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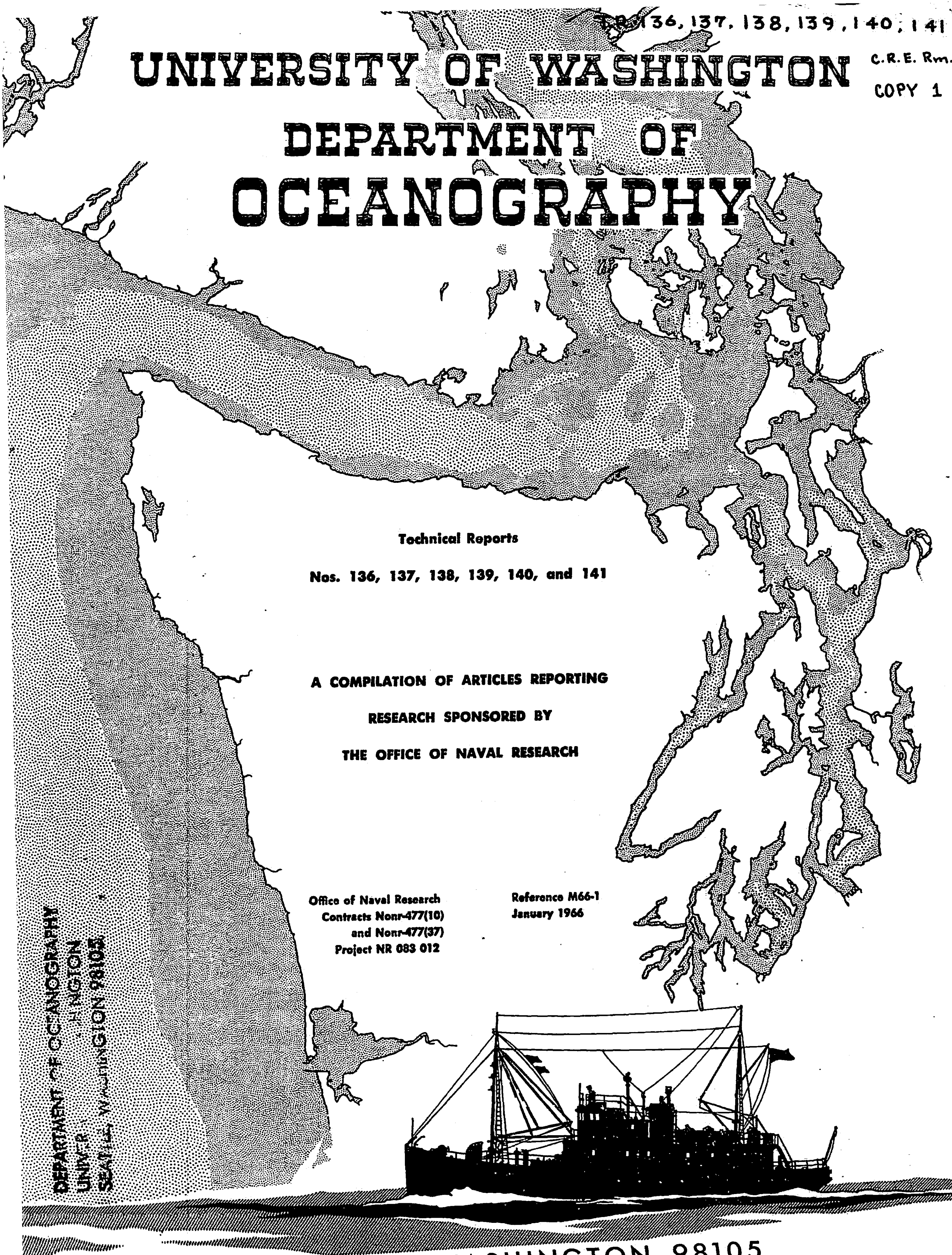

Technical Reports

Nos. 136, 137, 138, 139, 140, and 141

A COMPILATION OF ARTICLES REPORTING RESEARCH SPONSORED BY THE OFFICE OF NAVAL RESEARCH

Office of Naval Research
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January 1966

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RICHARD H. FLEMING
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ARTICLES REPORTING RESEARCH SPONSORED BY THE OFFICE OF NAVAL RESEARCH

Technical Report No. 136

ON THE VERTICAL DISTRIBUTION OF ZOOPLANKTON IN THE SEA, by K. Banse. Pp. 55-125 in Progress in Oceanography, vol. II (Mary Sears, ed.). Pergamon Press, London. 1964.

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SYNONYMS OF PROTODORVILLEA EGENA (EHLERS) (EUNICIDAE, POLYCHAETA), by K. Banse and G. Hartmann-Schröder. Proceedings of the Biological Society of Washington, 77:241-242. 30 December 1964.

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THE INFLUENCE OF VARIABLE DEPTH ON STEADY ZONAL BAROTROPIC FLOW, by Gene H. Porter and Maurice Rattray, Jr. Deutsche Hydrographische Zeitschrift, 17(4):164-174. 1964.

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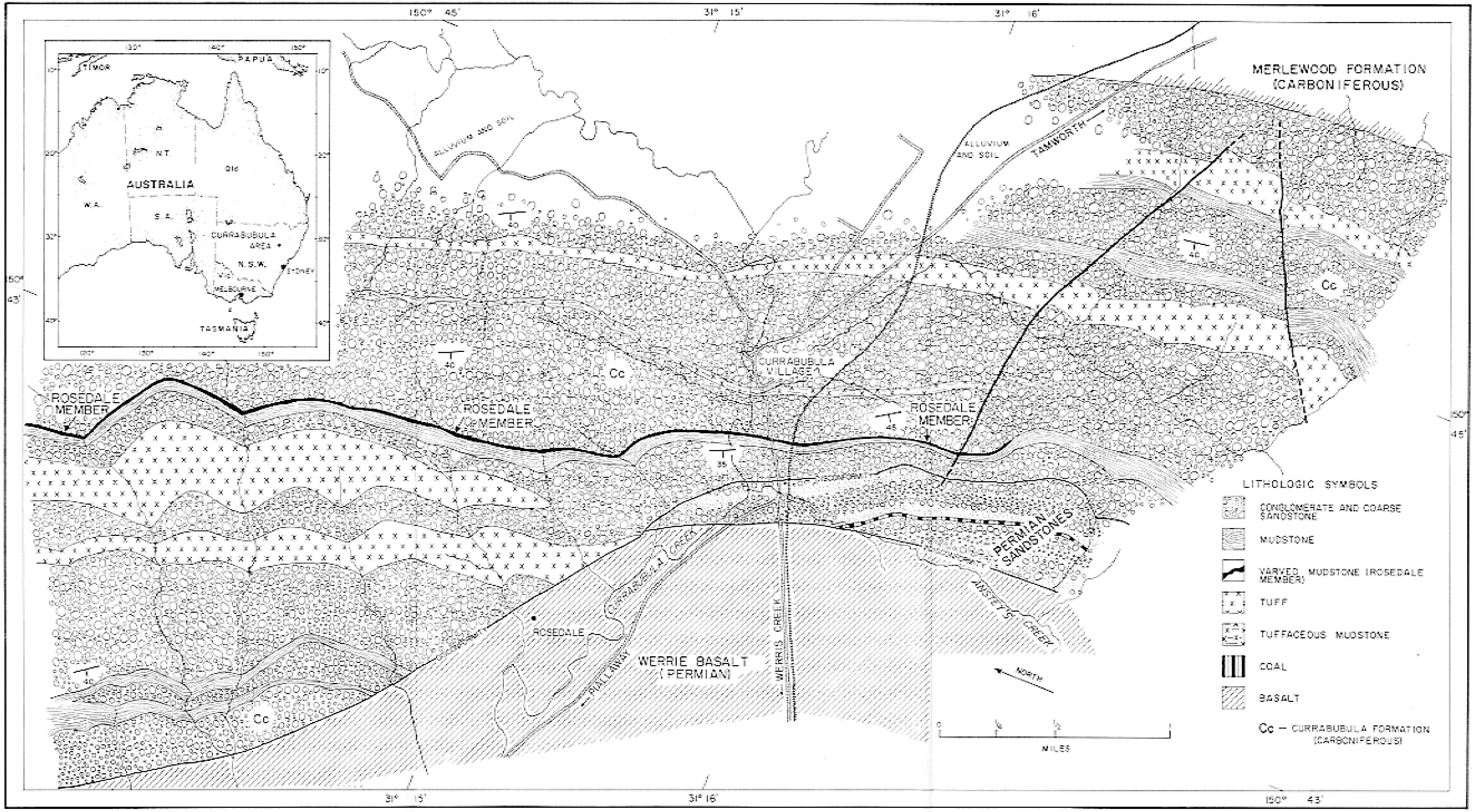
THE MESOPELAGIC CARIDEAN SHRIMP NOTOSTOMUS JAPONICUS BATE IN THE NORTH-EASTERN PACIFIC, by Belle A. Stevens and Fenner A. Chace, Jr. Crustaceana, 8(pt. 3):277-284. 1965.

Technical Report No. 140

CARBONIFEROUS GLACIAL ROCKS FROM THE WERRIE BASIN, NEW SOUTH WALES, AUSTRALIA, by John T. Whetten. Geological Society of America Bulletin, 76:43-56. January 1965.

Technical Report No. 141

THE ORIGIN OF MANGANESE NODULES ON THE OCEAN FLOOR, by Enrico Bonatti and Y. Rammohanroy Nayudu. American Journal of Science, 263:17-39. January 1965.



GEOLOGIC MAP OF THE CURRABUBULA AREA, NEW SOUTH WALES, AUSTRALIA

Sequence is dipping westward, on the east flank of the Werrie Basin. Currabubula Formation is overlain by Permian rocks (stratigraphically above disconformity) and underlain by the Merlewood Formation. Sills and dikes are numerous throughout the area but are not shown. Minor clastic and pyroclastic units have been omitted. Area varies in elevation from 1500–2600 feet above sea level.

WHETTEN, PLATE 1
Geological Society of America Bulletin, volume 76

JOHN T. WHETTEN *Dept. Oceanography, University of Washington, Seattle, Wash.*

Carboniferous Glacial Rocks From the Werrie Basin, New South Wales, Australia

Abstract: Glacial and probably fluvioglacial rocks are present in the Currabubula Formation, an 8500-foot unit of Carboniferous age (Westphalian) exposed in the Werrie Basin of the New England geosyncline, New South Wales, Australia. Approximately 70 per cent of the formation is conglomerate and coarse conglomeratic sandstone, approximately 10 per cent is mudstone and fine sandstone, and approximately 20 per cent is tuff. The Rosedale Member, about 60 feet thick at the type locality, occurs in the middle of the Currabubula Formation and consists largely of varved mudstone with abundant ice-rafted pebbles. The best evidence for Carboniferous glaciation in eastern Australia is from the Rosedale Member and similar units exposed in other areas of northeastern New South Wales.

The most common rock types in the Currabubula Formation are poorly sorted pebble conglomerates and lithic wackes composed largely of mineral grains and lithic fragments from flows and tuffs. Nearly all such rocks are stratified to some degree, and were probably deposited by streams, perhaps as glacial outwash. Rhyolitic and andesitic tuffs were deposited subaerially, in shallow lakes, and as ignimbrites.

The Currabubula Formation was probably deposited near a mountain range undergoing glaciation. Much of the clastic material is volcanic, and includes pyroclastic fragments similar in composition to the contemporaneously deposited tuffs. This suggests that the clastic sediments were locally derived, and supports the idea that glaciation was restricted to the alpine variety. It is not necessary to infer either widespread Carboniferous climatic cooling or a relationship with the more widely occurring Permian glacial rocks in other parts of Australia.

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INTRODUCTION

In 1914, while attending a field excursion of the British Association for the Advancement of Science, Professor T. W. E. David discovered a tillite of Carboniferous age at Seaham (Fig. 1), in the Hunter River Valley of New South Wales (Fairbridge, 1947). At the time of David's discovery, ancient glacial deposits had been found at many localities in other parts of Australia. The first evidence of glaciation, a magnificent striated glacial pavement (Selwyn's

Geological Society of America Bulletin, v. 76, p. 43–56, 3 figs., 3 pls., January 1965

Rock), was found by Selwyn (1859) in South Australia, and shortly thereafter, glacially grooved pebbles were reported by Daintree (quoted by David, 1896) from Bacchus Marsh, Victoria. Oldham (David, 1896) suggested a Permian age for these and other Australian glacial beds. In the years following, ancient glacial deposits were found in every state in Australia. David's Seaham discovery was thus accepted with little question, even though the Seaham rocks contained a *Rhacopteris* flora, characteristic of the Carboniferous, and were thus older than the previously reported Permian glacial deposits.

Sussmilch and David (1920) briefly described the glacial rocks at David's Seaham locality, and named the sequence of strata in which they occur the Kuttung Series, after an aboriginal tribe which once inhabited the area. Osborne mapped the distribution of Kuttung and other rocks in the Hunter Valley, and with Browne (Osborne and Browne, 1921), reported a striated pavement near Seaham. Caldenius (1938) measured varves near Seaham, and Fairbridge (1947) studied intraformational structures in the varves, concluding that they were caused by slumping and not by iceberg grounding, the then popular view.

Stimulated by David's discovery, others soon discovered glacial rocks in the Kuttung Series in other areas of eastern New South Wales. Eventually, glacial material was reported in discontinuous outcrops extending 250 miles from near Bingara to the coast near Newcastle (Fig. 1). Particularly fine examples of tillites and varves were found by Carey (1937) near Currabubula (Fig. 1) in the Werrie Basin.

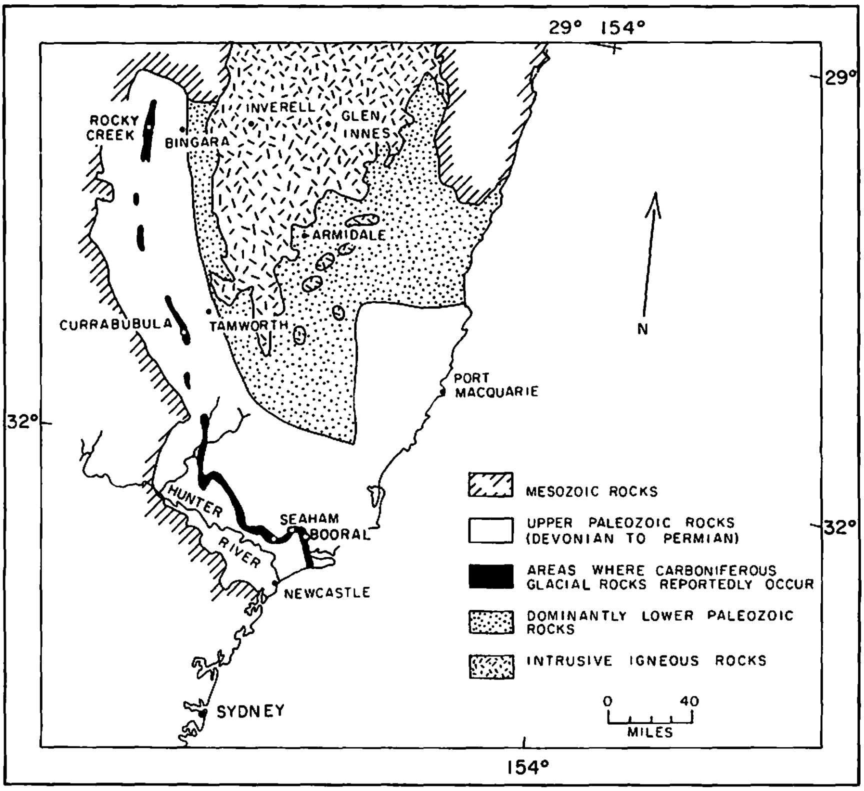

Figure 1. Geologic sketch map of northeastern New South Wales, Australia. Area shown is included in the New England geosyncline (*after* Voisey, 1959b; David, 1950).

In recent years, ancient glacial deposits the world over have been re-examined and, in many cases, re-evaluated. Dott (1961) has interpreted the Squantum tillite of eastern Massachusetts to be a turbidity current and submarine slump deposit, and tillites in the West Congo geosyncline have been attributed to a similar origin by Schermerhorn and Stanton (1963). Newell (1957) has disproved Permian tillites in northern Mexico, and the Ridgeway and Gunnison tillites of southwestern Colorado have been discredited by Van Houten (1957). Coombs (1958) studied samples of Australian Kuttung "varves" from Seaham and found they were composed almost entirely of zeolitized volcanic vitric ash. He remarks that subaqueously deposited fine ash could produce the delicate varvelike laminae of his samples, and that in this instance a glacial origin is not essential. However, Coombs states (1958, p. 19), ". . . it is not intended to imply that all the varves in the Seaham area are tuffs."

Dott (1961) emphasizes the difficulty in interpreting glacial-like deposits, and suggests that all such deposits from orogenic areas (including the Kuttung rocks of eastern Australia) be re-examined from the standpoint that they may result from subaqueous gravity slides.

The far-reaching implications of Carboniferous glaciation in eastern Australia have been used as evidence in arguments for Gondwanaland, cold climate, continental drift, and polar migration. Yet the deposits have not been examined or described in any detail. The purpose of the present study is to describe the sedimentology and sedimentary petrology from a small area where glacial rocks of the Kuttung Series have been reported (Carey, 1937) on the east flank of the Werrie Basin around the village of Currabubula[1], approximately 280 miles north of Sydney.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the assistance and helpful comments of Profs. A. H. Voisey and J. F. G. Wilkinson and Dr. B. C. McKelvey throughout the course of this project. Thanks are also due to Drs. B. J. Enbysk and M. G. Gross for reviewing and criticizing the manuscript. Field work was completed during the term of the author's Fulbright Grant at the University of New England, Armidale, New South Wales. Mr. and Mrs. R. L. Busby kindly provided housing and generous assistance at Currabubula. Laboratory work at the University of Washington was supported by Contract Nonr-477(10) Project NR 083 012 and Contract Nonr-477(37) Project RR 004-03-01, Office of Naval Research. James Becker drafted the illustrations.

REGIONAL SETTING

Carboniferous sedimentary rocks in eastern Australia are exposed only in northeastern New South Wales and eastern Queensland. The Queensland deposits consist of the Neerkol (Lower Carboniferous) and Rockhampton (Upper Carboniferous) Formations, marine rocks on the order of 14,000-feet thick, and scattered thin terrestrial beds (David, 1950, p. 287). In New South Wales, the Carboniferous rocks were deposited in the New England geosyncline, a "typical eugeosyncline" (Voisey, 1959a), where sediments from Lower Silurian to Upper Permian are exposed. The total thickness of the Carboniferous deposits in the Hunter Valley and in the Werrie Basin of New South Wales is said to be 14,000 feet (Voisey, 1952; Carey, 1934).

Glacial rocks are reported only in the upper part of the Kuttung sequence. These have been referred to as the Glacial Stage (Osborne, 1922), and Upper Kuttung Series (Carey, 1937). However, Voisey and Williams (1964) renamed the glacial sequence in and near the Werrie Basin the Currabubula Formation. Below the Currabubula Formation is a unit of tuffs and conglomerates approximately 5000 feet thick called the Merlewood Formation (Voisey and Williams, 1964), formerly the Upper Kuttung Series (Carey, 1937), that is equivalent to Osborne's (1922) Volcanic and Basal stages. This unit is mostly terrestrial, but is partly marine. The Namoi Formation (Voisey and Williams, 1964), consisting of approximately 2100 feet of marine mudstones and limestones, underlies the Merlewood Formation and overlies the Tulcumba sandstone which is considered to be well above the base of the Carboniferous in New South Wales (A. H. Voisey, personal communication, 1964). Eastward, near the coast, the Kuttung Group becomes largely marine, and has been named the Kullatine Series (Voisey, 1934). Permian rocks (paralic sandstones and mudstones with coal beds and basalts) overlie the Currabubula and equivalent formations. The most complete Permian section is in the Hunter Valley, where more than 17,000 feet is exposed (David, 1950).

CURRABUBULA FORMATION

Introductory Statement

The Currabubula Formation, a unit of conglomerates, tuffs, and mudstones, is exposed almost continuously for more than 75 miles

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[1] Pronounced Curra-BUB-you-la.

along the perimeter of the Werrie Basin, a faulted syncline mapped and described by Carey (1934; 1935; 1937) in the "Western Belt of Folds and Thrusts" (Voisey, 1959b) of the New England geosyncline. A generalized geologic map of a small area on the eastern flank of the basin (Pl. 1) shows the principal rock units which will be discussed further on. The observations and interpretations that follow are from this area only.

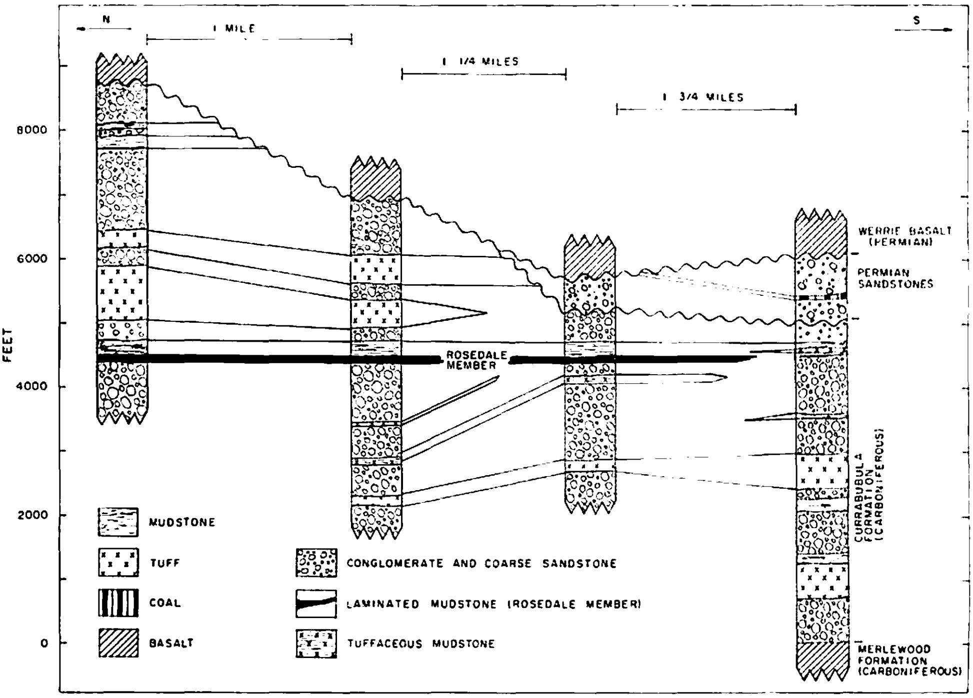

Figure 2. Stratigraphic columns of the Currabubula Formation and Permian sandstones

A marked disconformity separates the Currabubula Formation from the overlying Permian rocks (Fig. 2; Pl. 1) and indicates considerable erosion of the Currabubula Formation during the latest Carboniferous or earliest Permian. Because of the disconformity, the thickness of the Currabubula Formation varies from more than 8500 feet to about 5000 feet in the mapped area. At the type section, the thickness is 5000 feet (Voisey and Williams, 1964), but here the disconformity probably cuts low into the unit.

The dominant lithology of the Currabubula Formation is pebble and cobble conglomerate (Fig. 2). Approximately 70 per cent of the formation is conglomerate and coarse conglomeratic sandstone, approximately 10 per cent is fine sandstone and mudstone, and about 20 per cent is tuff.

Zeolites, including analcime, heulandite, clinoptilolite, and laumontite, are extensively developed in the Currabubula Formation as a result of the reconstitution of volcanic glass in tuffs and in the matrix of clastic rocks. The zeolitization is considered a result of zeolite facies burial metamorphism (Wilkinson and Whetten, 1964).

Individual rock units of conglomerates and tuffs are remarkably lenticular on all scales from single beds to mappable strata. For example, one of the thickest conglomerate units thins from a maximum of 1600 feet to less than 400 feet in approximately ½ mile along strike. Mudstone units are relatively thin, and their thickness is more or less constant.

One distinctive unit of the Currabubula Formation, a mudstone with delicately graded varvelike laminae and erratic pebbles is here called the Rosedale Member after a nearby farming property, and will be discussed in some detail.

The age of the Currabubula Formation is

Figure 1. Poorly sorted conglomerate (diamictite). Massive conglomerates are comparatively rare in the Currabubula Formation.

Figure 2. Stratified conglomerate and conglomeratic sandstone. Example shown is typical of the coarse clastic rocks in the Currabubula Formation.

CONGLOMERATES AND CONGLOMERATIC SANDSTONES, CURRABUBULA FORMATION

Figure 1. Thin section (× 3) of graded beds showing a variety of grain sizes in coarse layers. Coarse layers resemble "microbreccias." Fine layers are composed of silt-sized detrital grains and clay minerals.

Figure 2. Slump fold in laminated mudstone. Photograph taken at type locality on Currabubula Creek near Currabubula Village.

LAMINATED MUDSTONES, ROSEDALE MEMBER,
CURRABUBULA FORMATION

Late Carboniferous. It contains a *Rhacopteris* flora and lies above the Merlewood Formation (Lower Kuttung) which contains Visean fossils, and beneath Permian rocks containing *Glossopteris* and *Gangamopteris* floras (Carey, 1935; 1937). Beds which are probably equivalent in age to the Currabubula Formation in the Hunter Valley (Fig. 1) have been correlated with fossiliferous marine rocks near Booral, New South Wales (Fig. 1; Osborne, 1950). Campbell (1962) studied the marine fauna and concluded that the fossils are Westphalian and perhaps partly post-Westphalian. If the correlations are correct, this is the age of the Kuttung glacial rocks, including the Currabubula Formation.

Tuff

Tuff units in the Currabubula area range in thickness from more than 900 feet to less than 1 inch. Some vary greatly in thickness (one thins from 900 feet to a feather edge in about 1½ miles along the strike), but others have constant thickness over a distance of several miles.

Colors of fresh surfaces of tuffs range from lighter shades to darker shades of red, green and brown. Most tuffs are completely massive without any obvious bedding, including particle size grading, and were probably subaerially deposited. They contain coarse crystal and pumice fragments in a groundmass of shards. A few fine tuffs are finely bedded, commonly graded, but in some cases with cross-bedding. These tuffs are composed largely of microscopic shards with scattered volcanic pebbles, and were probably deposited subaqueously in shallow lakes similar to the lakes proposed by Coombs (1958) for the Seaham tuffs. Several ignimbrites occur, with characteristic welded glass shards.

Although both rhyolitic and andesitic tuffs are present in the Currabubula Formation, rhyolitic types are more common. All tuffs contain large quantities of shards which have altered, except in the case of a few pitchstones, to one or more of the following minerals: chlorite, K feldspar, quartz, albite, and zeolites. Petrographic details of five representative tuffs are set out in Table 1.

Sandstone and Conglomerate

The Currabubula Formation has an exceptionally large amount of coarse clastic rocks. Much more than half of the formation, or approximately 6000 stratigraphic feet, is conglomeratic and much of the rest, excluding the tuff, is coarse sandstone. Although massive conglomerate beds (Pl. 2, fig. 1) are comparatively rare, at least one is nearly 100 feet thick. Others are less than 1 foot thick and are interbedded with sandy layers (Pl. 2, fig. 2). Most beds vary in thickness, and many are lenticular.

Practically every outcrop shows some bedding, normally a result of crude particle size sorting. Alternating lenticular beds of conglomerate and sandstone are common, and such features as cross-bedding and scour structures are occasionally observed.

The conglomerates consist largely of pebbles. Fragments any larger than cobbles are extremely rare. The largest size grade is usually the most abundant, although every size down to microscopic matrix material may be present. In only two exposures, one at the railway cut near the Currabubula railway station and the other in Currabubula Creek in beds immediately underlying the Rosedale Member, were boulders (up to 2½ feet in diameter) observed in a sandy matrix without recognizable bedding. Other similar beds are undoubtedly present in the Currabubula Formation, but are certainly not common.

Subrounded to well-rounded grains are characteristic of the coarse-grained sediments. Generally roundness increases with increasing particle size. Several faceted cobbles were noted, but striated pebbles were not.

The coarse clastic rocks of the Currabubula Formation contain detritus which is derived in large part from volcanic terrain (Table 2). Fragments of volcanic flows and pyroclastic rocks are the most abundant constituents. The pyroclastic fragments petrographically resemble the tuffs and ignimbrites exposed in the Currabubula area. Most crystal grains have, besides the appropriate composition, zoning, crystal outlines, and embayed crystal edges which suggest derivation from the mechanical breakdown of volcanic rocks. On the other hand, nearly every specimen contains a few fragments of plutonic and metamorphic rocks.

Normally there is no distinct difference in grain size between the clastic and the matrix material. The matrix is usually composed of small, angular crystals and fragments similar in composition to the grains. The ratio of crystal fragments to lithic fragments is higher in the matrix. Extremely fine-grained weakly birefringent material is usually present in the matrix and may be partially devitrified ash.

In some rocks, authigenic minerals have replaced part of the matrix and vitric grains.

TABLE 1. PETROGRAPHY OF

Sample number	Estimated thickness of tuff unit (feet)	Estimated height of sample above base of Currabubula Formation (feet)	Name and probable origin	Mode (volume per cent)	Plagioclase	Alkali feldspar
C-17	330	6000	Coarse andesitic crystal vitric tuff; subaerially deposited	Plagioclase 52 Quartz 1 Pyroxene 4 Opaque oxide 3 Lithic fragments 8 Matrix 32	An_{41} $n_\beta = 1.553$	..
C-30	1000	5200	Coarse rhyolitic vitric crystal lithic tuff; subaerially deposited	Plagioclase 8 K feldspar 13 Quartz 10 Biotite tr Lithic fragments 29 Matrix 40	An_{12} $n_\beta = 1.539$	Sanidine-anorthoclase cryptoperthite $n_\beta = 1.524$; orthoclase-microperthite
C-140	5	4700	Coarse andesitic crystal vitric tuff; subaerially deposited	Plagioclase 46 Pyroxene 3 Opaque Oxide 2 Lithic fragments 3 Matrix 46	An_{33} $n_\beta = 1.549$	..
11-5-2	115	4100	Fine vitric crystal tuff; subaqueously deposited	Plagioclase 14 K feldspar 3 Quartz 1 Lithic fragments 11 Matrix 71	An_{27} $n_\beta = 1.546$	Sanidine-anorthoclase cryptoperthite $n_\beta = 1.525$
C-157	600	2600	Coarse rhyolitic vitric crystal tuff; subaerially deposited	Plagioclase 9 K feldspar 18 Quartz 11 Pyroxene tr Lithic fragments 17 Matrix 45	An_1 $n_\beta = 1.533$	Sanidine-anorthoclase cryptoperthite $n_\beta = 1.524$ $2V\gamma = 28°$; orthoclase-microperthite

Common alteration products are chlorite, K feldspar, quartz, calcite, albite, zeolites, rare epidote, and perhaps celadonite.

The volume of the matrix always exceeds 10 per cent of the rock, and is commonly 20–25 per cent. The clastic rocks are thus lithic wackes according to Gilbert's classification (Williams and others, 1955).

Mudstone

Less than 10 per cent of the Currabubula Formation is mudstone, generally not well-exposed. Individual mudstone units, however, are often continuous for long distances along strike with little variation in thickness. One unit, 150 feet thick, is traceable approximately 5½ miles in the mapped area.

Mudstones are dark brown, purple, or gray. Thin, fine- to medium-grained sandstones are interbedded with mudstones at regular intervals of a few inches or less in some areas. Locally, mudstones may tongue into fine sandstone. The characteristic lithology is siltstone, but finer-grained rocks (claystones) are also

Currabubula Formation Tuffs

Mineralogy				
Quartz	Ferromagnesian minerals	Lithic fragments	Matrix	Alteration products
Rare crystal fragments	Augite $n_\beta = 1.688$	Fragments of flows and tuffs	Shards	Shards altered to analcime and micas; feldspars kaolinized
Large embayed crystals showing outlines of β-variety	Very rare minute biotite flakes	Pumice fragments	Shards	Shards and pumice altered to clinoptilolite, chlorite, and red opaque dust
..	Augite $n_\beta = 1.664$	Tuff fragments	Shards	Shards altered to albite, K feldspar, quartz; feldspar partly kaolinized and sericitized
Rare crystal fragments	..	Fragments of flows and tuffs	Shards, minute crystals	Shards altered to clinoptilolite, chlorite, and red opaque dust
Embayed crystals showing outlines of β-variety	Minute pyroxene crystals	Largely pyroclastics similar to matrix material Rare metamorphic fragments	Shards, rare minute crystal fragments	Shards altered to laumontite and chlorite; feldspar partly kaolinized, chloritized

present. Quartz, K feldspar (confirmed by stain test), chlorite, and mica species clay minerals are the main minerals.

ROSEDALE MEMBER

Introductory Statement

The Rosedale Member is a sequence of laminated mudstones with erratics of all sizes and some massive sandstone and siltstone beds. It is approximately 60 feet thick where best exposed along the north bank of Currabubula Creek opposite the village of Currabubula. This exposure, located one quarter of a mile northeast of the confluence of Currabubula Creek and Anstey's Creek, is here designated the type locality. In other areas thin tuff beds are present. The Rosedale Member is not well exposed, but discontinuous outcrops can be traced from the northern boundary of the map (Pl. 1) for about 5 miles to the south, where the unit apparently thins to a feather edge. The thickness is probably uniform over most of the mapped area.

TABLE 2. PETROGRAPHY OF CURRABUBULA

Sample number	Stratigraphic unit	Estimated height above base of Currabubula Formation (feet)	Name	Mode (volume per cent)			
						Plagioclase	Alkali Feldspar
C-135	Permian Sandstones	5300	Coarse-grained volcanic arenite	Plagioclase K feldspar Quartz Lithic fragments Heulandite (cement) Quartz (cement)	1 3 6 80 7 3	An_1 $n_\beta = 1.533$	Dominantly orthoclase-microperthite
C-6	Currabubula Formation	5000	Conglomeratic volcanic wacke	Plagioclase K feldspar Quartz Amphibole Biotite Lithic fragments Matrix	8 18 13 tr tr 41 20	Average An_{15} $n_\beta = 1.541$	Anorthoclase-cryptoperthite $n_\beta = 1.525$; rare orthoclase microperthite and perthite
C-104	Currabubula Formation	4700	Very coarse-grained volcanic wacke	Plagioclase K feldspar Quartz Lithic fragments Matrix	3 12 3 43 39	An_{10}-An_{18} $n_\beta = 1.538$–1.543	Dominantly anorthoclase-cryptoperthite $n_\beta = 1.524$
6–5–2	Rosedale Member	4500	Medium-grained volcanic wacke	Plagioclase K feldspar Quartz Pyroxene Lithic fragments Matrix	20 1 8 tr 40 28	An_0-An_{45} $n_\beta = 1.532$–1.555	Same as C-6
C-154	Currabubula Formation	3500	Conglomeratic volcanic wacke	Plagioclase K feldspar Quartz Pyroxene Opaque oxide Lithic fragments Matrix	5 6 7 1 2 60 19	An_{20}-An_{31} $n_\beta = 1.544$–1.548	Same as C-6

The Rosedale Member is underlain by poorly sorted conglomerate and conglomeratic sandstone, and overlain by shaly mudstone approximately 150 feet thick. A covered area representing about 25 feet of strata separates the mudstone from the Rosedale Member at the type locality. The mudstone and the Rosedale Member are poorly resistant to weathering and can generally be mapped by stratigraphic interval even where the rocks are not exposed.

Lithology

At the type locality, the Rosedale Member is approximately 60 per cent laminated mudstone, 20 per cent thin sandstone beds, and 20 per cent siltstone. The laminated mudstone consists of alternating distinctly graded laminae of medium to fine sandstone, siltstone, and claystone (Pl. 3, fig. 1), with abundant plutonic and volcanic pebbles and cobbles (Fig. 3). Sandstone laminae

FORMATION AND PERMIAN SANDSTONES

Mineralogy				
Quartz	Ferromagnesian minerals	Lithic fragments	Matrix	Alteration products
Rounded grains	. .	Largely pyroclastics, rare quartz-mica schist fragments	No matrix, authigenic heulandite and quartz fill voids between grains	Alteration of pyroclastic fragments to quartz, chlorite, K feldspar
Angular fragments. Some grains show outlines of β-variety	Rare hornblende and biotite	Largely pyroclastics, with minor fragments from lavas, plutonic, and sedimentary rocks	Crystals and volcanic fragments, very fine-grained shard ? fragments	Alteration of matrix to chlorite, analcime, heulandite, calcite; devitrification of pyroclastic fragments to quartz, chlorite, K feldspar
Same as C-6	. .	Pyroclastic and flow fragments	Crystals and volcanic fragments, including shards	Shards altered to heulandite; glassy pyroclastic fragments to quartz and alkali feldspar. Chlorite in matrix. Kaolinization of feldspar
Same as C-6	Rare augite	Same as C-6	Crystals and lithic fragments, authigenic albite cement	Alteration of lithic fragments and matrix to quartz, feldspar, albite, hematite
Same as C-6	Augite $n_\beta = 1.695$	Ignimbrites common. Rare trachytes and hornfels.	Small crystals and volcanic fragments	Pyroclastic fragments largely altered to K feldspar and quartz. Authigenic chlorite and epidote in matrix. Laumontite vein. Kaolinization and sericitization of feldspars

are gray-green on a fresh surface, and siltstone and claystone laminae are normally deep purple, although they may be dark green.

The coarser laminae are similar in composition to the thin sandstone beds of the Rosedale Member (Table 2, Sample 6–5–2), and the finer laminae are similar to the massive siltstones. Although fragments of volcanic rocks are the dominant constituents of the sandstones, it should be emphasized that these rocks are not tuffs. Shards are rare, and the fragments of pyroclastic rocks which do occur are of clastic origin. Fine-grained matrix material is abundant. The sandstones are, therefore, lithic wackes.

The fine-grained siltstones and claystones of the Rosedale Member are composed largely of mica species clay minerals (identified by X-ray diffraction) and small amounts of quartz and feldspar. The clay minerals exhibit parallel orientation; in thin section under crossed nicols entire laminae extinguish parallel and at right angles to bedding.

Erratic fragments of volcanic and plutonic rocks and mineral grains are widely distributed throughout the laminated mudstones. These "pebbles" occur in all sizes, from sand-sized grains in the fine layers to boulders up to 16 inches in diameter. They vary from angular to rounded. Many are of plutonic origin. There is normally a pronounced bowing of the laminae around the pebble, and in many cases laminae are completely disrupted (Fig. 3).

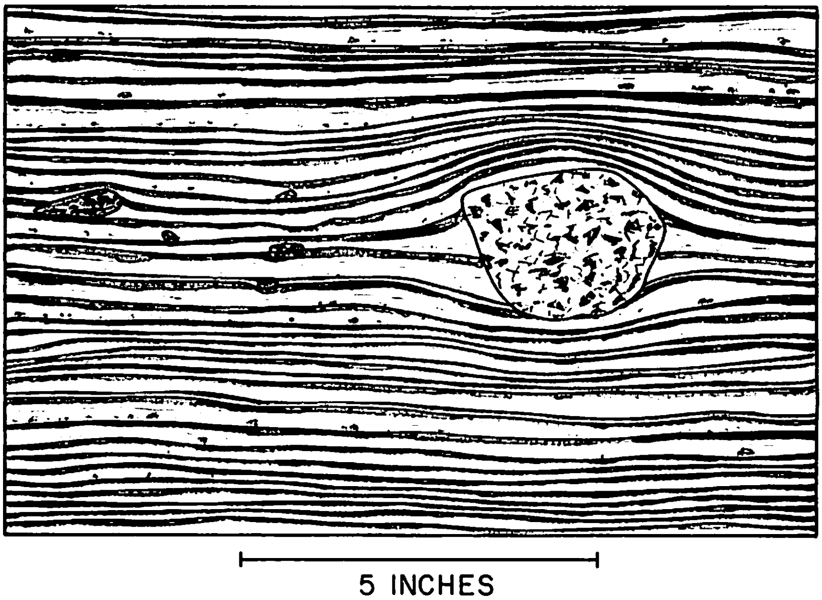

Figure 3. Ice-rafted pebble in laminated mudstones, Rosedale Member, Currabubula Formation. Sketch by L. G. Hanson from a photograph

A few beds or laminae of tuff up to 6 inches thick are present in some parts of the Rosedale Member. These tuffs normally contain shards which are replaced by clinoptilolite, and are recognized in hand specimen by the characteristic deep red color of ferric oxides associated with the zeolite.

Sedimentary Structures

The graded bedding of the laminated mudstones (Pl. 3, fig. 1) is perhaps the most characteristic feature of the Rosedale Member. The sandy laminae average about 2 mm in thickness, and the siltstone and claystone laminae are between 0.5 and 1 mm thick. The laminae are continuous on the scale of an outcrop. The gradation from coarse to fine laminae is accomplished by a reduction in the average grain size, although on every horizon there are particles larger and smaller than the mean. Mica species clay minerals are present in the coarse-grained as well as the fine-grained laminae. The contact between the sandstone and underlying siltstone is abrupt and nongradational, and is usually the surface along which the laminae are most likely to split during mechanical weathering.

Slightly weathered blocks of laminated mudstone commonly show markings on the top surface of mudstone layers which are probably animal trails or burrows.

Locally, beds of laminated sandstone and mudstone are deformed by what is apparently "soft-sediment" deformation. Large overfolds, commonly involving 50 to 100 laminae (Pl. 3, fig. 2), rest on flat-lying beds and are overlain by flat-lying beds with an erosion surface in between. The laminae are thickened in the fold hinges and attenuated in the limbs.

PERMIAN ROCKS

Conglomeratic sandstones with a *Gangamopteris* flora of Permian age (Carey, 1935) overlie the Currabubula Formation in the Currabubula area (Pl. 1). The contact between the Permian and Carboniferous rocks is a disconformity with about 3000 feet of relief (Pl. 1; Fig. 2). The Permian sandstones, which are a maximum of 1000 feet thick in the Currabubula area, resemble the coarse clastic rocks of the Currabubula Formation (Table 2) in that both are lithic sandstones, and most of the lithic fragments in both are tuffs and flows of similar composition. In contrast to the Currabubula Formation, Permian sandstones contain little, if any, matrix, and in any one bed the grains or fragments are moderately well sorted. There are no tuffs or mudstones in the Permian rocks. A coal bed 10 feet thick occurs in the middle of the sandstone sequence. Considering the similarity of the clastic material above and below the disconformity, it appears likely that the Permian sandstones were derived by erosion of the underlying Currabubula Formation.

The Werrie basalts, also of Permian age, overlie the Permian sandstones. The contact may be conformable, but the apparent truncation of a coal bed (Pl. 1) suggests at least a slight unconformity. Carey (1935) has estimated that the basalts are 5000 feet thick.

ORIGIN OF THE CURRABUBULA FORMATION

The interpretation of the origin of the Currabubula Formation is complicated by the contemporaneous volcanism and the orogeny apparently in progress at the time of deposition (Voisey, 1959b). Dott (1961) makes it clear that glacial deposits reported from such areas may be confused with volcanic and gravity slide phenomena capable of producing glacial-like structures in sediments. On the other hand, most glaciation today is associated with mountainous areas, many of which have active volcanoes. It is likely that a similar relationship existed in the past, except during periods of abnormally cold climate when glaciers may have been widespread over lowland areas. To exclude glaciation as a depositional process simply because of associated volcanism and tectonism is, of course, unwarranted. Obviously, better criteria are needed to distinguish these deposits.

Carey (1937) emphasized the over-all glacial aspect of the Currabubula Formation in the Werrie Basin and recognized many units of varves and tillites as well as strata containing striated pebbles. He identified a Lower Glacial, an Interglacial, and an Upper Glacial Stage; the glacial stages were each interpreted as containing evidence for several glacial advances and retreats. Carey also recognized the volcanic activity and refers to it as a complexity introduced into the sedimentary record.

It is not intended to detract from the over-all excellence of Carey's work to say that, in this writer's opinion, the evidence for glaciation in the Currabubula Formation is not as clear-cut as Carey indicates. A very small percentage of the rocks in the total stratigraphic column (Fig. 2) has a varved appearance, and it is questionable if any are true tillites. No obviously striated pebbles or striated pavements were found.

It is difficult, however, not to be impressed with the extremely large amount of conglomerate in the Currabubula Formation. Although most exposures show at least some semblance of stratification (Pl. 2, fig. 2), there are a few massive strata characterized by a wide range of size grades (Pl. 2, fig. 1), which could appropriately be termed diamictites (Flint and others, 1960). Diamictites are not abundant; they have only been observed in a few places. Perhaps they are more widespread than is reported here, but are covered, or were too conservatively evaluated by the writer. In any case, as Dott (1961) points out, most of the criteria for tillites, including lack of stratification and poor sorting, are not diagnostic. If evidence for glaciation in the Currabubula area rests solely on the conglomerates, there is but little support for the idea. Most of the conglomerates were obviously deposited by fluviatile means. It is conceivable, however, that the clastic material could have been produced in large part by glaciers and then deposited by streams as glacial outwash.

Certain features of the Rosedale Member are consistent with the hypothesis of glacial origin. It is largely a sequence of mudstones with fine laminae which perhaps are varves. The laminae are closely similar to Pleistocene varves the author has observed in Tasmania and New Zealand, and to Permian varves in South Australia. Erratic sand, pebble, cobble, and boulder-size fragments occur in abundance in the Rosedale Member; many of these are of plutonic origin. It is difficult to understand how they could have been transported by any other means but ice rafting. According to Dott (1961), large numbers of rafted erratic fragments in fine muds suggest ice movement, and Pettijohn (1957, p. 264) agrees:

> "The conglomeratic laminated lutites are obviously produced by dropping of coarse blocks into still bottom waters in which the finest silts and muds were accumulating. This normally is the

> product of raft action—most commonly by glacial ice although cobble-sized fragments may be carried in the roots of floating trees, by river or shore ice, or even be dropped into quiet waters by volcanic explosions. The latter case is most probable if the fragments are mainly volcanic rocks and the matrix is rich in volcanic admixtures especially glass."

It should be emphasized that for the most part the Rosedale Member is not a tuff. The large erratics, which are predominantly of plutonic origin, are decidedly not volcanic bombs, and it is difficult to understand how they could originate from volcanic explosions without the presence of large quantities of shards.

Although most of the laminated rocks occur in the Rosedale Member, several outcrops in other parts of the Currabubula Formation have characteristics suggesting varving with erratic pebbles. But in general, these strata are thin and laterally discontinuous and could not be mapped during the present study.

A few beds in the Currabubula Formation are laminated in hand specimen but exhibit pronounced pyroclastic texture in thin section. One such unit, mapped as "Tuffaceous Mudstone" (Pl. 1), is composed largely of devitrified glass shards with crystal fragments (Table 1, Sample 11–5–2) and is a vitric crystal tuff. Other thin beds, composed almost entirely of small crystal fragments, may be siltstones or fine crystal tuffs. Practically all the erratic fragments are of volcanic origin. It is possible that this unit was deposited in some way by glaciers. But it seems far more likely that the unit is a subaqueously deposited tuff, with the delicately graded laminations and occasional current bedding due to settling of volcanic ash through water and the erratics dropped in by volcanic explosions. S. W. Carey (oral communication) disagrees with this interpretation and contends that the same effect would be produced if volcanic ash were deposited on a glacier which subsequently melted, and the ash then redeposited at the same time that the larger volcanic fragments were brought in by ice. In either case, the rock is still a tuff. The point to be made here is that it is not necessary to invoke glaciation to account for its origin.

In contrast to the "Tuffaceous Mudstone," and other similar beds, the Rosedale Member is not a tuff. It contains varvelike laminae and abundant nonvolcanic erratic pebbles. It is hard to understand how this unit could have formed unless ice rafting and glacial melting were involved. Glaciation is the best explanation for the origin of the Rosedale Member. A fluvioglacial origin for most of the rest of the Currabubula Formation must in large part be based on the Rosedale member. There is no direct evidence that the conglomeratic rocks are glacial outwash except that they are intimately associated with the Rosedale Member. If a glacial origin is accepted for the latter, then it is the most obvious alternative to explain the coarse clastic rocks.

It would be difficult to accept a glacial or fluvioglacial origin for these rocks if this were an anomalous area isolated in time and in space, but such is not the case. Rocks similar to the Currabubula Formation, including the varved mudstones of the Rosedale Member, are found in approximately the same stratigraphic position throughout the area of the New England geosyncline (Fig. 1), although detailed work has yet to be done on most of the deposits. B. C. McKelvey has recently studied the Rocky Creek area (Fig. 1; Ph. D. thesis, 1964, University of New England).

Most of the clastic material in the Currabubula Formation is of volcanic origin and is petrographically similar to tuffs exposed in the Currabubula area (Tables 1, 2). In other words, the sediments were probably locally derived. This suggests that glaciation was of the alpine variety, restricted to a nearby mountain range where volcanic materials were abundant. The Currabubula Formation evidently accumulated in an area which received glacial outwash, as well as considerable volcanic ash. Lack of any obvious erosion within the Currabubula Formation indicates that the area of deposition was not extensively ice-scoured. Striated pavements do not occur and would not be expected unless the depth of glacial erosion was sufficient to reach consolidated bedrock. Glaciation may or may not have been extensive in the now eroded source area.

There is no evidence in the Currabubula Formation that the region was glaciated by a Carboniferous ice sheet of continental proportions, nor is it necessary to assume widespread Carboniferous climatic cooling. The Currabubula formation and similar sedimentary rocks of the New England geosyncline can probably be explained as local phenomena associated with nearby mountain ranges, and not necessarily related to the more widespread and younger Permian glacial rocks in other parts of Australia.

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