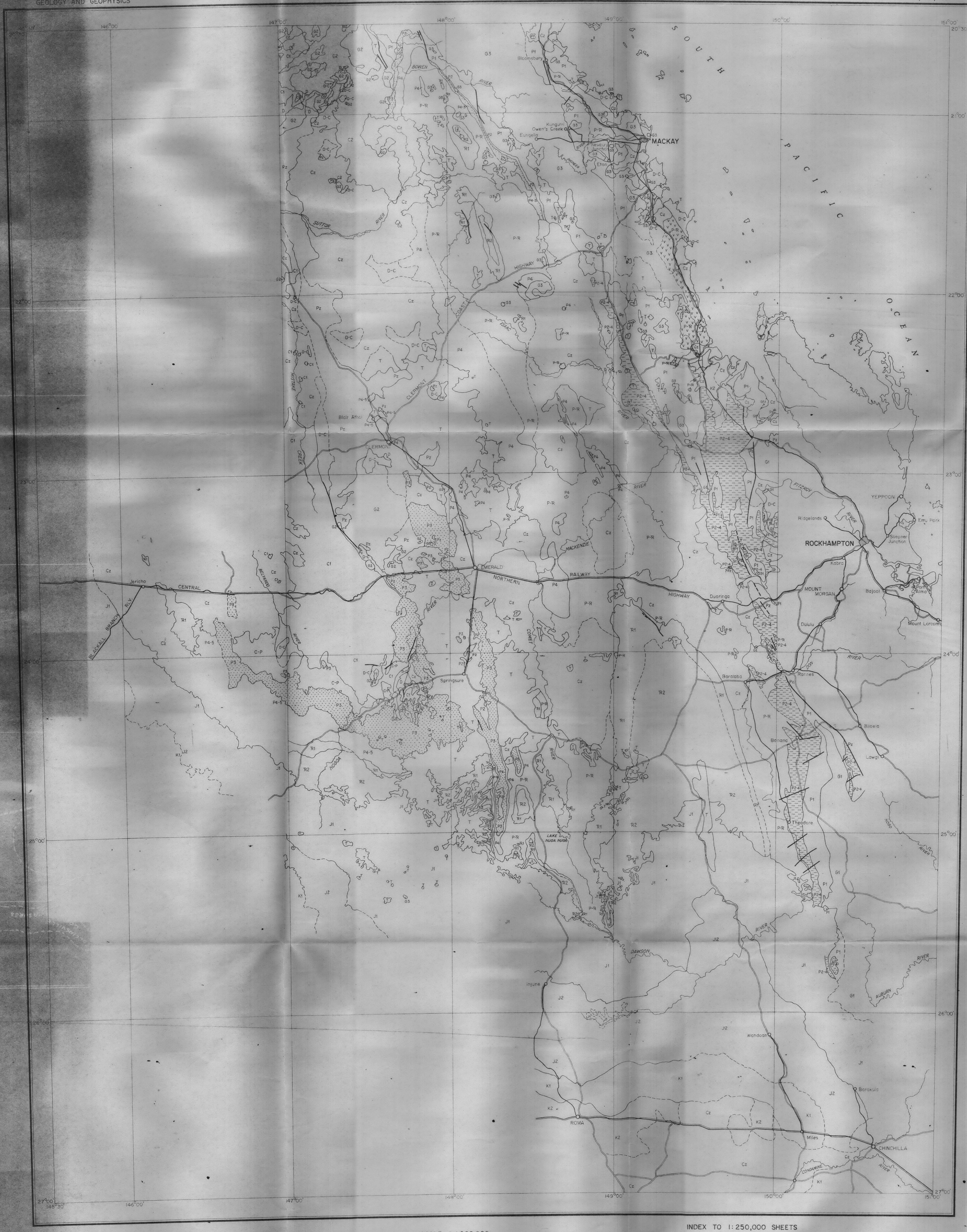
A4(BMR Bore 30, 80-82')	Barfield	0.4
A5(BMR Bore 31, 80-85')	Barfield	0.3
T155(25°14', 150°14')	Barfield	1.0

Plate 1

BUREAU OF MINERAL RESOURCES
GEOLOGY AND GEOPHYSICS

BOWEN BASIN
QUEENSLAND

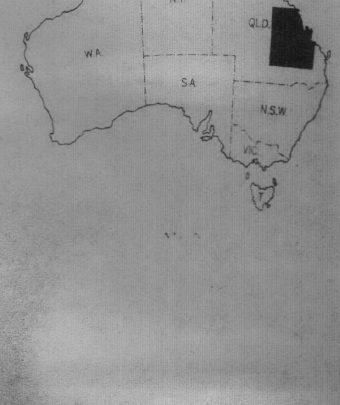
AUSTRALIA 1:1,000,000



SCALE 1:1,000,000

MILES 10 0 10 20 30 40 50 MILES

KILOMETRES 10 0 10 20 30 40 50 KILOMETRES



INDEX TO 1:250,000 SHEETS

CHARTERS TOWERS	BOWEN	PROSERPINE	
BUCHANAN	MT. COOLON	MACKAY	
GALILEE	CLERMONT	ST. LAWRENCE	PORT CLINTON
JERICHO	EMERALD	DUARINGA	ROCKHAMPTON
TAMBO	SPRINGSURE	BARALABA	MONTO
AUGATHELLA	EDDYSTONE	TAROOM	MUNDUBBERA
CHARLEVILLE	MITCHELL	ROMA	CHINCHILLA

REFERENCE

Rock units of approximately similar age are grouped for convenience. The units grouped do not represent stratigraphic successions nor are they necessarily time equivalents. Some of the rock unit names are synonyms.

CAINOZOIC	Cz	Undifferentiated.
TERTIARY	T	Basalt and other volcanics.
CRETACEOUS	K2	Roma Fn., Tambo Fn. Styx Coal Measures.
JURASSIC to LOWER CRETACEOUS	K1	Blythesdale Group.
JURASSIC	J2	Walloon Coal Measures.
	J1	Marburg Sandstone. Bundamba Group.
TRIASSIC	R2	Moolayember Formation. Teviot Formation.
	R1	Clematis Sandstone. Carborough Sandstone.
MESOZOIC or PERMIAN	P-R	Carmila Volcanics (mainly Permian). Unnamed volcanics (south-east of Duaringa).
UPPER PERMIAN - TRIASSIC	P-R	Rewan Formation. Upper Bowen Coal Measures. Taurus Formation. Upper Bandanna Formation. Theodore Group. Kianga Formation. Calen Beds.
PERMIAN	P4-5	Middle Bowen Beds, (probably Unit "C") with some Upper Bowen Beds (P-R) included. Colinlea Formation (top part). Cheshire Beds. ? Blair Athol Coal Measures.
	P4	Middle Bowen Beds, Unit C. "Passage Beds" (north of Clermont). Crocker Formation. Maria Formation. Lower Bandanna Formation. Mantuan Productus Bed. Big Strophalosia Zone. Dry Creek Shale.
	P3	Middle Bowen Beds, Unit B. Collinsville Coal Measures. Colinlea Formation, main part (may also be equivalent to lower rock units). Catherine Sandstone. Ingelara Shale. Aldebaran Sandstone.
	P2	Middle Bowen Beds, Unit A. Cattle Creek Shale. Staircase Sandstone, Sirius Shale. Orion Shale, Stanleigh Shale. Dilly Beds.
	P2-4	Middle Bowen Beds, Units A, B, and C undifferentiated. Apis Creek Formation. Back Creek Group. Prospect Creek Series. Cockatoo Creek Formation. Yatton Limestone.
	P1	Lower Bowen Volcanics. Camboon Andesite. Cracow Volcanics (?). Rookwood Volcanics. Dinner Creek Beds (may be in part Carboniferous).
CARBONIFEROUS to PERMIAN	C-P	Joe Joe Creek Formation.
CARBONIFEROUS	C2	Bulgonunna Volcanics.
LOWER to MIDDLE CARBONIFEROUS	C1	Ducabrook Formation. Raymond Sandstone. Mt. Hall Conglomerate. Undifferentiated sediments (north east of Duaringa).
DEVONIAN - CARBONIFEROUS	D-C	Campwyn Beds. Telemon Formation. Silver Hills Volcanics. Theresa Creek Volcanics. Mt. Wyatt Beds. Undifferentiated volcanics.
DEVONIAN	D	Dunstable Formation. Douglas Creek Limestone. Ukalunda Beds. Undifferentiated sediments.
SILURIAN - DEVONIAN	S-D	Undifferentiated sediments north-east and south-east of Duaringa.
PALAEOZOIC	Pz	Rannes Beds. Anakie Metamorphics (may include some Ukalunda Beds). Undifferentiated metamorphics in Marlborough area.
IGNEOUS INTRUSIVES		
POST-PERMIAN	G3	Urannah Complex (includes some pre-Permian intrusives). Gotthardt Granodiorite. Mt. Barker Granodiorite. Bundara Granodiorite. Undifferentiated intrusives. Serpentine (Chesterton Range).
PRE-PERMIAN	G2	Retreat Granite. Undifferentiated intrusives.
AGE UNKNOWN	G1	Auburn Complex. Undifferentiated intrusives.

Geological boundary — Road
Probable geological boundary — Railway Line
Fault
Probable Fault

This map has been compiled by B. TISSOT (Institut Français du Pétrole) from the following existing data:

Provisional geological maps at 1:250,000 scale (unpublished) prepared by the Bureau of Mineral Resources, Geology and Geophysics, in association with the Geological Survey of Queensland: Bowen, Proserpine, Mount Coolon, Mackay, Clermont, Saint Lawrence, Emerald, Duaringa.

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Drawn by G.J. Verburg
December, 1962.

IFP-AUS 359

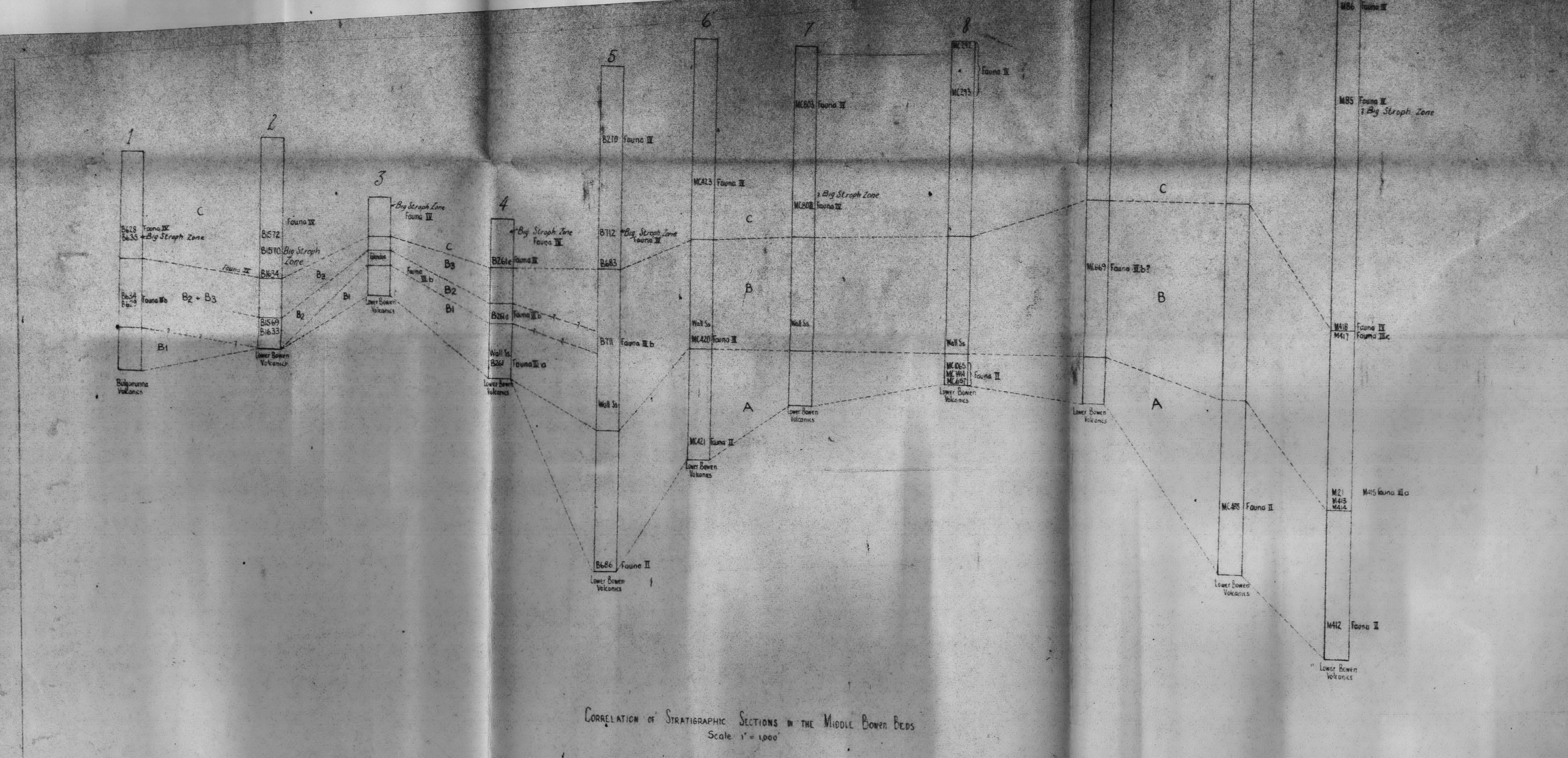
To accompany Record No: 1965/57

NORTH-EAST BOWEN BASIN

OUTCROP AREA OF MIDDLE BOWEN BEDS

Plate 2

LOCALITY DIAGRAM



CORRELATION OF STRATIGRAPHIC SECTIONS IN THE MIDDLE BOWEN BEDS

Scale 1" = 1000'

Bureau of Mineral Resources, Geology & Geophysics, April 1962

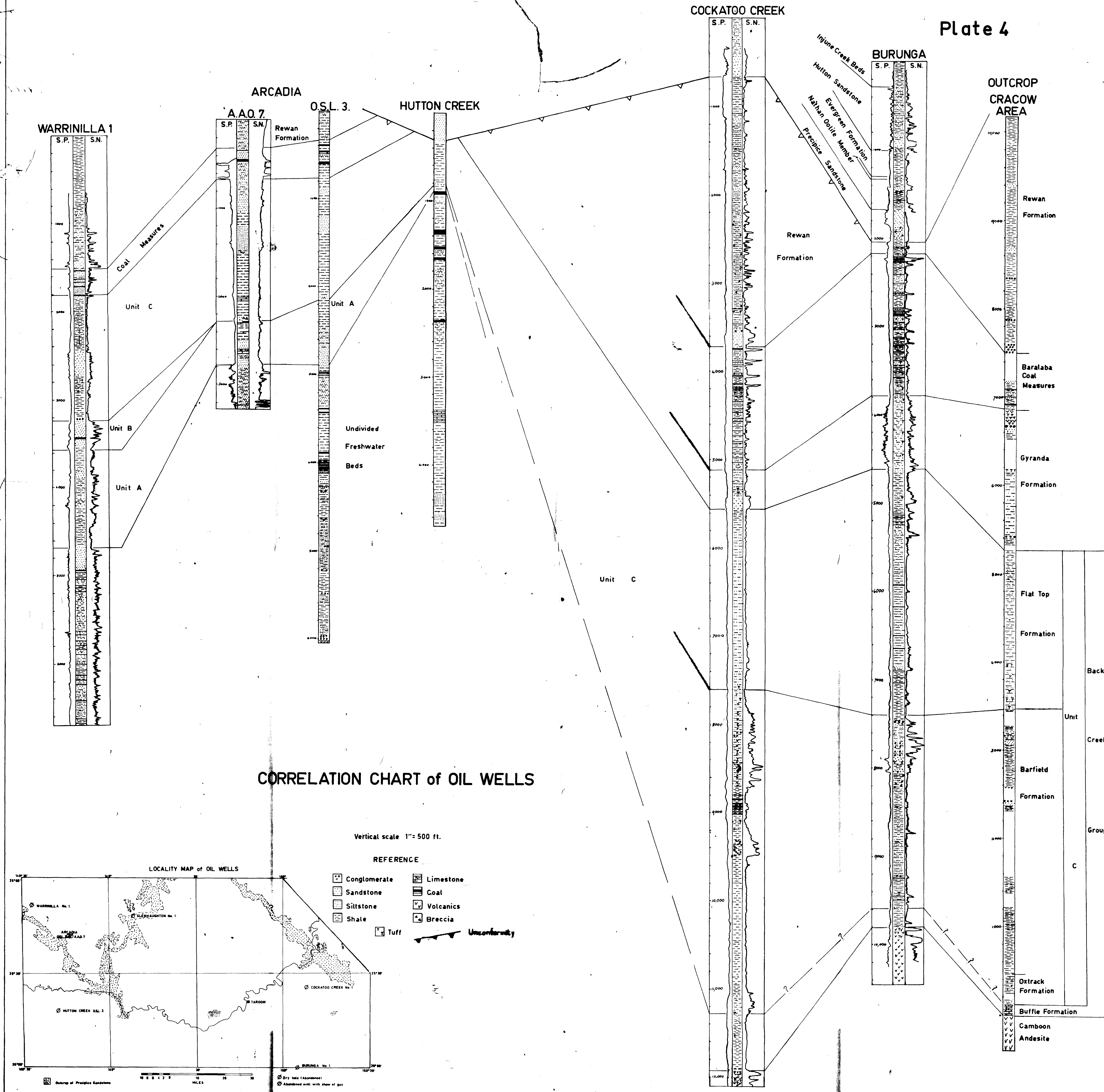
To accompany Record No: 1965/157

Plate 3

WELL CORRELATION CHART
VERTICAL SCALE 1" = 500'
Correlations based on outcrop mapping in the Springsure Anticline and Reid's Dome, oil company data Tissot (1961, 1963) and discussions with J.M. Dickins, P.R. Evans, and E.J. Malone.
A.O.E. No.1 (REID'S DOME)
A.O.E. No.3 (CONSUELO)
A.F.O. INDERI No.1
A.F.O. PURBROOK No.1
Planet WARRINILLA NORTH No.1
Planet WARRINILLA No.1
S.Q.D. MORELLA No.1
A.F.O. BANDANNA No.1
Aldebaran Sandstone
Sirius Formation
Staircase Sandstone
Stanleigh Formation
UNIT A (Cattle Creek Formation)
UNIT B (Aldebaran Sandstone + ? Ingelara Formation + ? Catherine Sandstone)
UNIT C Peawaddy Formation + ? Mantuan Productus Bed
Bandanna Formation (upper part)
Bandanna Formation (lower part)
? Rewan Formation
Rewan Formation
Peawaddy Formation
Ingelara Formation
Catherine Sandstone
Mantuan Productus Bed
Cong omerate (? Age, formation)
4755' ? Upper Devonian T.D. 4949'
'Undivided freshwater beds'
'Lower shales and mudstones'
Peawaddy Formation + ? Mantuan Productus Bed
UNIT B (Aldebaran Sandstone + ? Ingelara Formation)
UNIT A (Cattle Creek Formation)
Volcanics (? basement)
T.D. 9060'
T.D. 4437'
T.D. 5433'
T.D. 4040'
T.D. 4634'
T.D. 6701'
T.D. 6879'
LITHOLOGICAL REFERENCE
Shale and claystone
Siltstone
Sandstone
Conglomerate
Limestone
Coal
Marl
Anhydrite
Igneous rocks
Gas Show
Oil Show
Electric logs shown; S.P. log on left S.N. log on right
LOCATION OF WELLS
Inderi 1
Consuelo 3
Purbrook 1
Reid's Dome 1
Warrinilla North 1
SPRINGSURE
EDDYSTONE
Morella 1
BARALABA
TAROOM
Bandanna 1
Warrinilla 1
24°
25°
148°
149°
Bureau of Mineral Resources, Geology and Geophysics, April 1964
To accompany Record 1965/57

Q-A58

Plate 4



CORRELATION CHART of OIL WELLS

To accompany Record No. 1965/67 Bureau of Mineral Resources, Geology and Geophysics. April, 1964.

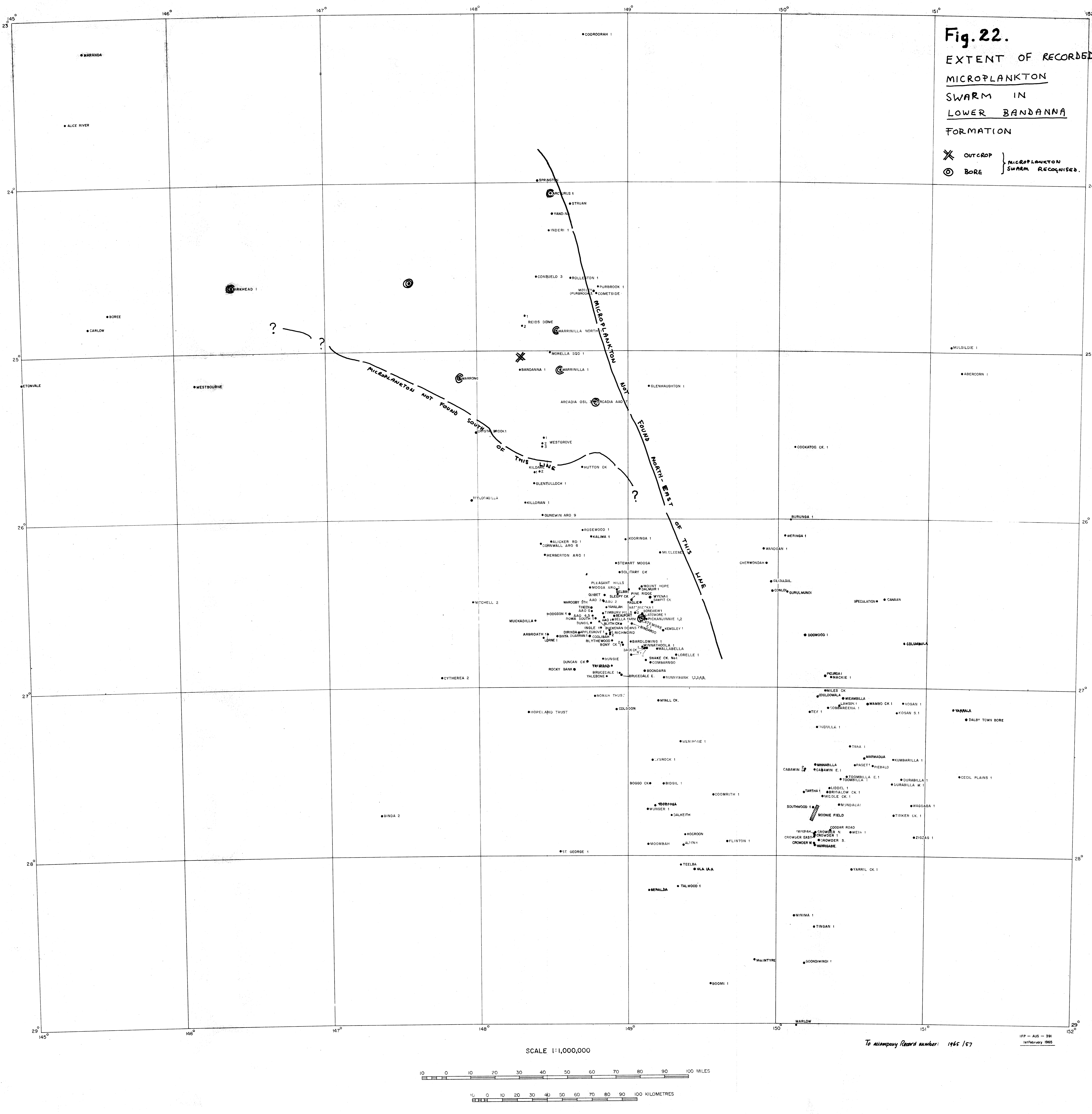


Fig. 22.
EXTENT OF RECORDED MICROPLANKTON SWARM IN LOWER BANDANNA FORMATION
OUTCROP
BORE
MICROPLANKTON SWARM RECOGNISED.
MICROPLANKTON NOT FOUND NORTH-EAST OF THIS LINE
MICROPLANKTON NOT FOUND SOUTH OF THIS LINE
?
145°
146°
147°
148°
149°
150°
151°
152°
23°
24°
25°
26°
27°
28°
29°
MARANDA
ALICE RIVER
BIRKHEAD 1
BOREE
CARLOW
ETONVALE
WESTBOURNE
COORDORAH 1
SPRINGTON
ARCTURUS 1
STRUAN
YANDINA
INDERI 1
CONSUELO 3
ROLLESTON 1
PURBROOK 1
COMETSIDE
REIDS DOME
WARRINILLA NORTH 1
MORELLA SQD 1
BANDANNA 1
WARRINILLA 1
WARRONG
GLENHAUGHTON 1
ARCADIA OSL 1
ARCADIA AAO 1
WESTGROVE
KILDARE
HUTTON CK
GLENTULLOCH 1
KILLORAN 1
GUNEWIN ARO 9
COCKATOO CK. 1
BURUNGA 1
ROSEWOOD 1
KALIMA 1
KOORINGA 1
CORNWALL ARO 6
HERBERTON ARO 1
STEWART MOOGA
SOLITARY CK
WANDOAN 1
CHERWONDAH
MITCHELL 2
MUCKADILLA
ARBROATH 1
PICKANJINNIE 1,2
BONY CK
WALLABELLA
LORELLE 1
SNAKE CK. No1
COMBARNGO
DUNCAN CK
ROCKY BANK
BOONDARA
SPECULATION
CANAAN
DOGWOOD 1
COLUMBOOLA
CYTHEREA 2
MYALL CK.
COLGOON
HOPELAND TRUST
PICURDA 1
MACKIE 1
MILES CK
WAMBO CK 1
KOGAN 1
YARRALA
DALBY TOWN BORE
TARA 1
MARMADUA
KUMBARILLA 1
CABAWIN E. 1
TOOMBILLA E. 1
DURABILLA 1
CECIL PLAINS 1
SOUTHWOOD 1
MOONIE FIELD
WAGGABA 1
TINKER CK. 1
BIDGIL 1
BOGGO CK
COOMRITH 1
DALKEITH
BINDA 2
ST. GEORGE 1
MOOMBAH
FLINTON 1
ZIGZAG 1
YARRIL CK. 1
TEELBA
TALWOOD 1
GERALDA
MINIMA 1
TINGAN 1
MacINTYRE
GOONDIWINDI 1
BOOMI 1
MARLOW
MULGILDIE 1
ABERCORN 1
SCALE 1:1,000,000
10 0 10 20 30 40 50 60 70 80 90 100 MILES
10 0 10 20 30 40 50 60 70 80 90 100 KILOMETRES
To accompany Record number: 1965/57
IFP — AUS — 391
1st February 1965