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1.—Topical chemistry in Perth's air

Presidential Address, 1975

by G. A. Bottomley¹

Delivered 28 July 1975

Introduction

Last year Dr. Trendall's Presidential Address dealt with the banded iron formations in the northwest of this State and their genesis associated with the change in the composition of the Earth's atmosphere perhaps 2 000 million years ago. I shall be discussing some quite recent atmospheric chemistry again particularly relevant to Western Australia and the metropolitan area.

At any one average moment over the State of Western Australia there is present 300 million, million tons of air (that is over 10,000 times the mass of our known iron ore reserves), carrying water equivalent to at least 10,000 times the annual consumption in the metropolitan area and "traces" of carbon dioxide enough to make a cubical block of wood two miles each edge. It is a big subject. By natural meteorological processes involving prodigious amounts of potentially useable solar energy and wind energy the lower atmosphere is generally changing, air arriving from the southwest for example, whilst the current air progresses generally eastward. We humans use it as a source of oxygen rejecting carbon dioxide to it, plants do the converse by day, and of course it is a rubbish disposal service for factory emissions and traffic exhausts. Though neither import duties nor export controls are imposed on its movement by the Federal Government, air is an important and precious commodity.

No previous President however has elected to talk about the Atmosphere, indeed, even in the Society's extensive publications going back to 1914 (and its antecedents to 1897) only a few papers touch the topic. The air's inland transportation of agriculturally significant chemicals is treated in the Royal Society's Report on 'Salinity in Rain in Western Australia' (Professor Wilsmore Chairman 1928) and in Professor Drover's 'Accessions of Sulphur' (1960). Would modern replications of the latter be higher? Dr. Speck reported in 1953 on 'Atmospheric Pollen in the City of Perth and Environs'. And four papers indirectly relate to massive combustion in air: Miss Baird's 'Regeneration on Garden Island after fire' (1958), Dr. Hatch's 'Burning of the jarrah' (1959), 'Man the destroyer', Dr. Merrilees' Presidential Address (1967), and 'Fire in the jarrah environment', Dr. Wallace's Presidential Address (1966).

Perhaps our oblique interest is because our city has never experienced pollution incidents such as the London pea-soup fogs (now almost eliminated by smokeless zone legislation) in which sulphur dioxide and smoke particles *jointly* disrupted the health and amenities of European industrial cities.

Be that as it may be, no professional chemist need apologise for discussing Air. No precise point can be given for the evolution of modern chemistry (just possibly Dalton's atomic theory 1807), but my biased choice as a gas experimentalist would be fellow Yorkshireman Joseph Priestley's characterisation and recognition of oxygen as a separate chemical species. Priestley knew about many of the gases I shall refer to later. Oxygen he prepared by the famous burning glass experiment. Solar energy again! Nitrogen he obtained by removing oxygen from air by combustion and by respiration (of mice and men). Nitric oxide he synthesised from the action of many metals on nitric acid. Most importantly for us, he knew that nitric oxide combined with oxygen to give the red water-soluble nitrogen dioxide, indeed this was Priestley's standard quantitative test for the 'goodness' of air, viz, its oxygen content. All firmly established by the 'pneumatic chemists' by 1775.

The compounds NO and NO₂ (quite distinct from N₂O-'laughing-gas') occur in barely measurable amounts, say a fraction of one part per hundred million in rural, uncontaminated air. Significant amounts are released during combustion of coal, of oil, of natural gas, etc., in furnaces and of petrol in the car engine, therefore both are found above natural levels in city, contaminated atmospheres. Neither is medically harmful at the levels I shall be speaking of tonight but they *are* centrally involved in photochemical smog.

Photochemical reactions

Controlled photochemical reactions in gases were first demonstrated a century ago by John Tyndall (1868) physicist, master experimentalist in bacteriology (he observed the inhibition of microbial growth by *Penicillium* fifty years before Fleming), noted science expositor, and a glaciologist who attempted to conquer the Matterhorn just before Whymper's tragic assault.

Air containing a trace of amyl nitrite vapour on illumination with sunlight, though initially optically clear, develops a brilliant fog as the energy of the light beam converts the amyl nitrite to a non-volatile material. The colours

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of Tyndall's fogs, pink and green in this replication, failed to attract adequate investigation: similarly coloured monodisperse sols were re-discovered by La Mer (1941) and are explicable with light scattering theories due to Lord Rayleigh.

Many commentators for instance F. W. Went (1966) noted plant physiologist, have suggested that the ethereal atmospheric effects over, for example, Australia's Blue Mountains might have their origin in extremely fine particulates formed by the *natural* photochemical process of intense sunlight acting on organic vapours emitted by trees. Perhaps some of Gruner's paintings depict the phenomenon.

Let me move now to an *artificial* photochemical experiment on a massive scale. A detailed chemical exposition would be out of place here, I merely remind you of the essential features of photochemical smog formation in air contaminated with automotive emissions. Energy from sunlight otherwise passing harmlessly to ground is intercepted by the NO_2 molecule which then sets in train chemical degradation of hydrocarbons from uncombusted petrol. The chemical sequence is such that the NO_2 molecule is regenerated and continues its cyclic, catalytic role. In stagnant air the photochemical process results in a marked and characteristic loss of visibility, the formation of eye irritating chemicals, and enhanced ozone levels. Well documented social, economic and medical disabilities follow severe and repeated exposure to such conditions. For example, in the Los Angeles basin photochemical smog of man-made origin has severely or at least moderately damaged over 100,000 acres of the San Bernadino National Forest. Restoration of the pre-car era air quality has so far defeated all attempts.

Perth air: background information

One of the great delights of Perth has been its brilliant atmospheric clarity—a tourist attraction too! In the mid sixties, fresh from eighteen months in Los Angeles, I began to have qualms of chemical conscience, qualms engendered on clear winter mornings by perceptible odours reminiscent of Los Angeles, recognisable by myself and several others with personal experience of L.A. photochemical smog. (Incidentally, only life-long non-smokers should serve on air-control bodies.) Is there, I mused, the slightest possibility that photochemical processes within the emissions from our expanding road traffic, perhaps compounded by natural terpenes from eucalyptus, might lead at some distant future time to an occasional L.A. type incident? Almost everyone dismissed this as fantasy in 'the windiest capital city in Australia'. What could I do with very limited facilities which might partially resolve this question? A remark of Charles Darwin helped: 'Once a week do a damn fool experiment, they hardly ever work but when they do they're marvellous'. Chemical analysis for ozone, hydrocarbons, 'oxidant', all indeed pose severe chemical and instrumental problems (i.e. financial problems) at the very low concentrations of interest to air chemists. The determination of NO and NO_2 together, collo-

qually NO_x , was a practical possibility which might be squeezed in alongside my mainstream research. The principal results are reported with detailed discussion in the Journal of the Royal Society (Bottomley and Cattell, 1975). Let me tonight emphasise the salient points, provide some illustrations, and add perhaps a little human interest.

Of about two hundred NO_x values measured at the University between June 1970 and June 1971 all the concentrations except two are inconsequential by world city standards. More interest arises when we note that most high NO_x values coincide with impaired atmospheric clarity of a special type. April 29th 1971 is particularly interesting. The NO_x value taken 8.00 a.m. to 10.00 a.m., following the morning traffic peak, was the highest recorded in that series, and is followed by a marked fall during the 10.00 a.m. to noon period just as the atmospheric clarity improves. This is simply a chemical verification that car (and other emissions) linger near the ground in stagnant late-autumn morning air.

Unauthorised release of this comparatively high value (23.6 pphm) unleashed in the media an obscuring controversy about Perth's air. Criticism was made that the University site was quite unrepresentative of the Metropolitan area (though 10 000 of us have to breathe its air) and that Chemistry's oil-fired boiler was the cause: no critic asked if the boiler was working that morning. Thus Peppermint Grove became the site for further studies of truly suburban air.

Long-term studies

Photochemical sequelae would be more likely if car emissions remained relatively unmixed throughout a full morning of intense sunshine: I resolved then upon a year long examination, for just such persistence, in the air at home between 10.00 a.m. and noon. The year's results are really a chemist's view of the fluctuating meteorology of that year. Examination of the maximum value (10.00 a.m. to noon) obtained in every month locates April, May, June and July to be when inadequate morning mixing occurs. Peppermint Grove experienced some ten incidents in a year comparable to the April 29th, 1971, event at the University. If data had been collected 8.00 a.m. to 10.00 a.m. (not two hours later) I believe we would have exceeded the 23.6 pphm figure.

The main meteorological cause of the inability of the air to disperse car fumes is the existence of a shallow and intense inversion layer, the air temperature rising with height above ground instead of decreasing as normal. Dispersion of contaminants is delayed until the sun rises high enough to destroy or 'break-up' the inversion, when sudden mixing and therefore clearing occurs. The data for 1962 shows how common these inversions can be in Perth (Mackey 1963). The chemical data confirm these shallow inversions as an extremely important feature of Perth's meteorology in relation to car and other low-level emissions.

Let me offer just one statistical argument which directs the blame for the NO_x levels

towards cars. Day by day the values fluctuate remarkably because of Perth's variable weather, but if you virtually eliminate that factor by averaging the results for every Monday, every Tuesday etc., then this Table is obtained (over 55 weeks):

Mon.	Tues.	Weds.	Thurs.	Frid.	Sat.	Sun.
1.28	1.22	1.32	1.64	1.79 Highest	1.37	1.07 Lowest

which surely reflects our car habits. Very simple, very convincing!

The scope of these studies was greatly enlarged hereabouts by parallel work at Caporn Street Nedlands, carried out by Dr. Frank Cattell as the Western Mining Corporation Fellow at the University of Western Australia in 1972 and 1973. Clear evidence was produced that Peppermint Grove and Nedlands experience somewhat similar effects from traffic emissions and that NO predominates in the ambient NO_x mixture. The daily data for both sites has been smoothed to reduce the effects of short term weather fluctuations by taking a thirty day moving average: it confirms again that the early winter period is of greatest concern. Furthermore when the NO_x on a daily basis is high at Peppermint Grove, it is high also at Nedlands. These highs are *not* from local sources like Chemistry's boiler acting in an uncoordinated way, very likely other parts of the Metropolitan area are similarly affected.

So far I have been concerned with morning traffic: what about the evening exhaust fumes? Mid April 1972 provided some novel and disconcerting information. The Bureau of Meteorology issued an air dispersion alert on April 14th, 1972, for the Friday evening to Saturday noon. The University wind records showed a forty hour calm starting 6.00 p.m. Friday the 14th. Thus alerted we instituted some special studies. We believe the massive late evening peaks to be due to the evening traffic emissions drifting very slowly westward from the city whilst held at high concentration in a very shallow layer by radiation inversions.

Perth weekday traffic covers at least a million car-miles between 3.00 p.m. and 8.00 p.m. At the then current Californian standard of 4 grams of NO per mile, this human mobility releases 3 tonnes of NO_x. If that is dispersed into a cylinder of air ten kilometres diameter and 100 metres deep (a rough guess for the affected air space) then the average concentration is 20 pphm.

The higher values in the evening peaks surely provoke speculation about other car emission chemicals. As a rough and ready rule overseas experience is that carbon monoxide levels are 40 times the NO_x: if so for our Perth suburbs, on these special occasions the United States air quality standards for carbon monoxide (not to be exceeded more than once a year) were violated on at least four evenings.

Photochemical events and ozone formation

Should the incidents detected in the evenings persist until well into the sunlit morning, perhaps with additional NO_x gained from the morning traffic emissions, then photochemical consequences would certainly occur. Possibly the April 29th, 1971, morning peak was indeed one such incident.

Dr. Cattell made some preliminary assessment of 'oxidant' (a photochemical component) by the buffered potassium iodide method and by the ethylene chemiluminescent reaction method which is specific for ozone. A study was made of how NO, NO₂ and ozone levels varied during one winter's day, the time sequence is typical of photochemical reactivity. Ozone concentrations on one of three summer days in November-December 1972 (part of a short series studied) reached levels which American authorities would regard as indicative of mild photochemical smog.

I mention-caveat-that 1972 was an unusual year weatherwise: ten air dispersion alerts were issued by the Bureau of Meteorology, compared to 2 in 1973 and (I think) one only in 1974. (current practice is different too.) A comfortably convenient viewpoint might well be that the air pollution features I have been talking about are really only of marginal concern in these special periods. Of course I can give you no guarantee for the future: our car traffic continues to grow, the weather is fickle—Melbourne recently had an unusual 11 day stagnation period. It is however certain that the basic air-chemistry here gives no built-in immunity, for that you must turn to town planners, controls, politicians, and perhaps the electric car.

Ozone levels in Perth were first "measured" almost a century ago. Towards the end of 1875 Sir Malcolm Fraser, then Surveyor General, had established at the Survey Office a meteorological station under his personal supervision and I think at his own expense. The data obtained are reported in the Government Gazette and starting August 18th 1876 include values for the blue colour developed on potassium iodide paper as natural air movement brought the ozone to it, not a method quantitatively validated today. Ozone was then thought to be good for you, you got it at the sunny sea-side and not in industrial towns because there the sulphur dioxide obliterated it: Perth scored well. We know something of the instrumentation: Sir James Clark's Ozone Cage, Dr. Moffat's papers and 'scale of tints', Negretti and Zambra's superior papers were in use later. Do specimens of these early ozone meters abandoned in 1900 still exist? Useful comparative information might yet be extracted from the historical Perth data?

Emissions from vegetation fires

Do we have sufficient knowledge of how Perth's air chemistry is affected by burning-off operations either far removed from the metropolitan area or by major local incidents [see postscript] such as the recurrent fires at Herdsman's Lake? The logs of Pelsaert, Vlaming and others show that dense smoke patches are not merely modern

events. The West Australian reported (Friday, December 11th, 1970) that 'A smoke haze covering the metropolitan area yesterday afternoon restricted visibility in some places to 1000 yards. Visibility was poor all day and at 5.00 p.m. it was impossible to see across the Swan River from 'Newspaper House'. Earlier that week on a day of similar obscuration my note book (and 'The West Australian', Dec. 9th) records that *at the edge of the Darling Scarp* I could definitely smell the Los Angeles odour.

That December week the CSIRO Division of Applied Chemistry (I learned rather surprisingly two years later through the scientific literature) were studying large scale prescribed forest fires in the Manjimup area; the fire on 7/12/70 consumed 110,000 tons of fuel, and the smoke from the one on the 9th Dec. could have reached Perth the next day. Aircraft flew through the smoke plumes to measure concentrations of smoke particles and many chemical substances.

No chemist expects ozone to form in a fire, directly through combustion alone. No ozone outside the normal natural air ranges was found in these plume experiments and 50 pphm for NO_x was never reached either. In the 1971 report's words '... it seems most unlikely that any prescribed burn could, of itself, start a photochemical incident' (Vines *et al.* 1971).

The matter has not ended there. Why "of itself"?

Since 1971 additional information has come from new CSIRO forest burn experiments. Excess ozone has now been detected, the peak concentration being several times that of the ambient atmosphere, though (I quote) 'excessive ozone was found only in the top layer in the plume and only when the sun was shining' (i.e. photochemical).

Let me read the two concluding paragraphs of a CSIRO paper available in January last year (Evans *et al.* 1974):

"It is indeed fortunate that the excess ozone is confined to a shallow layer at the top of the plume and that the plume from controlled burning rises above 1000 metres, thereby ensuring sufficient dilution of the ozone layer to eliminate any health hazard at ground level. Nevertheless, one should keep in mind that low-level smoke may well constitute a hazard, particularly if it drifts over urban areas and merges with other urban pollutants such as nitrogen oxides, the effects of which cannot yet be predicted.

We feel that it is strange that such high ozone concentrations have not been obvious elsewhere in the world. Perhaps the indigenous eucalypt fuels used in the present work yield smokes which are particularly photosensitive." Local research is important.

Perhaps my nose was right after all on December 8th, 1970! Ozone from massive burns? Ozone from cars? Are the native plants (whose sensitivity to ozone we do not know) absolutely safe in Kings Park? The experimentalist you see must first speculate, then measure.

Power stations as ozone sources

Until recently no one expressed concern about gaseous emissions from oil-fired power stations except over sulphur dioxide. Through steadily improving technology more compact, quickly responding and more sensitive analytical chemical apparatus can now be flown through stack plumes. Just such an experiment was reported by Davis *et al.* (1974) on the plume gases from a 1000 megawatt generating station near Washington, D.C., which operates on 75% oil 25% coal. In addition to the expected chemistry near the stack, at distances around 70 kilometres down wind through sunlight action on the effluent gases there was a nett production of ozone to levels double ambient values. A surprising finding which will provoke much new experimentation and some concern where large power stations are situated to windward of urban areas.

The role of a university

What should be the University's role in further atmospheric studies in Perth? It was Joseph Conrad who authoritatively described Cape Leeuwin as 'one of the three great Capes in the World'. Far to its west, north and south we have available a vast portion of the water surface of the world. Much of Perth's air comes to us over those oceans with—by world standards—remarkably little air-borne pollution from the few ships and the infrequent aircraft. Perth then is well sited for background studies of numerous naturally occurring chemicals in the uncontaminated atmosphere. Let me cite two examples only. Some splendid studies on gaseous iodine (not sodium iodide, the salt) have recently been done at the University of Hawaii (Moyers *et al.* 1971). A southern hemisphere replication would be a proper task. Secondly, if speaking to you three years ago I would have been urging studies on the rising levels of carbon dioxide. Again the deficiency that such studies had only been done in the northern hemisphere (predominantly) is now being corrected by CSIRO's program of Base Line Atmospheric Carbon Dioxide Monitoring on high altitude commercial flights between Christchurch, New Zealand, through Perth to Mauritius (Pearman & Garratt 1973, 1975). Welcome as this development is to me, it does point up the question of whether the University can organise, staff and finance environmental programs on more than a very minor scale unless there is a firm commitment from senior policy makers, perhaps even a national science policy.

Consider—sketchily—the time scale within which an Honours student in one year or a Ph.D candidate in three must face his problem. Lectures, associated study, three or more seminars weekly, laboratory teaching, all create a fragmented week within which to cope with the experimental problem and its literature, the apparatus and its problems, and for the Ph.D candidate—getting publishable work. For the regular staff member to deviate from his established research means serious inroads into his private time—a fact University wives will verify. Add that the air is variable daily, weekly, sea-

sonally, so that many observations are needed—a problem shared with biologists and farmers. Despite these very real constraints the University can act in exploratory roles of value to the Public Health Department and the Environmental Protection Department and this I wish to illustrate briefly with the two examples of lead, and “Freon” tracing.

Lead emission from cars

There is world wide interest in the urban distribution of lead-containing particulates emitted from the exhaust pipes of cars. Certainly humans near highways inhale lead from the air though the public health significance of this is controversial. Mr. L. Boujos as an Honours student in Physical and Inorganic Chemistry obtained local information on lead levels which supplemented the rather meagre public information available elsewhere in Australia (Bottomley & Boujos 1975).

The Causeway across Heirisson Island carries some 75,000 vehicles per day. In the 200 yard length of roadway on the Island roughly two pounds weight of lead is emitted daily through petrol combustion. The finely divided lead salts are brought to the ground to various extents and at various distances depending on the prevailing wind and weather conditions, that reaching the ground or plant surfaces is subject to weathering and leaching.

Sampling was undertaken to determine the average lead concentration in the top two centimetres of soil at various lateral distances from the edges of the roadway. The absolute values are somewhat lower than for some other Australian measurements and are considerably below extreme values for heavily urbanised areas in other countries. Whether simple intercomparison is legitimate or not is a matter itself requiring very close study.

The lead is of course not uniformly distributed in depth: there is a markedly raised concentration in the upper few centimetres of soil both near to and remote from the roadway. The immediate surface is richer still in lead, a fact of considerable importance for surface living and feeding animals. The shells of a common snail (*Pheba pisana*) at 50 metres from the roadway were five times higher in lead than comparison samples taken at Swanbourne Beach and at Rottnest Island. These snails are eaten by mice, themselves food for hawks.

The levels observed at Heirisson Island certainly do not account for all the lead emitted in past years. Some perhaps is broadcast very widely, some may be carried deep into the soil during the winter rains. Nor do we have any details of the lead run-off from the roadway into the storm drainage system, the river and the ocean. We have kept the recovered lead from Heirisson Island and Dr. Trendall urges an isotopic analysis.

An interesting experiment would be to follow the arrival rate of lead at newly created surfaces: we are doing this on artificial soil at the

University, but what about the accumulation in artificial lakes near the Narrows and Hamilton interchanges—both bird sanctuaries in effect. Possible lead insults to the flora and fauna should be examined further if Heirisson Island is to become a zoological reserve (Quarles *et al.* 1974; National Academy of Sciences 1972).

Let me now deflect your interest temporarily to lead contamination in a very distant part of the world, age-dated Greenland glacier ice (Murozumi *et al.* 1969). There is evidence for regional or hemispheric pollution consequences of the boom in extraction, processing, and utilisation of lead as the Industrial Revolution encompasses Europe, and further lead deposition is thought to be due to the general adoption of lead antiknock compounds combined with the expansionary phase of car traffic.

The Perth metropolitan area doesn't have convenient local glaciers, but can we think of a comparable test here? Perhaps dateable sediments in the Swan Estuary? Another possibility is a chemical examination of the annual growth rings of trees growing during the last fifty years alongside busy highways in Perth. Dr. Wycherley has provided me with samples from Kings Park, but what I really covet (I confess) is one of the Norfolk Island pines alongside Stirling Highway at Christ Church, Claremont.

Tracing of gas emission

By the early seventies a small number of Freon tracing experiments in the Northern Hemisphere had provided information on ground level concentrations of emissions from large scale powerstations as follows. Several kilograms of a Freon refrigerant gas are released up the working stack, and are diluted and dispersed just as the normal gases are under the prevailing weather. On the ground at distances up to 20 kilometres many air samples are taken in plastic bags for later laboratory analysis. This method is practicable only because as little as 10^{-12} gram of Freon in 1 cm^3 of air is detectable by gas-liquid chromatography. (On a mass per volume basis, we could detect one needle in 100 large haystacks). This extreme sensitivity is needed to study other industrial emission problems.

In Western Australia this system has been applied to determine ground level concentrations in the Coojee Air Pollution Study (Anon. 1974). It is worth a few moments delay to trace the origins of this local experiment, the first we believe in Australia, possibly in the southern hemisphere. The University Department of Organic Chemistry has owned a g.l.c. with e.c.d. (to use the jargon) for some years, invariably fully deployed but in very different directions. Perceiving the method's potentiality I wrote in mid 1973 to Dr. O'Brien suggesting that Dr. Cattell (then Western Mining Corporation Fellow) might develop the local instrumentation appropriately. The Department of Environmental Protection with personnel assistance from the armed services and from school children arranged the logistics of release, collection, and analysis on a day determined by the Common-

wealth Bureau of Meteorology. Remove any one of these links or the associated financial support and no data can be secured. Cooperation is important.

Such information is manifestly important to planning large scale industry within the metropolitan area or further afield and to practical verification of theoretical and simplified models of pollutant dispersion. Diverse additional applications come to mind easily. The emissions of one particular chimney can be distinguished from another emitting the same pollutant. Car emissions could be traced across the city suburbs after release from say a single car crossing the Narrows bridge. The movement of air into and from individual buildings can be followed in time and in amount. Information on persistent and troublesome odours can be obtained. My own home is frequently invaded by a smell similar to 'iodoform' arriving on gentle S. or S.E. winds in the evening. "Freon" releases from conjectured sources (decomposing lakes vegetation is one theory) could help disentangle the problem. The extreme sensitivity of the g.l.c. method might permit positive chemical identification of the offending chemical.

State Government funds, I am very glad to report, have been made available to the Department of Conservation and the Environment for an additional chromatograph housed at the University with priority use on further tracing experiments of these types.

I give one more academic example: industrial and domestic use of simple chlorinated hydrocarbons had resulted in the Northern Hemisphere air being burdened with escape material (Murray *et al.* 1973; McConnell *et al.* 1975; Wilkneiss *et al.* 1975). Comparable measurements using the chromatograph on Metropolitan air, for Indian Ocean air and at the Giles Weather Station would make an attractive Honours project and a useful contribution to world environmental information.

Funding of relevant university research

Recently the Organisation for Economic Co-operation and Development (1974) reviewed scientific and technological activity in Australia. The report states that '... much more could be achieved if industries, State agencies, and especially CSIRO would engage the Universities more in research work' and in urging that the Universities need more staff especially to develop their research capacities to fulfil the needs of society, notes that there cannot be a strict prerogative for so called academic research work. If the report's viewpoint becomes accepted Federal Government policy then the Universities must meet those suggestions by the creation of numerous purely research positions from Post Doctoral Fellows through to fulltime and permanent senior research appointments, which at present within Australia are virtually non-existent and in striking contrast to the position in centres of excellence elsewhere in the world.

For almost an hour you have been patiently absorbing my suggestion that atmospheric chemistry is a field to which those recommen-

dations might properly be applied at the tertiary educational level. Studies in the atmospheric environment may however extend from very advanced research levels of physical and mathematical sciences downwards to observations and experience by John Citizen's children, this is a superbly interdisciplinary subject which should I believe be part of everyone's education.

Whatever your assessment is, please bear in mind that in 'three score years and ten' most of us will breathe some five hundred tons of air, and what it contains.

Postscript.—Professor R. T. Prider kindly drew my attention at the close of the Address to the fire at Spectacles Swamp, Mandogalup, April 1939, having badly affected Perth residential suburbs with its smoke. The Annual Report of the Mines Department, Western Australia, for 1939 (p. 148) refers to 'choking fumes . . . plainly and objectionably noticeable even in Perth 20 miles away'.

The 'West Australian', April 28th 1939, p. 24, describes 1000 acres alight for about three weeks and includes a photograph of soil damage. Two days previously a letter headed 'Mandogalup Peat' and signed R.V.R. recalls its author's prophesy in 1914 when swamp drainage was undertaken.

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2.—The changing ecology of Western Australian wheat production

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15 December 1975.*

Abstract

The ecology of wheat production in Western Australia has changed considerably since the commencement of wheat breeding in 1902. The changes involved are numerous and include technological developments such as the application of artificial fertilizers, correction for trace element deficiencies, increased use of mechanization, herbicides and insecticides and, the introduction of subterranean clover, which encouraged changes in crop rotational practices.

Collectively the changes which have occurred led to greater diversification of farming systems and to the declining popularity of those cultivars that were previously adapted. Further changes in crop management practices are considered necessary if the cultivars which are currently dominant are to be replaced.

Introduction

Agricultural research commenced in Western Australia in 1894 with the establishment of the Bureau, later the Department of Agriculture (Anon. 1967). Since then, under the guidance provided and through the release of more adaptable cultivars, wheat production and the acreage sown to wheat have increased considerably (Figure 1a). In contrast, improvements on yield per hectare have been gradual (Figure 1b). In addition to these production statistics, which reflect considerable seasonal variability, changes have occurred in the regional distribution of the area sown to wheat, in the farming systems and rotational practices employed and, in crop management technology; including mechanization, fertilizer practices and herbicide use.

The purpose of this paper is to trace the agro-ecological changes which have occurred in wheat production in Western Australia and to examine their influence on cultivar adaptability.

Historical

(a) Early Establishment

Wheat production commenced with the initial settlement (1826) using cultivars of English origin which were, relative to the growing conditions prevailing, late maturing (Berthoud, 1903).

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For this reason their cultivation was restricted to the south-west coastal areas where reasonable prospects for spring rainfall occur (Berthoud, 1905). The discovery of gold at Coolgardie (1892) and at Kalgoorlie (1894) provided the incentive for an increase in population and for the expansion of inland communication and rural water supplies. These events, in turn, encouraged an increased interest in agriculture which intensified following the decline in gold production, in 1903. As a result there was increased clearing of land despite limited agronomic information and the absence of suitable adapted cultivars. Research stations were established at Narrogin (1901), Nabawa (1902), Merredin (1907) and Avondale (1911). In 1905 G. L. Sutton, a contemporary and disciple of W. Farrer, was appointed Cerealist (later Director of Agriculture) and brought with him, from Wagga (N.S.W.), F₃ seed of the cross Gluyas x Bunyip which was to have a major impact on Australian and local wheat production for many years.

(b) Breeding and Cultivar Popularity

Continuous export of wheat commenced from Western Australia in 1907 largely due to the popularity of the cultivar Gluyas.¹ In 1915, from the cross Gluyas x Bunyip Sutton released Nabawa and by 1926 this cultivar occupied nearly 50% of the area sown to wheat; becoming in addition, the most popular cultivar in South Australia (1930-34) and in New South Wales (1930-35). In 1934 the supremacy of Nabawa gave way to Bencubbin; a cultivar derived from back-crossing Nabawa back to its Gluyas parent. (Figure 2). Bencubbin, which flowered earlier than Nabawa, proved even more popular, and with its relative Gluclub, dominated wheat production in Western Australia until 1945 as well as becoming the leading cultivar in South Australia and New South Wales throughout the 1940's.

The popularity of Bencubbin (and Gluclub) then declined somewhat in competition with Bungulla, an early flowering line selected from Bencubbin, and together, these various "Gluyas" descendants retained their popularity until the 1953/54 season. (Figure 2). In today's local terminology the relative flowering habits of the Nabawa, Bencubbin and Bungulla would be considered as late, late/mid-season and early, respectively. The original cultivars of English origin would, by comparison, be "very late".

¹ A farmer selection in South Australia from Words' Prolific; itself a farmer's selection from the South African variety Du Toit.

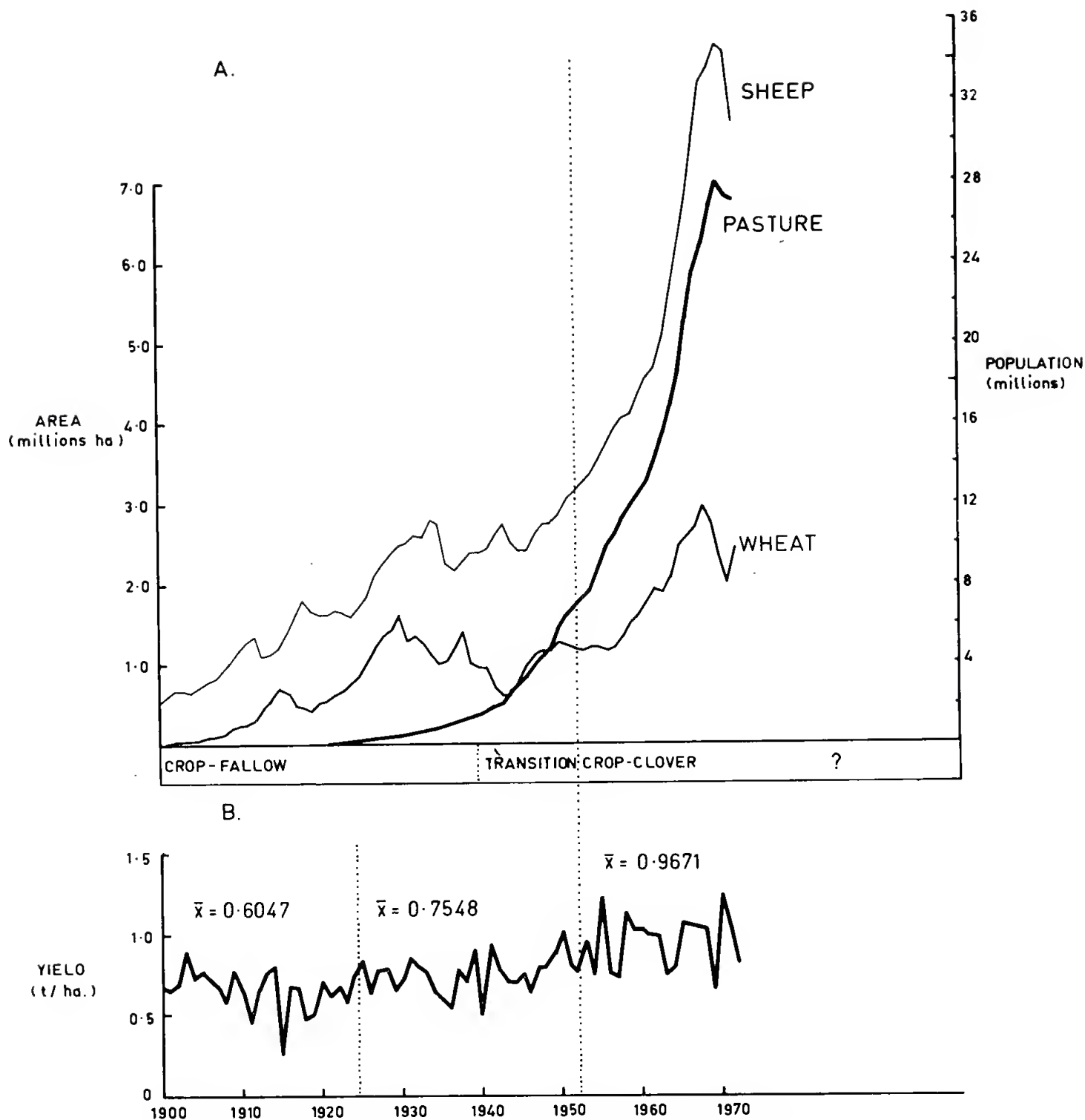


Figure 1.—(A) Changes in acreages sown to wheat and pasture and, in sheep population (1900-1972).—(B) Variation in state average wheat yields (1900-1972).

The popularity of the "Gluyas" cultivars decreased with the introduction of early/mid-season flowering semi-dwarf cultivars bred in New South Wales and Victoria. These cultivars, Gabo and Insignia, first introduced in the early 1950's, and their respective descendants, Gamanya and Heron, steadily increased in popularity until pressure for reasons of quality reduced the popularity of Insignia and Heron.

This brief review draws to attention the demise of local cereal breeding, following a period of prolonged success, and a gradual shift toward earlier flowering cultivars of short-stature.

This is interpreted as indicating a change in response to changes in the crop management practices under which wheat is grown in Western Australia and an attempt to account for it is presented below.

(c) Changes in Farming Systems and Cultural Practices

In the early days of settlement the differential land clearing of soils of high fertility led to sporadic settlement throughout those areas in which spring rainfall was sufficiently reliable to provide for the very late maturing cultivars then

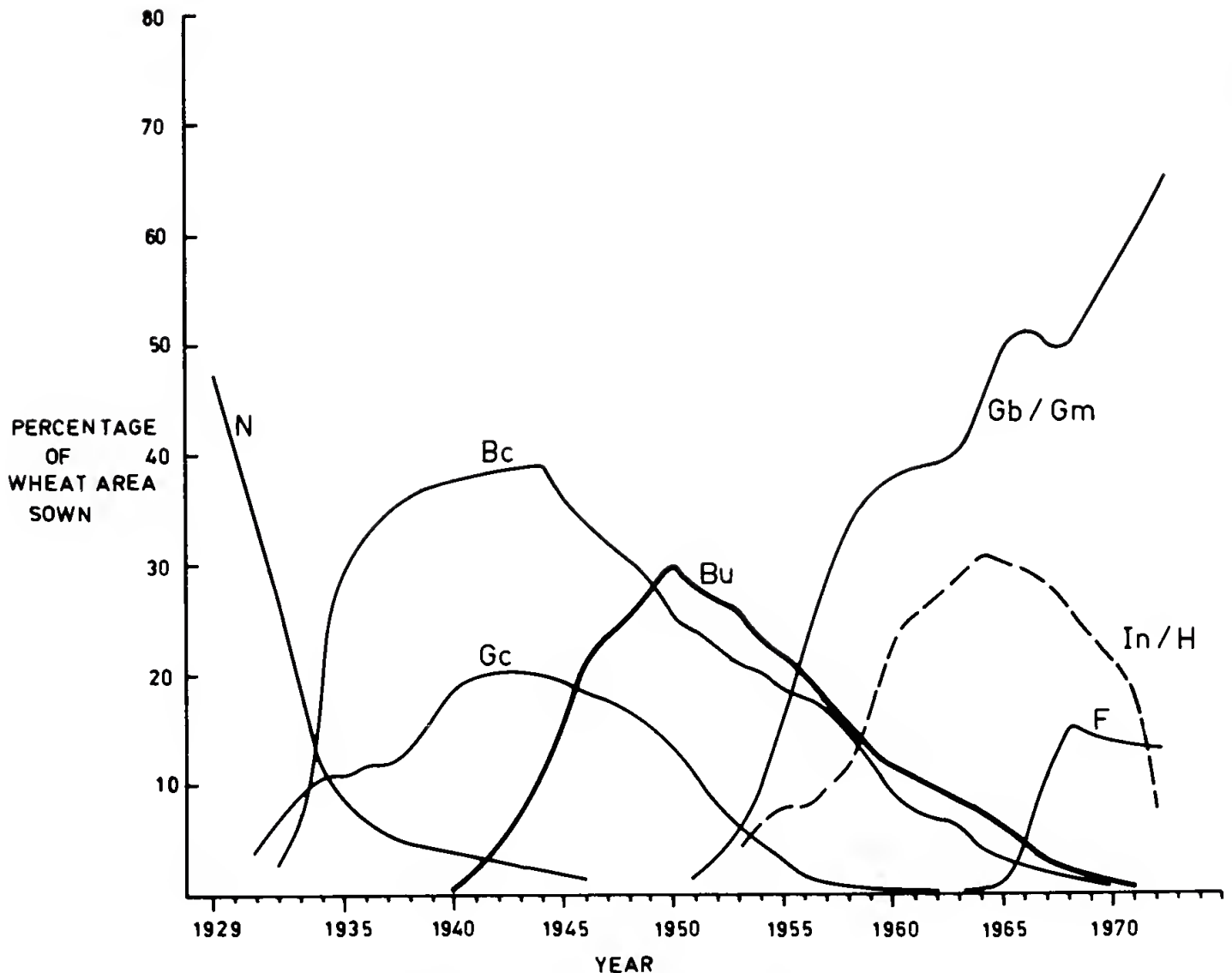


Figure 2.—Changes in wheat cultivar popularity (1929-1972). N = Nabawa (Gluyas x Bunyip—released 1915). Bc = Bencubbin (Gluyas x Nabawa—released 1929). Gc = Glucub (Gluyas x Clubhead—released 1922). Bu = Bungulla (Selⁿ from Bencubbin—released 1939). Gb = Gabo (Bobin x Gaza x Gular—released 1945). Gm = Gamenya (Gabo⁵ x Mentana//Gabo² x Kenya 117A—released 1960). In = Insignia (Ghurka x Ranee—released 1946). H = Heron (R.D.R. x Insignia⁴—released 1959). F = Falcon (Dundee x Gular²//Bencubbin—released 1960).

available. The limited extent of such soils and their exploitive use led to declining production and widespread recognition of the need for fertilizers, particularly phosphates (Callaghan & Millington, 1956; Wicken, 1904; Mann, 1905). Such a trend is demonstrated by the declining yield/hectare between 1900 and 1925 (Figure 1b). However, the increasing availability of phosphate fertilizer and the release of more adaptable cultivars, as discussed above, arrested this trend and encouraged a further increase in the area sown to cereals (Figure 1a). This expansion was suspended temporarily during the years of the depression and World War II and, again, in 1968-71, due to the imposition of quotas.

During the 1920's and 30's cereal crops were managed with horse-drawn equipment under a crop-fallow rotation which permitted pre-season weed control and early seeding to which the late and late/mid-season cultivars then available were well adapted. Early flowering cultivars such as Sunset and Noongaar were released but attained little popularity. These generalizations

represent a consensus of opinion expressed by Thomas and his co-workers (1926 to 1933) who were responsible for much of the experimentation that developed the basis for current cultural practices. The practice of bare fallow under continuous cultivation resulted in deterioration of the physical status of soils and emphasized the need to incorporate a pasture break in the rotation under a ley-farming system (Shier, 1956). At the time the availability of suitably adapted leguminous pasture cultivars was limited. The eventual release of sub-clover cultivars led to an exponential expansion of the pasture acreage (Figure 1a), a matching increase in sheep numbers (Figure 1a), increased soil fertility and a gradual conversion to crop-pasture rotational practices. A measure of these modifications on farming systems is provided by regional changes in the proportional utilization of cleared land for cereal crops (Figure 3).

The spread of sub-clover pastures and adoption of ley farming coincided with other significant technological events including the

REGIONAL DISTRIBUTION OF FARMING SYSTEMS SINCE 1929

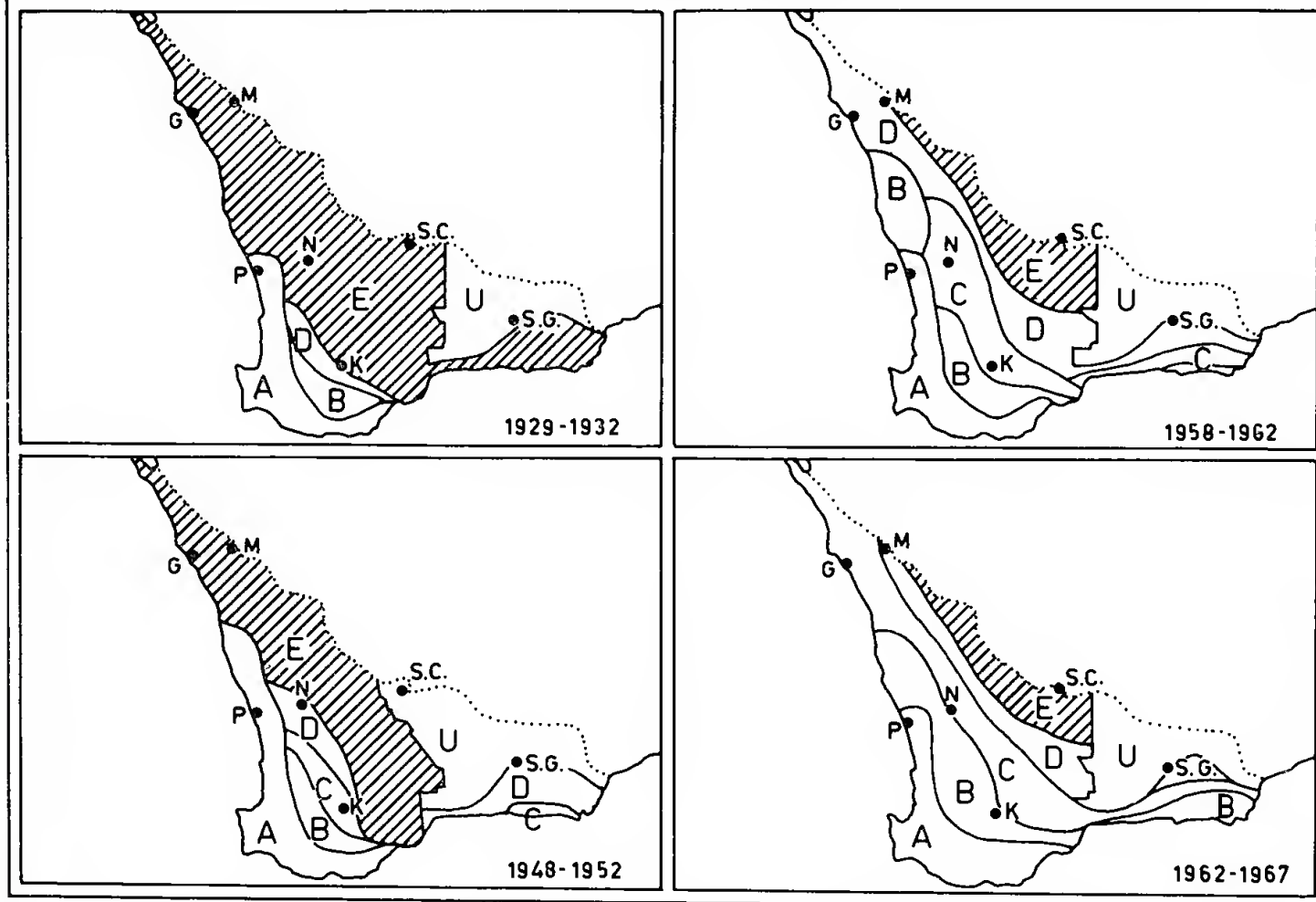


Figure 3.—Regional distribution of cropped acreage, at intervals from 1929 to 1967. A <10% Cereals, balance in pasture. B >10 <25% Cereals, balance in pasture. C >25 <50% Cereals, balance in pasture. D >50 <75% Cereals, balance in pasture. E >75 Cereals, (shaded) balance in pasture. U Unallocated.

recognition of, and correction for, trace element deficiencies (Burvill, 1965), the replacement of horsepower by mechanization and the introduction of herbicides and weedicides to control increased weed problems arising from the absence of fallow. The use of artificial fertilizers, principally superphosphate, has increased in conjunction with crop and pasture acreage. This has led to improved soil phosphate levels and further enhancement of soil fertility status, even though, from 1925 to 1960, application per unit area (ranging between 0.113 to 0.125 tonnes/ha has hardly altered. (Figures 4a and b).

The change in rotational practices together with the adoption of technological developments have stimulated more diversified farming systems (Figure 3) and, in more recent years, greater intensification within them—as evidenced by increased use of nitrogenous fertilizers (Figure 4). These developments have had numerous implications in the management of cereal crops; including the need to delay seed-bed preparation so as to conserve pasture for increased stock numbers and, a decrease in the use of cereal crops for purposes other than grain production i.e. for hay and stubble grazing purposes. Delay in seed-bed preparation has contributed to the later seeding of cereal crops

and greater weed control problems—disadvantages which have been only partly compensated for by increases in soil fertility and increased mechanization because of the need to await opening rains and weed germination before cultivation can proceed.

Discussion

The introduction of leguminous pastures in particular, and the adoption of improved fertilizer and weed control technologies, have directly led to diversification of farming systems in Western Australia, and to changes in crop management practices. These changes include conversion from crop-fallow rotational practices favouring pre-season weed control, early seeding and the use of tall growing late to late/mid-season cultivars, to crop-pasture rotations characterized by increased soil fertility, increased weed problems, and an enforced delay in seedings to permit seed-bed preparation. Under these circumstances short-stature cultivars of early to early/mid-season maturity have gained in popularity. (Figure 5). The sequence of events which has occurred represents a classical case history of changes in cultivar adaptation because, at no stage has disease or con-

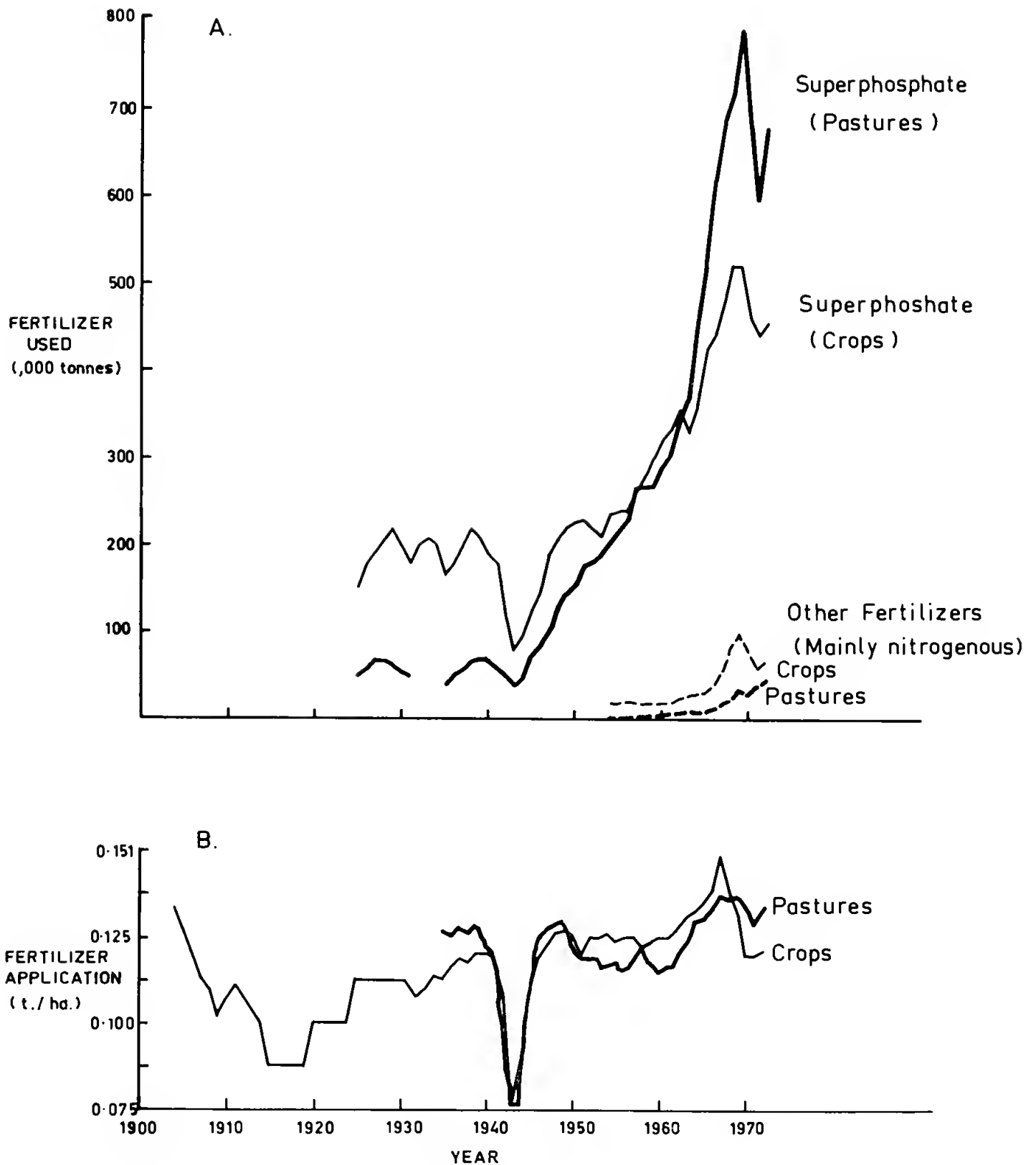


Figure 4.—Changes in fertilizer consumption, particularly superphosphate (A) and in application rate (B), on both crops and pastures

siderations of quality been responsible for directing major changes in cultivar use. Unpublished data indicate that whilst the currently popular cultivar (Gamenya) is over 20% more productive than its predecessor (Bencubbin) under crop-pasture rotations, these cultivars are of equivalent performance if planted early on fallow. In fact Bencubbin was still being recommended for early planting as recently as 1965,

even though its popularity was low (Figure 2). Despite the current and relative yield advantage of Gamenya over Bencubbin district average wheat yields/ha have increased to a more limited extent. This suggests, that the contribution of plant breeding in recent years has been one of developing cultivars more adapted to the changes in cultural practices and farming systems that have taken place.

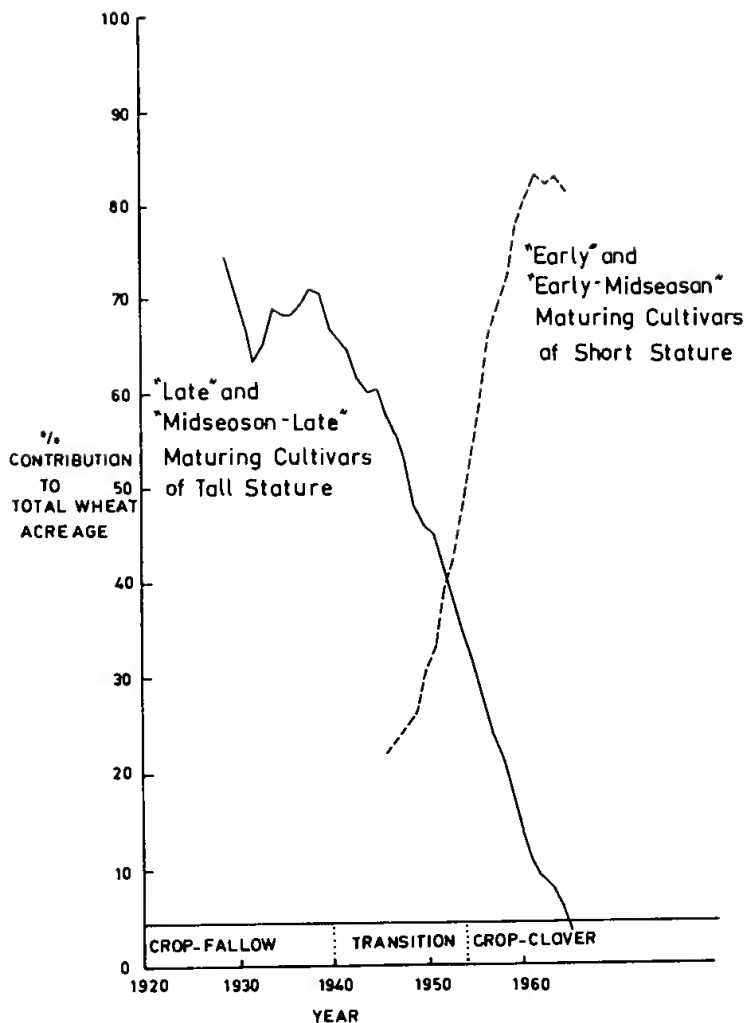


Figure 5.—Changes in the adaptive characteristics of wheat cultivars with changes in cultural practice.

The changes which have occurred illustrate the important ecological principle of a dynamic, and delicate, balance between genotype and environment. Modification of the environment affects the productivity and survival of biological organisms within the biosphere. Man's current concern over his own survival as a consequence of his interference with the environment (e.g. pollution of air and water) stands in sharp contrast to his ancient and continuing need to modify the agricultural environment for the benefit of crops he grows and the livestock he tends. With increasing understanding of plant growth, development and genetics, man has the capacity, through plant breeding, to modify his crop plants to exploit the environmental conditions he can provide for them. The changes in cultural practices discussed in this paper have had the effect of rendering less adaptable and less efficient those

cultivars that were once so popular (Figure 2). The continued popularity of Gamenya, despite breeders efforts to improve upon its performance, suggest that additional changes in the crop environment could be a prerequisite to further breeding progress. As the previous changes led to greater diversification of farming systems it is most probable that increased intensification within those systems will now become more urgent.

Acknowledgements.—The W.A. State Wheat Industry Research Committee and the W.A. Barley Research Trust Fund provided financial support.

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3.—The nutrients and plants of Lake Joondalup, a mildly eutrophic lake experiencing large seasonal changes in volume

by R. A. Congdon¹ and A. J. McComb¹

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21 October 1975.

Abstract

Lake Joondalup is a shallow body of fresh water in a calcareous stable dune system 6 km from the ocean. The fringing and aquatic vegetation is described. Cation ratios resemble sea water apart from relatively high calcium, attributed to leaching from limestone. Seasonal changes in volume greatly affect ionic concentrations. A bloom of the green alga *Dispora* coincides with low volume and high ion levels. Total nitrogen is relatively high compared with phosphorus. The surrounding land is becoming urbanized, and the data provide a baseline for future reference.

Introduction

Problems associated with the enrichment of lakes in urban areas, with 'blooms' of planktonic algae (some of them toxic to animals), increased bacterial activity, and oxygen depletion at depth, are of worldwide occurrence (e.g. Jackson, 1964). Press reports of the death in late summer of fish and birds in certain lakes of the metropolitan area of Perth indicate that Western Australia is no exception. While it is easy to suggest that the addition of nutrients derived from septic tanks, garbage disposal, and agricultural and lawn fertilisers, are primarily responsible for the eutrophication of these waters, quantitative data concerning nutrient levels and algae are lacking.

The present paper is concerned with the nutrients and plants of Lake Joondalup, which lies in a region of rapid urbanization and development. The lake is 32 km north of the centre of Perth and 6 km from the Indian Ocean, and is one of a chain of lakes which reaches Yanchep, 20 km further north. The lakes are linear, parallel to the coast, and lie in depressions in a Quaternary dune system (McArthur and Bettenay, 1960). They are an important component of the wetlands of the Swan Coastal Plain, which are being reduced in total area by draining and reclamation (Riggert, 1966).

The aim of this work was to place on record the seasonal fluctuations in certain nutrients and in the density of planktonic algae to provide a reference against which future changes in the lake may be assessed. A description of the fringing vegetation is also included to allow comparison with Loch McNess in the Yanchep National Park (McComb and McComb, 1967), and because much of this vegetation, which must relate to the nutrient status of the water, will be altered in the future.

Materials and methods

Collection of samples

Water samples were collected from 6 sites (Figure 1) over a period of one year. Samples for oxygen analyses were collected directly into a sample bottle where the water was shallow, or with a Hale's water sampler (Welch, 1948) where the water was sufficiently deep to allow use of this apparatus. Other samples were collected with a plastic bilge pump at a depth of 5 cm. All were collected between 1000 and 1600 hr. At each site measurements were made of water temperature and pH (BpH Electrometer, N. L. Jones, Melbourne). A comparative measure of light transparency was obtained with a 20 cm-diameter Secchi disc divided into black-and-white quadrants.

Samples for metallic cations were stored in clean 250 ml glass bottles, with 1 ml of 1:1 (by vol.) nitric acid added to prevent adsorption and biological activity. Other samples were stored at 4° in thoroughly-washed, 5 l polyethylene jars.

Water analysis

Dissolved oxygen was initially measured in the field with an oxygen meter (Beckman Fieldlab Oxygen Analyser, Beckman Instruments, Fullerton, California) and subsequently by the azide modification of the Winkler Method (Anon. 1955). *Conductivity* was determined on return to the laboratory with a conductivity meter (E 382, Metrohm Ltd., Herisau, Switzerland). *Ammonia* was determined by distillation and nesslerization (Anon. 1955); *organic nitrogen* by Kjeldahl digestion (Anon. 1955) followed by titration with an automatic titrator (W. G. Pye, Cambridge, England); *inorganic phosphorus* as orthophosphate by the molybdate-blue reaction using stannous chloride as the catalyst (Anon. 1955); *total phosphorus* as orthophosphate after perchloric acid digestion (Robinson, 1941); and chloride by potentiometric titration using a Clinical Chloride Titrator (4-4415, American Instrument Co., Silver Spring, Maryland). *Carbonate/bicarbonate* was determined on one occasion using the double-indicator method (Anon. 1955).

Samples for analysis of *metallic cations* were given the pretreatment for total metals described by Parker (1972). Calcium and magnesium were then determined by atomic absorption spectrophotometry (Varian 1000, Varian Techtron Pty. Ltd., Springvale, Victoria), and sodium and potassium by flame photometry (EEL Flame Photometer, EEL International Ltd., Bayswater, Victoria).

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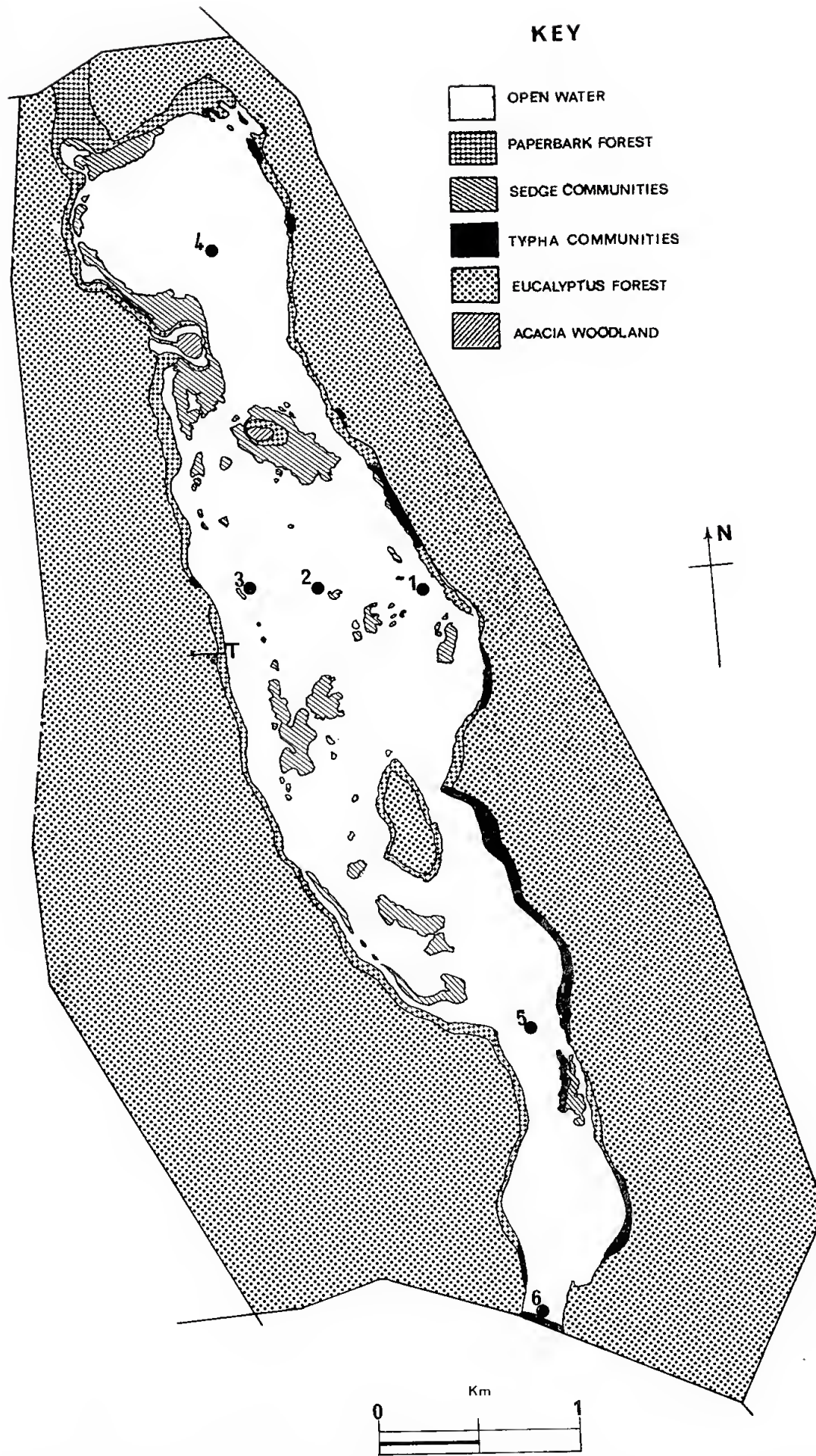


Figure 1.—Lake Joondalup, showing general features, vegetation, and sampling sites.

Productivity

Samples of 500 ml of water from each site were centrifuged (660xg; 10 min) and the supernatant removed with a suction pump to leave 10 ml of water plus centrifugate, which was transferred to a stoppered flask and stored in the dark at 4° until phytoplankton counts were made with a Neubauer counting chamber. The problem of obtaining truly representative plankton samples for the lake is great, as the large area and shallow water leads to lack of homogeneity in phytoplankton populations. For example, although in October counts were generally low at the six sites, it was clear that a bloom, primarily of *Oscillatoria* and a colonial alga, was present in parts of the lake not included by the six sites. Nevertheless, seasonal trends are clear, main species were identified, and general variability is reflected in the standard errors of the site means, as given below.

Seston productivity was estimated on duplicated 500 ml aliquots, centrifuged as for the phytoplankton counts. Each 10 ml residue was transferred to a 50 ml porcelain crucible, dried at 80° overnight, placed in a desiccator for 30 min and weighed. It was then ashed in a muffle furnace at 650° for 30 min, cooled in a desiccator and reweighed. Seston productivity was calculated as loss on ignition in grams per litre.

Observations and discussion

General features

The lake (Figure 1) is a shallow, closed body of fresh water 8 km long and 1.2 km wide at its broadest point. The depth varies seasonally but has never exceeded 3.3 m. The water surface is some 18 m above mean sea level, and the area is 6.1 km² (610 hectares). There is no surface outlet for the lake, and it is believed that water passes through the limestone on the western shore, towards the sea. The western bank is relatively steep and little disturbed. To the east the land slopes more gently, and there is a housing settlement. Deep sewerage has become available in the area, and at the time of the study about 25% of the 630 houses present had been connected to the system.¹

The mean depths of the sampling sites were between 10 and 190 cm during the period of the study, the changes in depth following changes in rainfall (Figure 2). By international standards, therefore, Lake Joondalup is very shallow, and because of this shallow character the changes in depth represent large changes in lake volume. One would therefore expect significant seasonal changes in concentrations of dissolved elements because of this factor alone. The water level has been even lower in the past, as indicated by the presence of submerged fence posts in the open water of the southern and eastern regions of the lake; there is evidence

that the general water level of wetlands in the coastal plain has increased, presumably as a result of clearing (Evans and Sherlock, 1950; Speck, 1952).

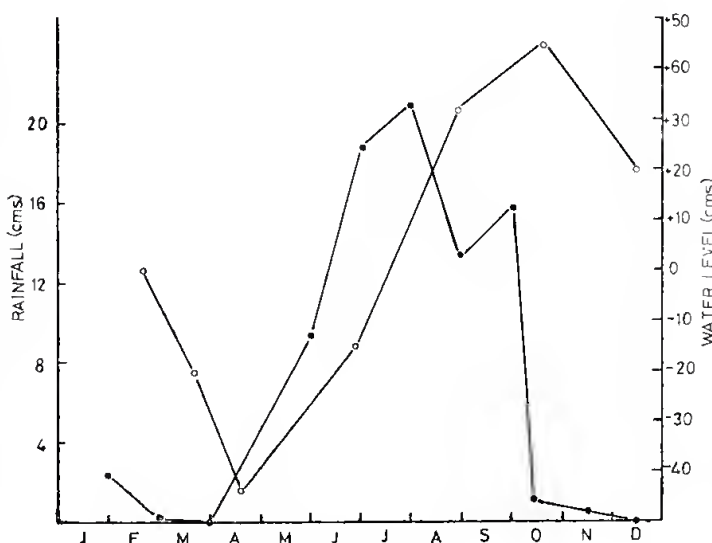


Figure 2.—The water level of Lake Joondalup (o), plotted with monthly rainfall data (●) for the townsite of Wanneroo, which lies immediately east of the Lake.

Vegetation

The distribution of main communities is shown in Figure 1, and a transect through the fringing communities on the western shore is presented in Figure 3.

Open Water and littoral fringes—Shallow waters, less than about 70 cm in summer, are densely populated with the benthic stoneworts, *Nitella congesta* and *Chara baueri*, and *Potamogeton pectinatus*. *Najas marina* and *Myriophyllum propinquum* are also found in the shallow waters, but are more common in the deeper waters at the northern end of the lake. The floating plants *Lemna minor* and *Azolla filiculoides* were collected in the fringing sedge communities, but were never numerous during the period of study.

The sedge *Baumea articulata* (*Machaerina articulata*, *Cladium articulatum*) is the dominant macrophyte of the lake, occurring generally in pure stands. It attains a height of 2 to 3 m and, through decomposition, is the main contributor to a fibrous peat of the lake margins and sedge banks. *B. articulata* is replaced by *Typha* in restricted areas where pasture or roads encroach on the lake edge. *Scirpus validus* and *Juncus pallidus* also occur in restricted areas.

Fen vegetation.—This is represented by a few small pockets of *Baumea juncea* (*Machaerina juncea*, *Cladium junceum*) located on the northern fringes of the two islands, and in scattered areas beneath swamp paperbarks. On Malap Island and on the lake margin to the north *Lepidosperma longitudinale* occurs in drier areas behind *B. juncea*.

¹ The general information included in this paragraph was provided by courtesy of the Shire Clerk, Shire of Wanneroo.

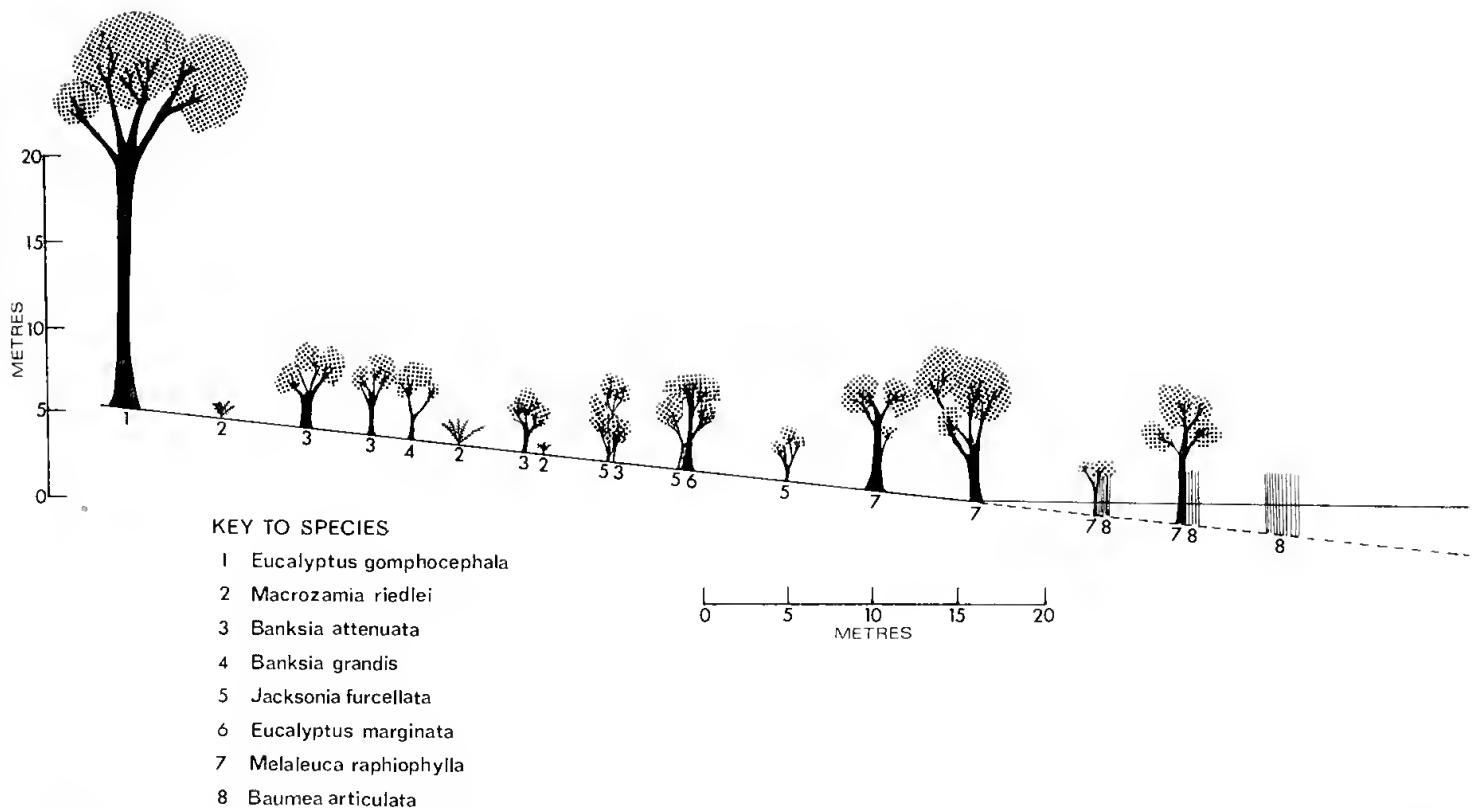


Figure 3.—The vegetation fringing Lake Joondalup. The profile was drawn from a 2 m-wide transect situated at site T, Figure 1.

Paperbark woodland.—A woodland of swamp paperbark (*Melaleuca raphiophylla*) borders the fringing sedge communities, and the bases of the trees are inundated during the winter months. The woodland consists of a narrow belt of trees with dense, touching canopies, and often includes *Eucalyptus rudis*. *Baumea juncea* and *Centella asiatica* are common. Seedlings of *M. raphiophylla* are established in meadows of *Baumea articulata* and this 'carr' is extensive on the north-western side of the lake and to the south-east of Malap Island.

Surrounding woodland.—An ecotonal community can be recognized between the paperbark woodland and the surrounding forest. It consists of a number of species which occur in both communities, including *Acacia cyclops*, *Acacia saligna*, *Jacksonia furcellata*, *Banksia littoralis* and *Banksia attenuata*. *Banksia ilicifolia* occurs in the ecotonal region on the north-eastern shore. In two small areas there are patches of *Acacia cyclops* sufficiently distinct to be designated 'Acacia woodland' (Figure 1). The surrounding forest has been described by Speck (1952) as tuart forest and jarrah-tuart-ecotone forest, and by Seddon (1972) as tuart-jarrah-marri tall open forest formation; its composition has been well documented by these authors. Much of the forest has been felled to the south for farming, and on the eastern shore is being cleared for housing developments.

General.—The fringing vegetation is in general similar to Loch McNess (McComb and McComb, 1967), but there is less species diversity at Lake Joondalup, and fen vegetation is not extensive. *Scirpus validus* is a more prominent member of the sedge communities at Loch McNess, and

this may be related to the seasonally more constant water level there. In contrast to the sedge communities, the benthic vegetation is more strongly developed at Lake Joondalup, in terms of both species number and plant density.

As there is evidence that the level of the lake has increased in relatively recent times, one might expect the swamp and fen successions to be disturbed, and it is quite possible that fen vegetation may have been more extensive in the past. The *Melaleuca* woodlands are more inundated in winter, and the root systems of the trees may be adversely affected by increased waterlogging. *Typha* appears to be associated with shore disturbance, and further disturbance may lead to an increase in this species.

Temperature and light

Water temperatures are closely correlated with mean monthly air temperatures (Figure 4). Light penetration as measured with the Secchi disc is shown in Table 1; the disc was visible to the substratum during February to June, but in August to December, when the lake was relatively deep, the limit of Secchi disc transparency was 30 to 130 cm above the substratum. As the point at which the Secchi disc becomes invisible is a useful guide to the depth at which light penetration allows the survival of benthic plants, light may well be a limiting factor for the growth of benthic plants at depth in the lake in August to December. Low light intensities and lower temperatures thus combine to reduce productivity of the benthic plants in winter. As shown below, plankton densities and seston productivity are at their lowest in August to

December, so that it is depth rather than density of suspended matter which is the prime factor influencing light penetration.

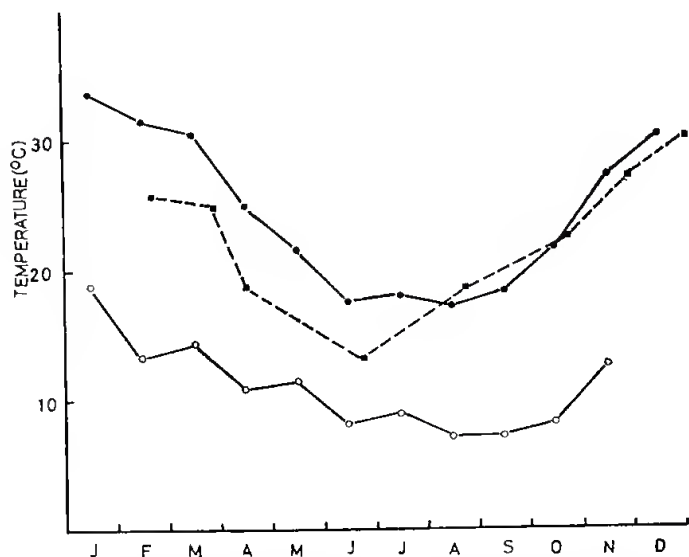


Figure 4.—The temperature of Lake Joondalup (broken line), plotted with atmospheric temperatures at the Upper Swan Research Station: (●, mean monthly maximum; o, mean monthly minimum).

Chemical characteristics

Oxygen.—The dissolved oxygen concentration varied seasonally between 6 and 9 mg/l (Table 1). This range is relatively high, since the solubility of oxygen at 760 mm Hg is 8.1 mg/l at 25° and 10.3 mg/l at 13° (Hutchinson, 1957). (Oxygen becomes critical to aquatic life at 3 mg/l; Welch, 1952). These high levels are accounted for by the large surface area of the lake in relation to its volume, and exposure of the surface to agitation by wind and rain. The rich growth of benthic plants and presence of phytoplankton indicates a contribution to the oxygen concentration through photosynthesis during daylight hours. The possibility of oxygen depletion at night was not investigated in the present study.

Specific conductivity.—This ranged from 1068 to 3114 $\mu\text{mhos.cm}^{-1}$ (0.7—1.8% Total Dissolved Solids) (Figure 5). At Loch McNess a mean conductivity of 394 ($\mu\text{mhos.cm}^{-1}$) was reported on one occasion (McComb and McComb, 1967). The concentrations of dissolved salts in Lake Joondalup are comparatively high for a freshwater lake—for example Juday and Birge (1933) obtained a range of 9 to 124 (μmhos for more than 500 Wisconsin lakes, and Welch (1952) found lakes in Michigan to have a range of 10 to 330. Inland Australian lakes are characteristically much more saline (Bayly and Williams, 1973). The high conductivity is a reflection of high concentrations of individual ions (see below). The high conductivities of Lake Joondalup and Loch McNess are partially explained by their locations near aeolian limestone deposits. In addition, they are situated within 6 km of the

Indian Ocean, and undoubtedly receive ions by wind and rain from that source. Evidence for this is discussed further below, but here we may note that the levels of chloride in the lake are relatively high. Chloride levels and conductivity show an expected trend in relation to change in lake volume, (cf. Figures 2 and 5), the increased water of the winter season diluting the dissolved ions.

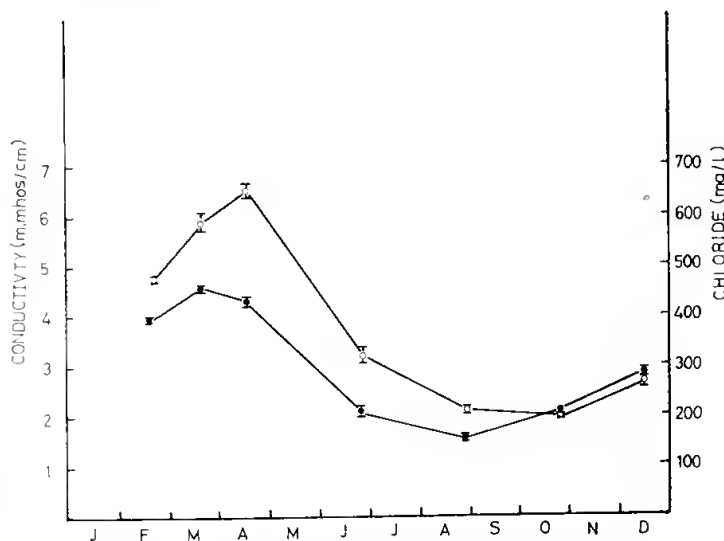


Figure 5.—Specific conductivity (●) and chloride concentrations (o) for Lake Joondalup.

Acidity.—The lake is alkaline, and pH did not vary greatly with season, the range being 8.4 to 9.2 (Table 1). Constancy can be at least in part attributed to the buffering effect of carbonate and bicarbonate ions, the levels of which are expected to be high in view of the amounts of calcium and magnesium present (see below). An analysis of carbonate-bicarbonate carried out in December gave an alkalinity of 180 mg CaCO_3/l . Leaching of calcareous deposits is presumably the main factor determining the high pH. For example, a South Australian volcanic lake in contact with limestone gave a pH of 8.2 (Bayly and Williams, 1964), while 19 eastern Australian lakes in silicious dunes had a pH range of 4.3 to 6.0 (Bayly, 1964). Loch McNess has a lower pH than Joondalup, a mean of 7.8 being reported (McComb and McComb, 1967), and this correlates with the lower conductivity of that lake.

Metallic ions.—Like chloride and conductivity, the concentration of metallic ions decreases with increase in water level (Figure 6). The levels of these ions are compared with certain other lakes in Tables 2 and 3. The first of these tables gives absolute levels, and the second the equivalents of each ion expressed as a percentage of the whole. It is clear that the levels of metallic cations at Joondalup are relatively high for a freshwater lake. The relative proportions of cations resemble those found by Bayly (1964) for 19 coastal dune lakes in Queensland and New South Wales, and are also similar to those found in seawater, and in rainwater collected 16 km from the coast (Hutton and Leslie, 1958), except for the higher level of calcium. The proportions in Lake Joondalup

Table 1*Seasonal changes in light penetration, oxygen and pH at Lake Joondalup**Means are of 6 sites; standard errors are in brackets*

	February	March	April	June	August	October	December
Secchi disc transparency (m)	> 0.90 ¹	> 0.90 ¹	> 0.80 ¹	> 0.95 ¹	0.63(0.04)	0.61(0.02)	0.58(0.04)
Dissolved oxygen (p.p.m.)	8.85(0.59) ²	8.60(0.45) ²	6.12(0.60) ²	8.91(0.14)	8.82(0.51)	8.23(0.16)	8.15(0.62)
pH	.....	9.22(0.14)	8.97(0.21)	8.45(0.11)	8.58(0.23)	8.54(0.24)	8.73(0.53)

¹ maximum depth of water at time of sampling² determined with oxygen probe; other oxygen data by titration**Table 2***Concentrations of ions found in various lakes**Data are in mg/l*

Lake	Na	K	Ca	Mg	Cl	Reference
Joondalup, W.A.	140 to 513	8 to 20	44 to 57	21.5 to 43.5	212 to 655	This paper
Coastal dune lakes, N.S.W. and Queensland	7.9 to 26.3	0.2 to 1.2	0.2 to 0.8	0.7 to 2.8	12.5 to 43.3	Bayly 1964
Croispol Loch, Scotland	20.9	1.6	27.1	22.2	.....	Spence et al. 1971
German lakes	.....	.....	43.6 to 46.3	.....	.....	Hutchinson 1957
Tasmanian inland lakes	.....	.....	0.8 to 82.4	0.2 to 118.6	.....	Williams 1964
Blue Lake, S.A.	63	4	36	21	116	Bayly and Williams 1964
Cowan, W.A. ¹	74 276	387	689	10 435	138 638	Williams 1966

¹ Lake Cowan is a salt lake, the others are freshwater lakes**Table 3***The proportions of cations found in various waters**Data are percentages of total equivalents of the ions*

Source of Water	Na	K	Ca	Mg	Reference
Lake Joondalup, W.A.	56.5 to 77.8	1.5 to 2.4	9.0 to 20.2	11.4 to 20.9	This paper
Coastal dune lakes, N.S.W. and Queensland	78	2	4	16	Bayly 1964
Seawater	77	2	3	18	Bayly 1964
Rainwater, Vic.	73 ¹	.....	9	18	Hutton and Leslie 1958
Lake Cowan, W.A.	78	0.2	0.8	21	Williams 1966
Sedimentary source	5	8	53	34	Hutchinson 1957
Loch Croispol, Scotland	22	1	32.7	44.3	Spence et al. 1971
Blue Lake, S.A.	45 ¹	.....	28	27	Bayly and Williams 1964

¹ includes sodium and potassium

are also similar to those found for Lake Cowan, a salt lake, despite the dramatically-different total ion concentrations present (Table 3 cf. Table 2). However, they contrast, (with the possible exception of calcium), with mean values for sedimentary sources (Hutchinson, 1957); and Spence *et al.* (1971) report that a truly calcareous loch in Scotland, Croispol, had higher milliequivalent proportions of calcium and magnesium. At Blue Lake, which has somewhat intermediate ratios, Bayly and Williams (1964) attribute the proportions to the combined influence of leaching from limestone in the lake's watershed, and influx of ions from the sea via precipitation. The data from Lake Joondalup, which is situated only 6 km from the ocean, are consistent with the interpretation that precipitation has been the main determining factor in controlling ionic composition, the raised value for calcium being attributable to the leaching of this metal from limestone.

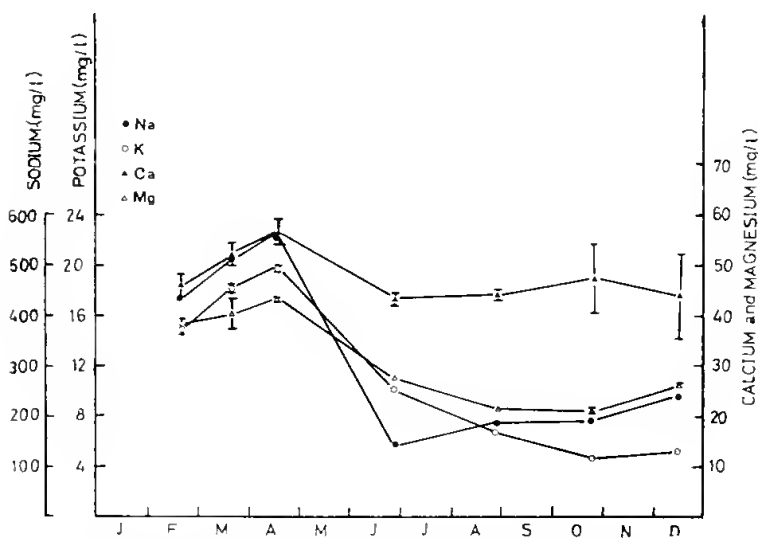


Figure 6.—Seasonal changes in concentrations of metallic cations at Lake Joondalup.

Organic nitrogen and ammonia.—Both of these parameters show the same general seasonal trend of decreasing concentration with increasing water level (Figure 7), but superimposed on this trend there is an increase in the concentration of organic nitrogen from June to August. For comparison, Lake Mendota, a eutrophic lake in Wisconsin, had an organic nitrogen concentration ranging from 0.3 to 0.6 mgN/l (Peterson *et al.*, 1925), values considerably lower than those obtained at Lake Joondalup, where the range was 1.5 to 3.00 mgN/l. One explanation for the high levels is the release of organic nitrogen by the decomposition of organic material derived from the dense macrophytic vegetation and benthic hydrophytes. Another possible source of nitrogen is seepage of nutrients from septic tanks. The concentration of ammonia-nitrogen was between 0.05 and 0.48 mg/l. Hutchinson (1957) gives a range of 0.05 to 0.54 mg/l for the Madison lakes of Wisconsin, and attributes the upper values to derivation from sewage.

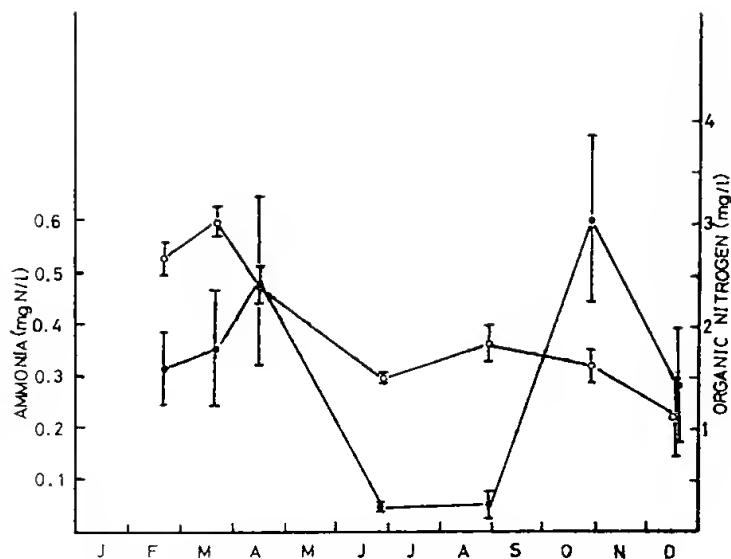


Figure 7.—Ammonia nitrogen (●) and organic nitrogen (○) in Lake Joondalup.

Phosphorus.—The curves for phosphorus are reminiscent of those for nitrogen. Inorganic phosphorus showed the familiar trend of decreasing concentration with increasing lake volume, whereas organic phosphorus increased when the levels of the lake were increasing (Figure 8). This increase may be due to increased assimilation of inorganic phosphorus by phytoplankton (see below), increased decomposition of organic material in the lake margins and floor, leaching of phosphorus into the lake, and to the release of phosphorus from the sediments because of agitation by wind.

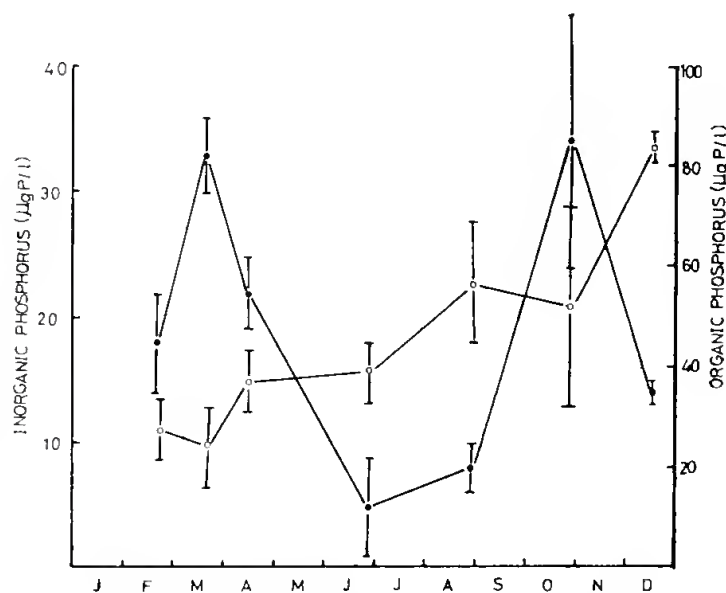


Figure 8.—Inorganic phosphorus (●) and organic phosphorus (○) in Lake Joondalup.

Inorganic phosphorus varied between 0.006 and 0.04 mgP/l which compares with the range of 0.001 to 0.04 given by Pearsall (1930) for 9 lakes of the English Lake District. There phosphate was the nutrient in relatively smallest quantity, and concentrations were lowest in the shallower lakes. At Joondalup the ratio of nitrogen to phosphorus varied between 70:1 and 140:1, and the ratio would be higher if nitrate

had also been determined. As the ratio in plants is about 15:1 to 2:1 (e.g. Gerlaczynska, 1973), one may speculate that of nitrogen and phosphorus, the level of phosphorus is more likely to be limiting for plant growth.

Phytoplankton

Total numbers of phytoplankton are shown in Figure 9, where it can be seen that there was an algal bloom, some 4×10^7 organisms per l, in the period April to June. The highest den-

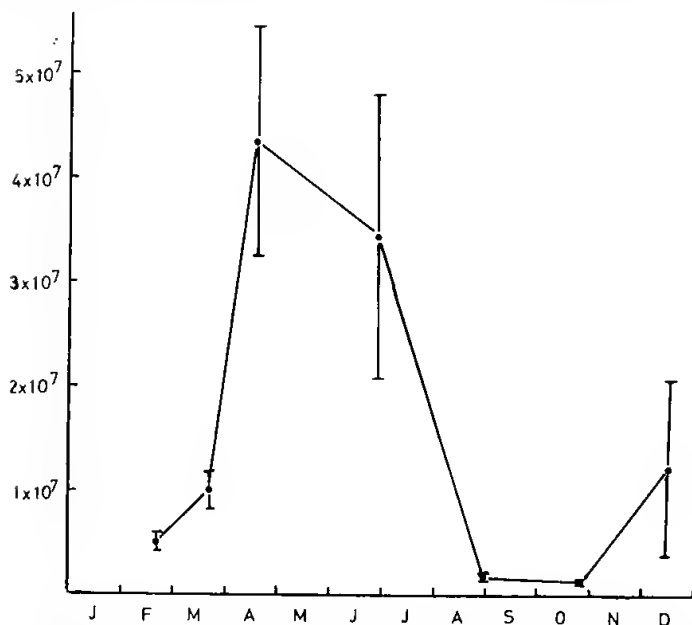


Figure 9.—The planktonic algae of Lake Joondalup. The number of individuals of all species is expressed per litre.

sity of the bloom was in mid April, coinciding with minimum lake level (Figure 2) and highest concentrations of metallic cations (Figure 6). Temperature was falling (Figure 4). Phosphate phosphorus (Figure 8) peaked a month before the maximum algal bloom, and an increase in the organic P fractions is associated with the bloom. Not surprisingly, organic N is also relatively high (Figure 7). Both organic P and N remain relatively high after the bloom, and no

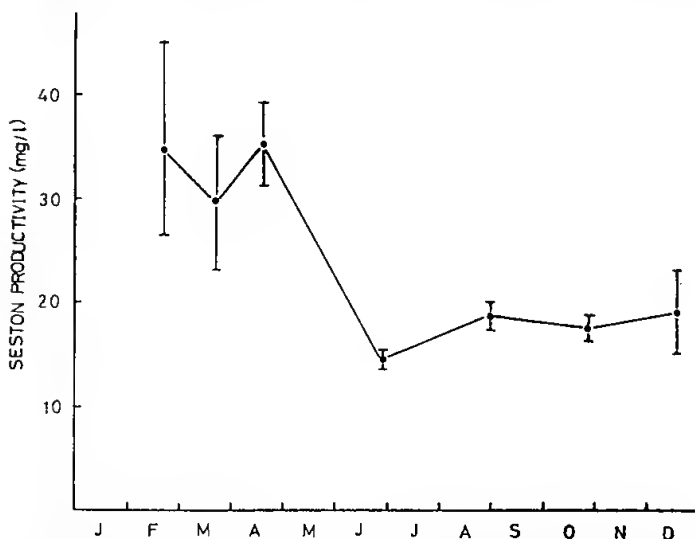


Figure 10.—Seston productivity of Lake Joondalup.

doubt part of this organic material is derived from algal decomposition and bacterial action. Seston productivity (Figure 10) is more closely correlated with organic N than with total plankton, again suggesting relatively high levels of organic material in the lake.

The distribution of particular species of algae is shown in Figure 11, and it is immediately apparent that the main bloom is due to the presence of *Dispora crucigenoides*, a green alga. In December there was a minor bloom of a blue-green, *Raphidiopsis*, but distribution in the lake was very patchy as indicated by the large standard error on the December figure in Figure 9.

Occurrence of the blue-green *Anabaena spiroides* is of interest, as this is known to fix atmospheric nitrogen (Cameron and Fuller, 1960). It appears in the lake in significant numbers in August, at a time when ammonia levels are low and organic N high, and this suggests that levels of available nitrogen may have become limiting to the growth of algae at that time. *Anabaena* and *Anacystis* (which is also present in the lake but in low numbers) can produce blooms toxic to animals (e.g. Jackson, 1964). There have been no reports, to our knowledge, of the death of fish or waterfowl in the lake, as there have been in summer for certain other Perth lakes. There is, however, a possibility of such toxic blooms occurring in Joondalup if further enrichment occurs.

General

Lake volume is the major factor determining seasonal changes in concentration in dissolved substances. The data are consistent with the view that phosphorus levels may limit algal productivity in the lake, except for a short period of the year when there is a small increase in *Anabaena*. Suitable culture experiments could be carried out to examine these possibilities. The observations indicate a need for further monitoring as urbanisation around the lake progresses, and a need for comparable data on the trophic status of other lakes, including those in national parks not affected by urbanisation. The relatively high levels of phosphorus and nitrogen in the water, and the occurrence of algal blooms, justify the provisional designation of the lake as 'mildly eutrophic'.

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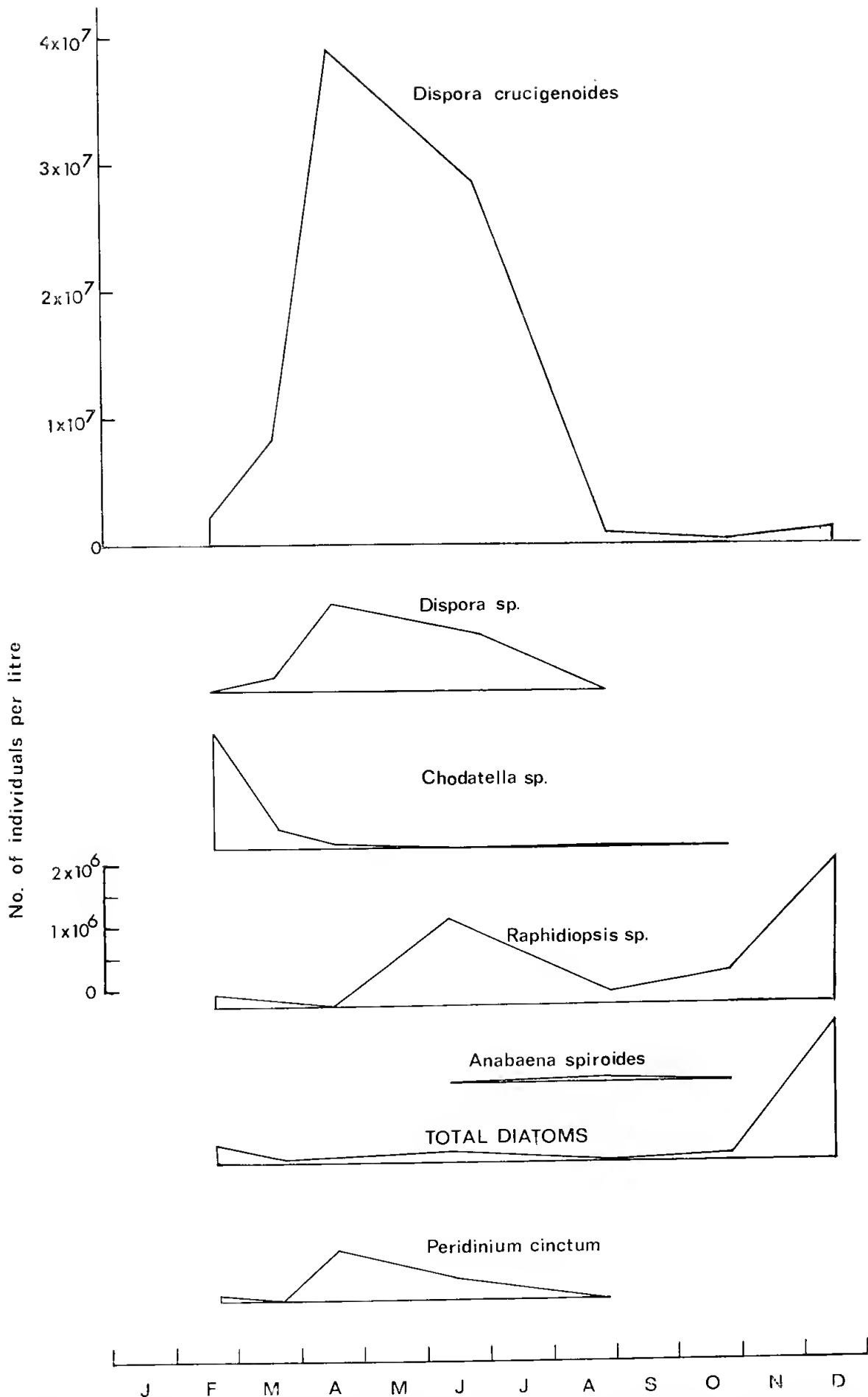


Figure 11.—Planktonic algae of Lake Joondalup, showing the number of individuals of the main taxa present, expressed per litre. Note that the scale for *Dispora crucigenoides* is reduced as compared with that for the other algae, which is the same in each case.

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4.—Descriptions of three new fishes from Western Australia

by Gerald R. Allen¹

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Abstract

Three new species of marine fishes are described from coastal waters of Western Australia. Two of the species, *Ellerkeldia rubra* and *Anthias georgei* are serranids and the third, *Parapercis biordinis*, belongs to the Mugiloididae. The three species are illustrated and keys to the *Ellerkeldia* and *Parapercis* from Western Australia are provided.

Introduction

The most recent comprehensive listing of Western Australian fishes is that of Whitley (1948). He included approximately 740 species, but this work desperately needs to be updated. In recent years several authors including Mees (1959; 1960a and b; 1961; 1962; 1963; 1964; 1966); Scott (1959); and McKay (1963; 1964; 1966; 1967; 1969; 1970; 1971) have added about 200 additional records. Collections by J. B. Hutchins and the author from 1972 until the present time have contributed nearly 400 more. However, the latter collections remain largely unreported. These will be included in an annotated checklist of the fishes of Western Australia currently in preparation by the author. The present paper includes descriptions of three new species. The majority of specimens involved were located amongst large holdings of unsorted material during a re-organisation of the Western Australian Museum fish collection in 1975. In addition, three specimens, including the holotype of *Ellerkeldia rubra* were collected by the author at the Abrolhos Islands.

Measurements were made with dial calipers to the nearest 0.1 millimetre (mm). Standard length is abbreviated as SL. The counts and proportions which appear in parentheses under the description section for each species apply to the paratypes when differing from the holotype except for the single specimen of *Parapercis biordinis*, in which case the actual millimetric measurement is given.

Type specimens have been deposited at the Australian Museum, Sydney (AM); United States National Museum of Natural History, Washington, D.C. (USNM); and the Western Australian Museum, Perth (WAM).

The author is grateful to Mr. Jeremy N. Green, Curator of Marine Archaeology, for providing

¹ Western Australian Museum, Francis Street, Perth, 6000.

accommodation during the visit to Beacon Island (Abrolhos) in May 1975. Thanks are also due Mr. Pat Baker, who assisted with collections and Mrs. C. Allen who prepared the typescript.

Family Serranidae

Ellerkeldia rubra n.sp.

(Fig. 1; Table 1)

Holotype.—WAM P25314-003, 71.0 mm SL, collected with multiprong spear off Beacon Island, Wallabi Group, Abrolhos Islands, Western Australia in 3-4 metres by G. R. Allen on 20 May 1975.

Paratypes.—AM I.18476-001, 59.7 mm SL, collected at Abrolhos Islands, Western Australia by A. Robinson, no other collecting data; USNM 214701, 67.5 mm SL, collected with bottom trawl approximately 40 nautical miles west of Bernier Island, Western Australia (25°59'S, 112°27'E) in 71 fathoms by R. George and crew of "Diamantina" on 8 October 1963; WAM P25226-001, 72.6 mm SL, collected with bottom trawl off Cape Inscription, Western Australia in 40 fathoms by Poole brothers aboard "Bluefin" on 9 October 1967; WAM P25311-007, 2 specimens, 29.2 and 49.6 mm SL, collected with rotenone in Goss Passage off Beacon Island, Abrolhos Islands, Western Australia in 30 metres by G. R. Allen on 18 May 1975.

Diagnosis.—A species of *Ellerkeldia* with the following combination of characters: soft dorsal rays 19; soft anal rays 8; tubed lateral-line scales 41-45; colour mostly pale with broad brown stripe on sides from snout to caudal base and series of brown spots and blotches on snout, interorbital, and nape.

Description.—Dorsal rays X, 19; anal rays III, 8; pectoral rays 15 (16); gill rakers on lower portion of first gill arch 8 + 4 to 5 rudiments; tubed lateral-line scales 44 (41 [1], 42 [2], 43 [2]); horizontal scale rows from lateral-line to base of middle dorsal spines 2-3; from lateral-line to anus 17.

Body ovate and compressed, the greatest depth 2.7 (2.5 to 2.8), head length 2.4 (2.2 to 2.4), both in standard length. Snout 3.9 (4.2 to 5.0), eye diameter 4.1 (3.8 to 4.0), interorbital width 8.4 (8.9 to 11.2), length of maxillary 2.4 (2.1 to 2.2), least depth of caudal peduncle 3.4 (3.2 to 3.8), length of caudal peduncle 4.1 (3.8 to 5.2), of

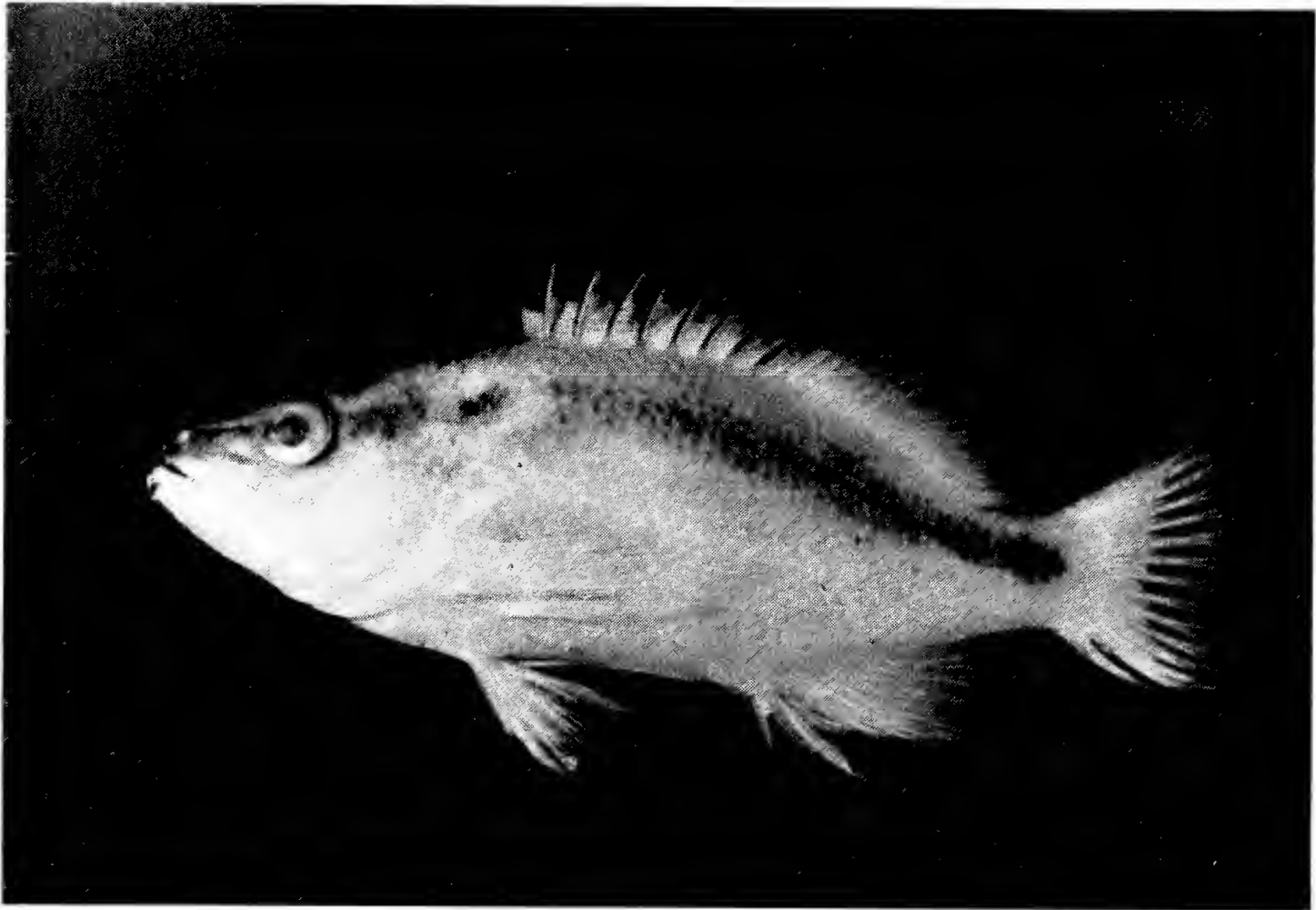


Figure 1.—*Ellerkeldia rubra*, holotype, 71.0 mm SL, Abrolhos Islands, Western Australia.

Table 1

Morphometric Proportions of Type Specimens of Ellerkeldia Rubra
(In thousandths of the standard length)

Characters	Holotype WAM P25314-003	Paratypes				
		WAM P25226-001	USNM 214701	AM 1.18476-001	WAM P25311-007	WAM P25311-007
Standard length (mm)	71.0	72.6	67.5	59.7	49.6	29.2
Greatest body depth	369	355	394	360	383	366
Head length	415	402	437	412	454	435
Snout length	106	96	89	94	91	103
Eye diameter	101	99	114	104	115	110
Interorbital width	49	41	44	47	40	45
Length of maxillary	194	168	200	198	192	199
Least depth of caudal peduncle	123	117	119	127	121	137
Length of caudal peduncle	101	99	84	107	101	103
Snout to origin of dorsal fin	397	406	406	399	395	387
Snout to origin of anal fin	687	694	726	717	726	678
Snout to origin of pelvic fin	411	415	433	404	440	394
Length of dorsal fin base	546	527	527	564	534	548
Length of anal fin base	183	178	178	183	173	205
Length of pectoral fin	293	307	324	305	341	342
Length of pelvic fin	197	204	233	226	222	240
Length of 1st dorsal spine	41	55	59	40	54	55
Length of 4th dorsal spine	120	152	156	134	151	137
Length of last dorsal spine	97	102	95	101	101	106
Tallest dorsal ray	169	179	190	171	171	188
Length of 1st anal spine	99	84	96	69	87	89
Length of 2nd anal spine	152	172	173	173	177	171
Length of 3rd anal spine	146	139	159	132	141	154
Longest anal ray	197	204	212	204	206	223
Length of caudal fin	207	241	246	224	242	267

pectoral fin 1.4 (1.3 to 1.4), of pelvic fin 2.1 (1.8 to 1.9), of first dorsal spine 10.1 (7.4 to 10.3), of fourth dorsal spine 3.5 (2.8 to 3.2), of last dorsal spine 4.3 (3.9 to 4.6), of longest soft dorsal ray 2.4 (2.2 to 2.6), of first anal spine 4.2 (4.5 to 6.0), of second anal spine 2.7 (2.3 to 2.7), of third anal spine 2.8 (2.8 to 3.2), of longest soft anal ray 2.1 (2.0 to 2.2), of caudal fin 2.0 (1.6 to 1.9), all in the head length.

Pair of nasal openings on each side of snout, anterior opening with dermal flap; mouth large, oblique, with lower jaw protruding slightly; supramaxillary present; lateral-line gradually ascending to within 2-3 scales below middle dorsal spines, then gradually descending to middle of side of caudal peduncle, proceeding to base of caudal fin; snout tip, lips, chin, most of dentary, isthmus, and maxillary naked; remainder of head and body with finely ctenoid scales; sheath scales covering about basal $\frac{1}{2}$ - $\frac{3}{4}$ of dorsal, anal, caudal, and pectoral fins; pre-orbital entire; preopercle with 3 antrorse spines on lower border and about 25 small serrae on posterior edge; subopercle with a few small serrae on postero-ventral border; opercle with 3 spines.

Upper and lower jaws with bands of depressible villiform teeth, narrowing in width posteriorly; in addition, two widely spaced tusk-like canines at front of lower jaw and 1-2 similar teeth about midway back on each dentary, upper jaw with pair of enlarged tusks anteriorly and several enlarged retrorse canines on either side of median diastema; vomer with patch of small conical teeth; palatines with small biserial conical teeth; length of maxillary 2.1 (2.1 to 2.4) in the head length.

Colour of holotype in ethyl alcohol; head and body generally pale (yellowish); faint brown stripe (about 3-4 scales wide) extending from snout tip (also on upper lip), interrupted by eye, then continuing along upper sides to base of caudal fin, pigmentation most intense just behind eye and on caudal peduncle; a pair of brown spots on anterior portion of upper and lower lips, these continuous with brown streak extending across side of snout to front corner of eye; diffuse broken brown stripe on mid-dorsal line from interorbital to occipital region, followed by a pair of short brown streaks, one on each side of mid-dorsal line, then an isolated brown spot on middle of nape and another at base of first dorsal spine; similar brown spot behind upper, posterior corner of each eye; small brown spot on anteriormost extension of isthmus; fins uniformly pale except basal part of first dorsal spine brown.

The paratypes exhibit the same basic pattern except on the 67.5 mm specimen the mid-dorsal stripe is not apparent except as an isolated streak on the post-interorbital. In addition, the broad stripe behind the eye has the appearance of two, large isolated blotches, one immediately above the preopercle opening and the other just above the opercle opening. The 59.7 mm paratype is much darker than the other specimens and the markings on the head are mostly obscured except the spots on the isthmus and lower lip.

Colour in life.—Head and body generally pinkish-red grading to darker red dorsally; lower portion of head, breast, and abdomen white; prominent red stripe from snout to eye, continued behind eye to upper portion of opercle and two short oblique bands of similar colour and width immediately behind, near upper corner of gill opening; diffuse, dusky brown band running longitudinally on upper sides from upper corner of gill opening to caudal base, more intense posteriorly, forming more or less isolated dark brown spot on caudal peduncle; fins pale pink.

Remarks.—The genus *Ellerkeldia* is a small group of serranid fishes consisting of 5 species confined to the southern Australia-New Zealand region. *E. rubra* is separable from the other members of the genus on the basis of the characters given in the following key.

Key to the species of *Ellerkeldia*

- | | | |
|---|---|-------------------------------|
| 1a. Body with series of 6-7 dark transverse bands (may be faint in preservative) | 2 | |
| 1b. Body without series of 6-7 dark transverse bands, either with horizontal stripe or mottled with irregular broken bands | 4 | |
| 2a. Soft dorsal rays 17-18; soft anal rays 7; dark bands distinct on both upper and lower half of sides (southern Queensland; New South Wales) | | <i>annulata</i>
(Günther) |
| 2b. Soft dorsal rays 20 to 21, soft anal rays 8; dark bands, except those on caudal peduncle, either absent or indistinct on lower portion of sides | 3 | |
| 3a. Greatest body depth 2.8 to 2.9 in standard length; dark bands usually well defined, confined mainly to upper sides (Lord Howe Island; New Zealand) | | <i>huntii</i> (Hector) |
| 3b. Greatest body depth 2.4 to 2.5 in standard length; dark bands usually not well defined (at least in preservative), extending well below middle of sides (New South Wales; Western Australia) | | <i>maccullochi</i>
Whitley |
| 4a. Colour mostly pale with faint to prominent longitudinal band on upper sides from snout to base of caudal; soft dorsal rays 19 (Western Australia) | | <i>rubra</i> n. sp. |
| 4b. Colour not as in 3a, dark olive-brown above and grey below, mottled with irregular broken transverse bands; soft dorsal rays 20 (southern Queensland; northern New South Wales) | | <i>jamesoni</i>
(Ogilby) |

In the Abrolhos Islands this species was occasionally encountered at the bottom of Goss Passage at depths between 25 and 35 metres. It was usually seen resting on the bottom at the entrance of small crevices of the coral reef or near the base of rocky outcrops or sponges. The holotype was the only individual observed outside of the deeper waters of Goss Passage. It was collected from a large patch of staghorn coral (*Acropora*) in only 3-4 metres depth.

This species is named *rubra* with reference to the red coloration in life.

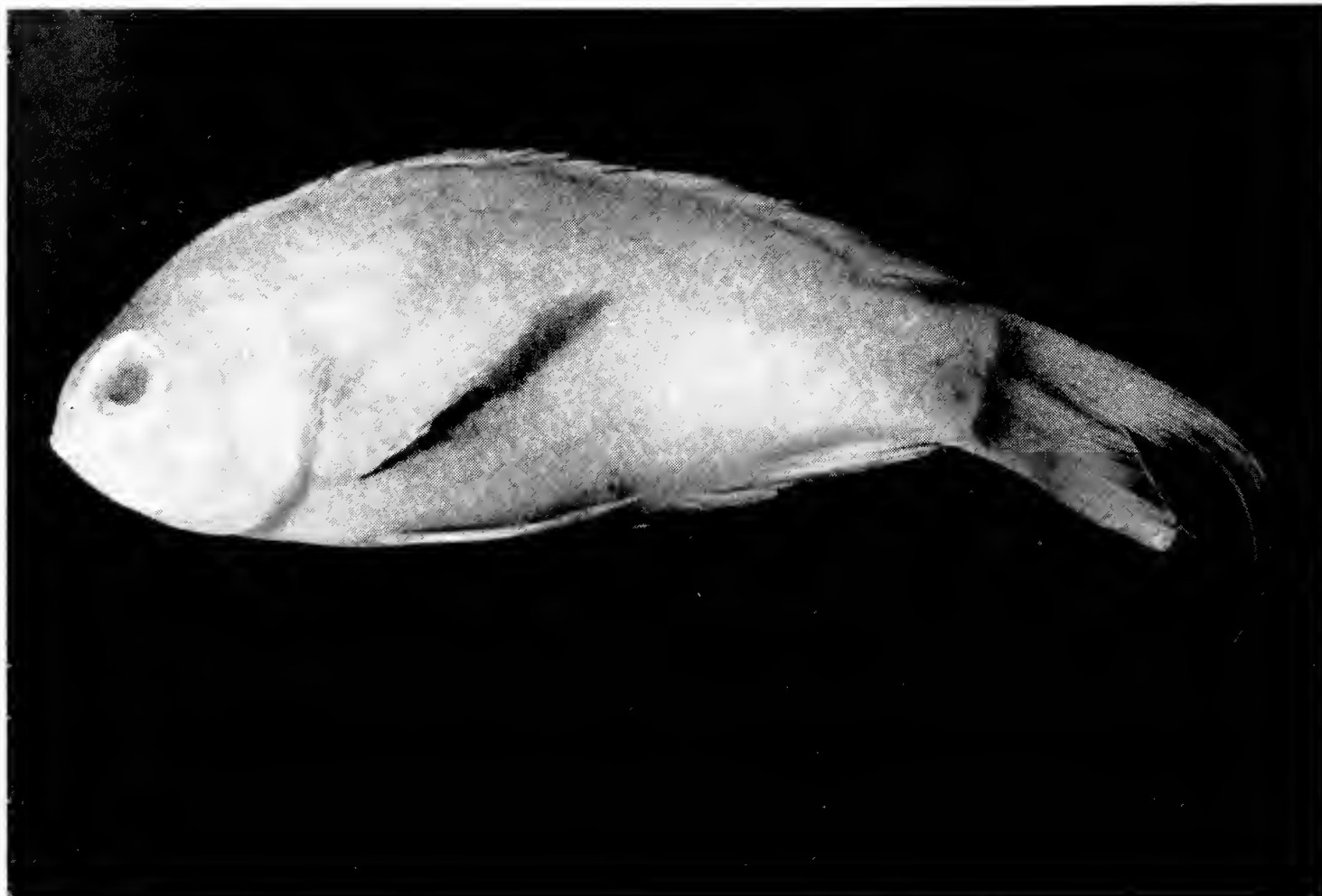


Figure 2.—*Anthias georgei*, holotype, 79.5 mm SL, off Bernier Island, Western Australia.

Table 2

Morphometric Proportions of Type Specimens of Anthias georgei
(In thousandths of the standard length)

Characters	Holotype WAM P25205-001	Paratypes	
		WAM P25205-002	WAM P25205-002
Standard length (mm)	79.5	32.8	29.0
Greatest body depth	392	390	366
Head length	345	375	331
Snout length	69	55	59
Eye diameter	108	125	141
Interorbital width	84	82	75
Length of maxillary	147	159	159
Least depth of caudal peduncle	143	143	159
Length of caudal peduncle	147	116	131
Snout to origin of dorsal fin	350	372	348
Snout to origin of anal fin	660	680	659
Snout to origin of pelvic fin	355	360	355
Length of dorsal fin base	629	595	572
Length of anal fin base	165	174	166
Length of pectoral fin	317	305	297
Length of pelvic fin	337	311	300
Length of 1st dorsal spine	57	55	66
Length of 3rd dorsal spine	167	122	131
Length of last dorsal spine	107	107	117
Tallest dorsal ray	197	183	159
Length of 1st anal spine	57	73	69
Length of 2nd anal spine	136	177	148
Length of 3rd anal spine	131	137	128
Longest soft anal ray	192	220	245
Length of caudal fin	574	*	545

* damaged

***Anthias georgei* n.sp.**

(Fig. 2; Table 2)

Holotype.—WAM P25205-001, 79.5 mm SL, collected with bottom trawl approximately 40 nautical miles west of Bernier Island, Western Australia (24°59'S, 112°27'E) in 71 fathoms by R. George and crew of "Diamantina" on 8 October 1963.

Paratypes.—WAM P25205-002, 2 specimens, 29.0 and 32.8 mm SL, collected with holotype.

Diagnosis.—A species of *Anthias* with the following combination of characters: two and a half to three rows of scales between middle of spinous dorsal fin and lateral-line; tubed lateral-line scales 39-40; gill rakers on first arch 10 or 11 + 22 to 26; third dorsal spine slightly elongate; caudal fin deeply forked with prolonged rays (at least in adult males); pectoral rays 18; body depth 2.5 to 2.7 in standard length; colour generally pale in preservative, probably reddish in life.

Description.—The proportional measurements of the holotype and paratypes are expressed as percentage of the SL in Table 2.

Dorsal rays X,16; anal rays III,7; pectoral rays 18; gill rakers on first arch 10 + 23 (11 + 25 or 26); tubed lateral-line scales 39 (39-40); horizontal scale rows from lateral-line to base of middle dorsal spines 2-3; from lateral-line to anus 16-17.

Body ovate and laterally compressed, the greatest depth 2.5 (2.6 to 2.7), head length 2.9 (2.7 to 3.0), both in standard length. Snout 5.0 (5.6 to 6.8), eye diameter 3.2 (2.3 to 3.0), inter-orbital width 4.1 (4.4 to 4.6), length of maxillary 2.3 (2.1 to 2.4), least depth of caudal peduncle 2.4 (2.1 to 2.6), length of caudal peduncle 2.3 (2.5 to 3.2), of pectoral fin 1.1 (1.1 to 1.2), of pelvic fin 1.0 (1.1 to 1.2), of first dorsal spine 6.1 (5.1 to 6.8), of third dorsal spine 2.1 (2.5 to 3.1), of last dorsal spine 3.2 (2.8 to 3.5), of longest soft dorsal ray 1.7 (2.1), of first anal spine 6.1 (4.8 to 5.1), of second anal spine 2.5 (2.1 to 2.2), of third anal spine 2.6 (2.6 to 2.7), of longest soft anal ray 1.8 (1.4 to 1.7), of caudal fin 0.6 (0.6 to 1.1), all in the head length.

Pair of nasal openings on each side of snout, anterior opening with dermal flap on posterior edge; mouth large, oblique, with lower jaw protruding slightly; lateral-line gradually ascending to within 2-3 scales below middle dorsal spines, then gradually descending to middle of side of caudal peduncle, proceeding to base of caudal fin; area around nostrils, lips, chin, and isthmus naked; remainder of head (including maxillary) and body with finely ctenoid scales; sheath scales covering about basal $\frac{1}{2}$ - $\frac{2}{3}$ of soft dorsal, anal, caudal, and pectoral fins; rear edge of preopercle serrate, several serrae present on exposed edge of subopercle and interopercle; opercle with three spines, the uppermost blunt and inconspicuous.

Upper jaw with inner band of small depressible canines and outer row of larger, fixed canines; pair of large tusks on each side at front corner of jaw and a pair of equally large inner

teeth on either side of median diastema. Anterior portion of lower jaw with dense patch of small villiform teeth and 1-2 large, laterally flared tusks on each side at front corner; 1-2 large tusks near middle of each dentary with row of small depressible canines on posterior part of jaw.

Colour of holotype in ethyl alcohol; head and body generally pale (yellowish-tan), slightly reddish on upper portion of head and back; faint suggestion of three pale stripes on sides, each about one scale wide, first just below lateral-line, second at level of upper corner of opercle, third at level of lowermost pectoral rays; fins uniformly pale.

The two paratypes, which are juveniles, are uniformly pale with several rows of small brown spots below the spinous dorsal fin.

Remarks.—*A. georgei* appears to be allied to *A. conspicuus* Heemstra and *A. townsendi* Boulenger from the western Indian Ocean and Arabian Sea. These species were reviewed by Heemstra (1973) and are characterised by 2-3 scales between the lateral-line and the base of the middle dorsal spines, 37-41 tubed lateral-line scales, and 15-17 soft dorsal rays. *A. georgei* differs from *A. conspicuus* by having the third dorsal spine slightly elongate rather than subequal, and the caudal fin deeply forked with prolonged filaments instead of lunate. In addition, there is a significant colour difference. The holotype of *A. georgei* possesses elongate whitish gonads and is therefore presumed to be a male. The males of *A. conspicuus* have two wide, dark stripes on the sides, which join on the caudal fin in contrast to the complete absence of distinguishing marks on *A. georgei*. *A. townsendi* differs by being less deep bodied (2.9-3.2 vs. 2.5-2.7 in SL), and by having a rounded rather than acute anal fin tip, and a lunate caudal.

Named in honour of Dr. Ray W. George, Curator of Crustacea at the Western Australian Museum and collector of the only known specimens.

Family Mugiloididae

***Parapercis biordinis* n.sp.**

(Fig. 3)

Holotype.—WAM P25206-001, 70.0 mm SL, collected with beam trawl southwest of Point Cloates, Western Australia (22°59'S, 113°25'E) in 71 fathoms by C.S.I.R.O. research ship on 31 January 1964.

Diagnosis.—A species of *Parapercis* with the following combination of characters: palatine teeth absent; 6 or 7 teeth in outer row of lower jaw; last dorsal spine connected by membrane to first dorsal ray opposite tip of last dorsal spine; five dorsal spines; about 24 zigzag rows of scales around caudal peduncle; lateral-line scales 54; colour largely pale with 4-5 pairs of brown spots along sides and four spots on caudal fin.

Description.—Dorsal rays V,21; anal rays I, 18; pectoral rays 18; pelvic rays I,5; branched caudal rays 15; gill rakers on first arch 5 + 12

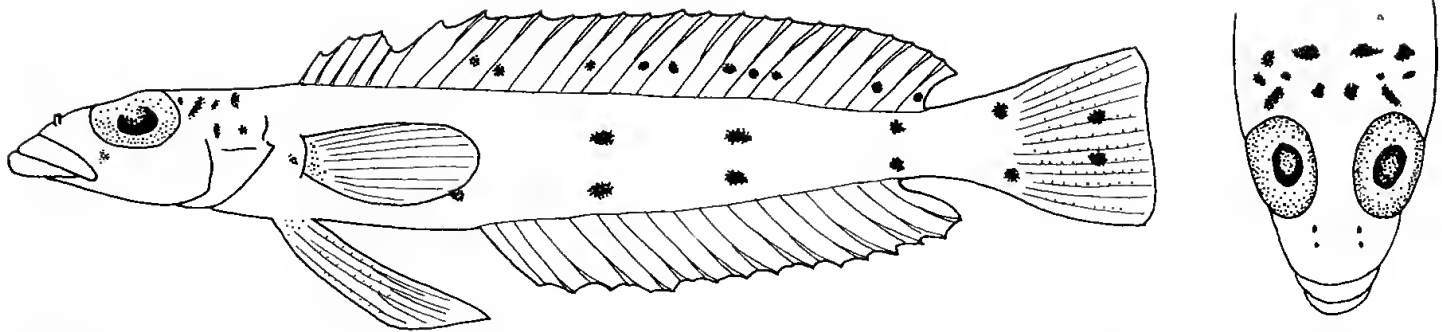


Figure 3.—*Parapercis biordinis*, holotype, 70.0 mm SL, off Point Cloates, Western Australia (scales not shown). The pattern of dark spots on the dorsal surface of the head is shown in the drawing on the right.

= 17; lateral-line scales from upper edge of gill opening to base of caudal fin 54; horizontal scale rows from lateral-line to base of first dorsal spine 3; from lateral-line to anus about 8 (most are missing on the holotype); predorsal scales 7-8.

The following measurements (in mm) were recorded for the holotype (only known specimen): length of head 20.0 (3.5 in SL); length of snout 5.0 (4.0 in HL); diameter of eye 7.5 (2.7 in HL); postorbital length of head 8.5 (2.4 in HL); interorbital width 2.0 (10.0 in HL); snout tip to rear edge of maxillary 7.7 (2.6 in HL); least depth of caudal peduncle 5.7 (3.5 in HL); greatest depth of body 9.5 (7.4 in SL); length of fourth dorsal spine 4.9 (4.1 in HL); longest pectoral ray 14.2 (1.4 in HL); longest pelvic ray 16.4 (1.2 in HL); longest caudal ray 13.8 (1.4 in HL); length of dorsal fin base 42.3 (1.7 in SL); length of anal fin base 29.5 (2.4 in SL).

Teeth absent on palatines, vomer with 8 relatively large conical teeth arranged in a single row; lower jaw with outer row of 6 or possibly 7 (count includes 1 and possibly 2 teeth which are missing) hooked canine teeth on anterior-most portion, inside these a band of villiform teeth and a single row of smaller canines on the side of each dentary; upper jaw with about 56 canines in outer row and inside these a dense band of villiform teeth.

Scales of body mostly ctenoid, those of preopercle region relatively small, embedded, and cycloid; occipital, interorbital, and snout naked.

Colour of holotype in ethyl alcohol: head and body mostly yellowish-tan; scales on upper part of body with dusky edges; a series of diffuse brown spots, about pupil size, on sides; the first at level of middle dorsal spines, just below lateral-line, the remainder occurring in 4 pairs at equal intervals below soft dorsal fin (except for first pair, which both lie below lateral-line, the members of each pair are separated by the lateral-line); caudal fin with 2 pairs of similar spots, one at base of fin and the other near the centre; pectoral base with faint brown streak; series of dark markings (see Fig. 3) on nape and upper part of opercle; faint brown streak below lower anterior corner of eye connecting suborbital and maxillary; small brown spots on soft dorsal fin as shown in Fig. 3.

Remarks.—Cantwell (1964) revised the genus *Parapercis* and Schultz (1968) published a supplemental paper with a key to the Indo-Pacific

members of this group and descriptions of four new species. On the basis of coloration and the combination of other characters listed in the diagnosis, *P. biordinis* is distinct from the 32 species treated by these authors. They recorded four species from Western Australia: *P. allporti* (Günther); *P. emeryana* (Richardson); *P. haackei* (Steindachner); and *P. nebulosa* (Quoy and Gaimard). In addition, the WAM recently received a specimen (WAM P25342-002) of *P. ramsayi*, 146 mm SL, which was trawled off Cape Naturaliste, and two specimens (WAM P24582 and P25367-006) of *P. cephalopunctata*, 56-125 mm SL, collected at North West Cape and the Dampier Archipelago. These represent new records for Western Australia; the latter species, which ranges widely in the Indo-W. Pacific, is also new for Australia. *P. ramsayi* was previously recorded from New South Wales and South Australia. The species presently known from Western Australia are distinguished in the following key.

Key to the species of *Parapercis* from Western Australia

- 1a. Palatine teeth present 2
- 1b. Palatine teeth absent 3
- 2a. Dorsal rays V,22; 10 teeth in outer row of lower jaw; last dorsal fin spine connected by membrane to base of first soft dorsal ray; lower portion of sides without row of seven spots *haackei* (Steindachner)
- 2b. Dorsal spines IV,24; 8 teeth in outer row of lower jaw; last dorsal fin spine connected by membrane to first soft dorsal ray at about level of tip of last dorsal spine; lower portion of sides with row of seven large spots *ramsayi* Steindachner
- 3a. Last dorsal fin spine connected by membrane to base of first soft dorsal ray; horizontal scale rows between lateral-line and first dorsal spine 8-10; soft dorsal rays 22; zigzag row of scales around caudal peduncle 35-44 4
- 3b. Last dorsal fin spine connected by membrane to first soft dorsal ray at about level of tip of last dorsal spine; horizontal scale rows between lateral-line and first dorsal spine 3-5; soft dorsal rays 21; zigzag row of scales around caudal peduncle 24-29 5

- 4a. Total gill rakers 17-20; oblique scale rows above lateral-line 70-77; 3 dark stripes across interorbital space; 5 V-shaped dark bars below dorsal fins, but no broad, light, lengthwise streak with dark edge along middle of side, interrupting the dark bars .. *emeryana* (Richardson)
- 4b. Total gill rakers 11-17 (usually 13-14); oblique scale rows above lateral-line 77-87; no dark stripe across interorbital space; dark bars somewhat V-shaped below dorsal fins, interrupted along middle of side by dark-edged, broad, light streak *nebulosa* (Quoy and Gaimard)
- 5a. Lower portion of sides with a single row of 10 dark spots, about pupil size, extending horizontally from lower pectoral base to lower caudal peduncle; a dark spot or ocellus on each side of head just above opercle on larger specimens (over about 130 mm SL); vomerine teeth in 2 rows *cephalopunctata* (Seale)
- 5b. Colour pattern not as in 5a; vomerine teeth in 1 or 3 rows 6
- 6a. Eight vomerine teeth in 3 horizontal rows (2 + 4 + 2); sides with seven dark bars, the anterior four extending from dorsal fin base to below lateral-line, the posterior three above the lateral-line; no markings on caudal and dorsals fins *allporti* (Günther)
- 6b. Eight vomerine teeth in a single row; sides with 4-5 pairs of spots; 2 pair of similar spots on caudal and several small spots on basal part of soft dorsal fin *biordinis* n.sp.

This species is named *biordinis* (Latin; "double-row") referring to the double row of spots along the sides.

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CORRECTION

Geometric microliths from a dated archaeological deposit near Northcliffe, Western Australia. By C. E. Dortch, Volume 58, Part 2, Paper 5.

The last sentence of the abstract should read:

“Analysis of pollen samples taken from the deposit show that *Eucalyptus diversicolor*, *E. calophylla*, and *E. marginata* existed in the locality prior to about 6780 years BP and that all three species were present at times since.”

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4. Descriptions of three new fishes from Western Australia. By Gerald R. Allen.

Correction:

Paper by C. E. Dortch, Volume 58, Part 2.

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5.—The petrology and archaeological significance of mylonitic rocks in the Precambrian shield near Perth, Western Australia

by J. E. Glover¹

Manuscript received 18 November 1975; accepted 15 December 1975

Abstract

Mylonitic rock from shear zones in Archaean granitoids on the western margin of the Yilgarn Block, near Perth, Western Australia, has been used extensively for flaked tools by Aborigines. The rock is epidote-rich and flinty, with quartz veinlets, and commonly has a subconchoidal fracture.

Flakes are found in the Perth Basin between Eneabba and Mandurah. They are common at eastern sites near the mylonitic zones, but are sparse or absent near the west coast.

Introduction

The duration of Aboriginal occupation in Australia exceeds 32 000 years (Barbetti and Allen, 1972), and workers from the Western Australian Museum have provided evidence of occupation in southwestern Australia of at least 25 000 years (Dortch and Merrilees, 1973). Localities strewn with their artifacts are numerous in the southwest (Hallam 1972, Glover 1975).

Outcrop in the central Perth Basin (*i.e.* that part of the basin between Eneabba and Mandurah) is sparse, and most of the rock is limestone or sandstone, which is unsuitable for flaking. Artifacts in the area have generally been made from quartzite, quartz, silcrete, granite and dolerite, which have been carried westward from the Yilgarn Block, or from bryozoan chert which may have been carried eastward from quarries now covered by the Indian Ocean. Eastern sites are dominated by quartzite flakes, but bryozoan chert tends to become increasingly important toward the west. One rock represented at many localities, and referred to previously as green non-fossiliferous chert (Hallam 1972; 1974) or veined epidote-bearing chert (Glover 1975) has been an enigma, for both its provenance and petrology have been speculative. Outcrops of the parent rock have now been identified as mylonite and altered mylonite in shear zones on the western part of the Yilgarn Block, and confirm earlier suggestions that the flakes were of Precambrian rock derived from the east. This note is concerned with the description of the cherty epidote-bearing flakes and their distribution, and with the nomenclature and petrology of their parent rock.

The colours and corresponding numerical designations used below refer to the Rock-color chart distributed by the Geological Society of America (Rock-color Chart Committee 1963).

¹ Geology Department, University of Western Australia, Nedlands, Western Australia, 6009.

The flakes

Appearance and typology

The flakes of cherty epidote-bearing rock range considerably in size, but many of them have a maximum dimension of about 3 cm. The Aborigines seem to have preferred this kind of rock for making small flat adzes and backed blades (see Hallam 1974, p. 83). The rock generally breaks with subconchoidal fracture, and consists of small disseminated quartz and feldspar grains (porphyroclasts) in an aphanitic groundmass of silica and epidote granules. Many flakes are cut by thin quartz veins and minute faults. Flakes are commonly light greenish grey (5GY8/1), pale greenish yellow (10Y8/2), or pale olive (10Y6/2), and where they have been stained or bleached in surrounding soil or sand, they generally retain a greenish cast because of their epidote content.

Distribution in the Perth Basin

Cherty epidote-bearing flakes have been found at 31 sites in or just outside the eastern margin of the Perth Basin between Eneabba in the north and Mandurah in the south, a distance of about 300 km (see Fig 1). The sites are commercial sandpits or sandy areas in which the artifacts have been concentrated by deflation of sand. Although widespread, the cherty epidote-bearing flakes are generally not abundant at artifact localities in the central Perth Basin: they are absent from 13 sites, and form less than 1% of the flake population at 18 sites (see Table 1). Sites near the west coast are without exception low in these flakes, but higher proportions (8-39%) are found near the eastern margin of the basin, in the Gingin-Bullsbrook-Walyunga area. It should be borne in mind that the proportion of any one rock type in flakes found on the surface of a wind-deflated area depends on many factors, including the history of human occupation at the site, the depth of erosion, the availability of the particular rock type, the rock's suitability in the light of typological changes, its durability, and its distance from the source. The last-mentioned factor seems to have been the most significant here, for the distribution north of the Swan River accords well with a mylonitic source in the Walyunga region, where there are numerous outcrops of mylonite.

The mylonitic rocks

Outcrop distribution

Mylonite and blastomylonite have been recorded by Wilde (1974) in Archaean granitoid of the Walyunga area, and in the Chittering Metamorphic Belt at Mogumber, about 130 km

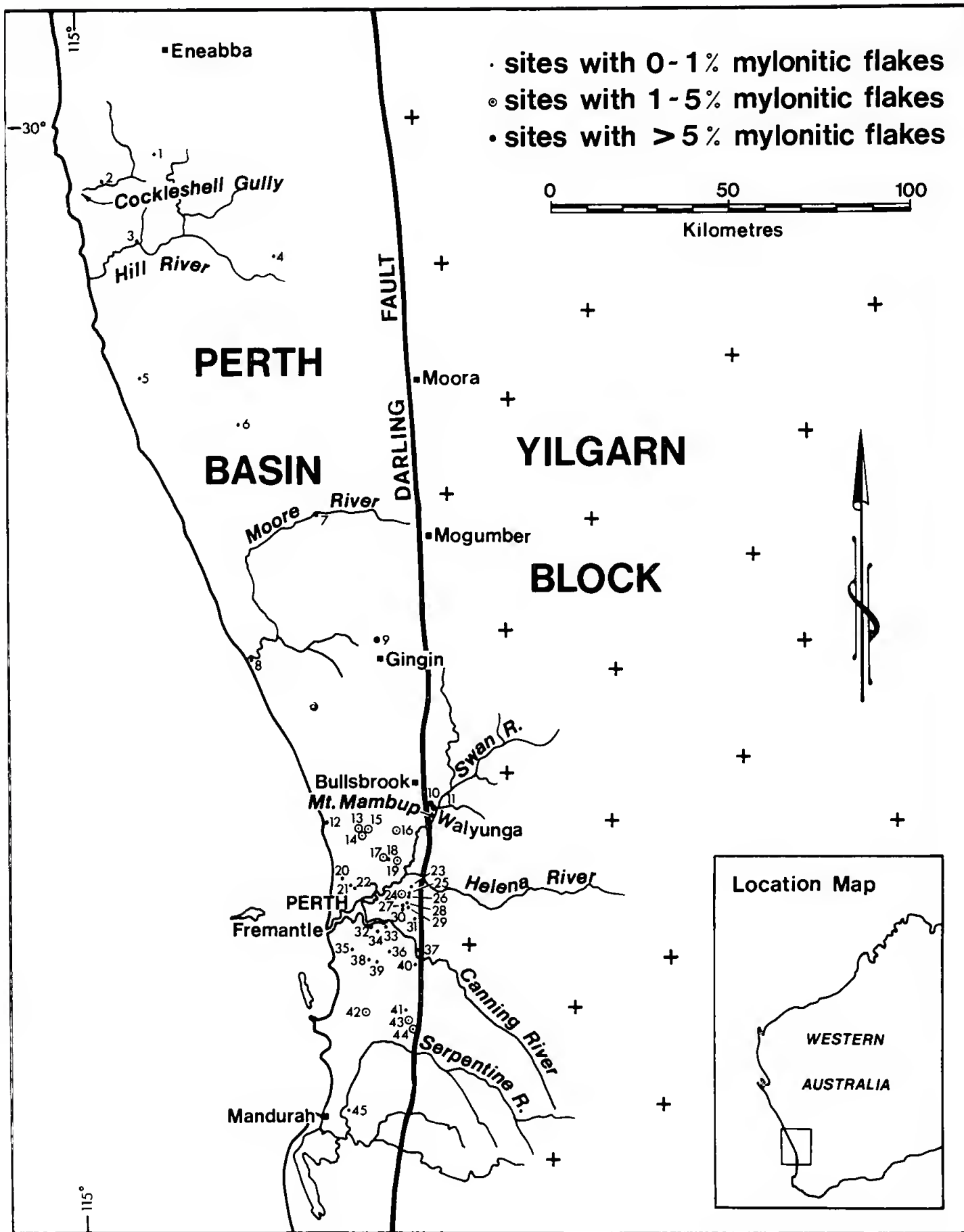


Figure 1.—Map of the central Perth Basin, showing location of artifact sites described in Table 1.

Table 1

Proportion of flakes of mylonitic rock at sites in the central Perth Basin. Sites were located on 1 : 250 000 Series R 502 maps, and co-ordinates are based on grid references estimated to the nearest hundredth. Co-ordinates refer to centre points of large sites.

Site No.	Type of site	Map	Map co-ordinates	Flakes counted	Percent mylonitic rock
1	Road cutting in sand, Kooringa area	SH50-9	32002760	319	0
2	Sandy soil, N bank Cockleshell Gully	SH50-9	30372666	215	0
3	Sand blow-out N bank Hill River	SH 50-9	31492481	310	0
4	Sand spoil from dam about 1 km W Dimer Hill	SH50-10	35772452	154	0
5	Sand blow-outs, Pinnacles area	SH50-9	31692063	2 107	0
6	Sand near dam, Caro Station	SH50-9	34651927	249	0.4
7	Road cutting in sand, S bank Moore River, Regans Ford	SH50-10	36921652	133	0.7
8	Blow-outs in yellow sand, near mouth of Moore River	SH50-14	34851205	886	0.3
9	Sand blow-out 2 km NNW Gingin Railway Station	SH50-14	38801260	406	8.4
10	Sandy area 6 km S Bullsbrook East	SH50-14	40370758	290	39.0
11	Sandy area Walyunga National Park	SH50-14	40640743	1 624	10.7
12	Blow-outs in yellow sand, 1 km north Mullaloo Beach	SH50-14	37190695	127	0
13	Gnangara Sandpit	SH50-14	38370671	249	3.0
14	Brambles Sandpit	SH50-14	38410669	193	2.6
15	Sandy area, SW margin of L. Guangara	SH50-14	38550680	684	1.0
16	Bell Bros Sandpit, Guangara Road	SH50-14	39730675	309	3.3
17	Ready Mix Sandpit, Beechboro	SH50-14	39040592	307	4.2
18	Road cut in sand, Beechboro Road	SH50-14	39180588	228	0.9
19	Widgee Road Sandpit, Beechboro	SH50-14	39380584	291	2.7
20	Sand patch, S side Talbot Way, Woodlands	SH50-14	36880540	373	0
21	Sand dune, NW of L. Monger	SH50-14	38120517	344	0.3
22	Red sand, E shore of L. Monger	SH50-14	38220512	642	0.5
23	Sandpit, Maida Vale	SH50-14	39880510	347	0.3
24	Exposed sand, airport runway extension	SH50-14	39600492	348	1.4
25	Rail cutting in sand near Wittenoom Road, Maida Vale	SH50-14	39820496	353	0.2
26	Sand blow-out near Bingham Street, Maida Vale	SH50-14	39800490	384	0.2
27	Exposed sand, Kewdale	SH50-14	39550449	669	0.4
28	Sandpit, Hardey Road, Cloverdale	SH50-14	39630455	717	0.1
29	Exposed sand, Newburn Road, Kewdale	SH50-14	39690452	413	0.2
30	Sand blow-out N side Dowd Street, Kewdale	SH50-14	39550434	318	0.5
31	Sandpit NE White Street, Orange Grove	SI50-2	40140397	306	0
32	Exposed dune, corner High Road, Leach Highway, Riverton	SI50-2	38700377	378	0
33	Exposed sand, Metcalf Road, Lynwood	SI50-2	39160377	181	0.5
34	Sand blow-out, corner Riley Road, Nicol Road, Lynwood	SI50-2	38980364	317	0
35	Snashall Bros Sandpit, Bibra Lake area	SI50-2	38080308	394	0.2
36	Coopers Sandpit, Canning Vale	SI50-2	39220303	277	0.4
37	Hot Mix Sandpit, Gosnells	SI50-2	40110265	361	0.3
38	Ready Mix Sandpit, Forrest Road, Jandakot	SI50-2	38590273	299	0
39	Calsil Sandpit, Forrest Road, Jandakot	SI50-2	38780266	118	0
40	MWSS & OB Sandpit, Lilian Avenue, Armadale	SI50-2	40110266	359	0.6
41	Fremnells Sandpit, Hopkinson Road, Cardup	SI50-2	39710126	1 589	0
42	Wellard Sandpit, Parmelia	SI50-2	38540114	174	1.7
43	Sand blow-outs, Lang's Farm, Mundijong	SI50-2	39820092	500	2.5
44	Sand blow-out, 0.5 km S railway bridge, Mundijong	SI50-2	40040058	374	1.6
45	Sandpit 4.5 km E Stake Hill Bridge, Mandurah	SI50-2	38049805	116	0

to the north. The rocks are found in a NNE-trending zone. Wilde suggests that the present Darling Fault runs subparallel to an ancient zone of north to north-east shearing that may have been reactivated many times.

Mylonite is also known at Cookernup over 100 km south of the area mapped by Wilde, and is likely to crop out in intervening country.

Terminology

Two terms are commonly used for strongly coherent fine-grained rocks of shear zones, namely mylonite and cataclasite (or cataclasite). Modifications of these terms are numerous, but only the most important are considered here.

The nomenclature of cataclastically deformed rocks has recently been discussed by a large number of authors, including Christie (1960), Reed (1964), Joplin (1968), Spry (1969), Bell and Etheridge (1973) and Zeck (1974), and a confusing array of names has arisen. Even the style of deformation is now questioned, so that although most authors have assumed a predominance of brittle deformation as implied by the terms mylonite (Gr. *myle*, mill) and cataclasite (Gr. *klastos*, broken in pieces), Bell and Etheridge believe that deformation can be essentially ductile.

It is commonly held that mylonite is characterized by foliation, as indicated by Lapworth (1885) in his original definition, whereas cataclasite is said to lack foliation (see Christie 1960 Reed 1964, Spry 1969). Christie, in addition, implies that cataclasite is derived from mylonite by ultrabrecciation. On the other hand, Zeck (1974) uses the term cataclasite in a fairly wide sense for fine-grained foliated and massive rocks that have been formed by rupture and show no noteworthy recrystallization.

Cataclastic rocks whose rupture has been accompanied or followed by sufficient recrystallization or neomineralization to obscure their cataclastic nature have commonly been given names prefixed by *blasto*, e.g. blastomylonite, blastocataclasite.

In this paper, the term mylonitic rock is used to include all the varieties of strongly coherent, fine-grained rock considered above.

Petrography

Mylonitic rocks from the bed of the Swan River 0.8 km SSE of Mt Mambup range from mylonite to blastomylonite. They are greenish

grey (5GY6/1-5G6/1) to medium bluish grey (5B5/1) with rough to subconchoidal fracture, and some are strongly foliated. Here and there folia are displaced a few millimetres by faults, and are cut by thin quartz veins. The mylonites contain elongate, aligned quartz and feldspar porphyroclasts set in a poorly foliated groundmass mainly of very finely divided silica and epidote. The quartz porphyroclasts show undulose extinction or have been converted into numerous subgrains. Some rocks have a granular groundmass with a mean grainsize of 0.06 mm, evidently due to recrystallization, and are best called blastomylonite.

At Walyunga, the mylonitic rock is a flinty, almost aphanitic, pale greenish yellow to pale olive (10Y8/2-10Y6/2) rock that is practically massive and breaks with subconchoidal fracture. Porphyroclasts of quartz and subordinate sodic plagioclase occur in a groundmass of epidote granules having a mean grainsize of about 5 μ m, and a little silica. A few porphyroblasts of epidote attain a diameter of 100 μ m. The quartz porphyroclasts are strained or finely granulated, whereas the feldspar has survived well except for local displacement of twin lamellae by micro-faults. The porphyroclasts compose only about 5% of the rock and tend to have a common lineation. The rock is cut by veins of microcrystalline quartz that are generally less than 0.5 mm thick. The veins have many orientations, but there is commonly one set more or less parallel to the orientation of the porphyroclasts, and two other sets at about 60° to that direction. Some veins pinch and swell, others consist of narrow lenses arranged *en echelon*. This rock is difficult to fit precisely into existing classifications, but is evidently an altered mylonite or cataclasite.

Comparison with flakes.

The cherty epidote-bearing flakes of the Perth Basin, and of the Walyunga area just outside its eastern margin, are very like the mylonitic rocks in colour, fracture, mineralogy and texture. Thin sections of flakes and mylonitic rock are practically indistinguishable (see Fig. 2 A-F).

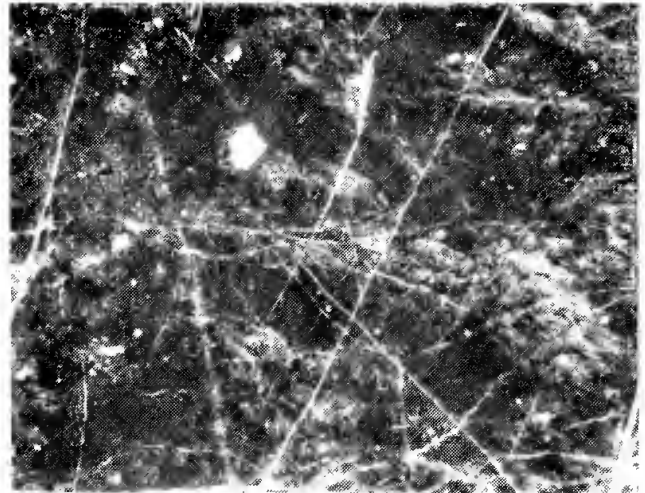
Discussion

The pronounced lithological similarity between the cherty epidote-bearing flakes and mylonitic rocks of the Walyunga area provides a clear indication of their mylonitic origin. As noted earlier (Glover 1975), the textures of some flakes resemble those of metasedimentary and meta-

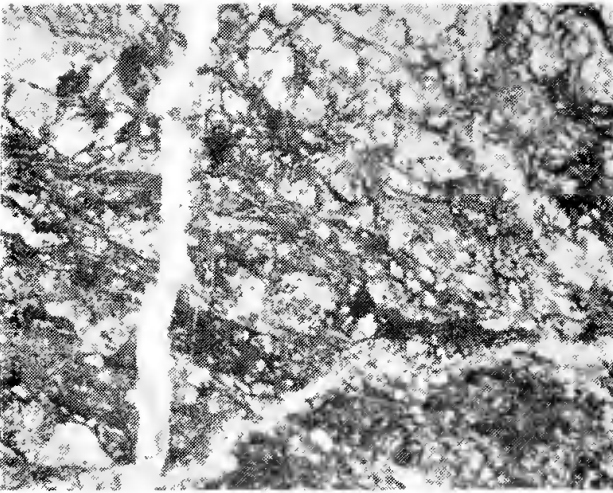
Figure 2.—A.—Mylonitic rock from outcrop at Walyunga. White porphyroclasts are strained to finely granulated quartz, groundmass is finely granular epidote with a little silica. Veins are quartz. University No. 74903. Width of field 4.75 mm. Plane polarized light. B.—Artifact from Bell Bros Sandpit, Gnangara Road, Grid Ref. 39730675 (locality 16). White porphyroclasts are finely granulated quartz, groundmass is finely granulated epidote and a little silica. Veins are quartz. University No. 74737. Width of field 4.75 mm. Plane polarized light. C.—Mylonite from outcrop in bed of Swan River, 0.8 km SSE of Mt Mambup. White porphyroclasts are strained and granulated quartz with subordinate sodic plagioclase, groundmass is a fine mixture of silica and epidote. Veins are quartz. University No. 74900. Width of field 4.75 mm. Plane polarized light. D.—Artifact from sand, Kewdale, Grid Ref. 39550449 (Locality 27). White porphyroclasts are strained and granulated quartz, groundmass is a fine mixture of silica and epidote. Veins are quartz. University No. 74617. Width of field 4.75 mm. Plane polarized light. E.—Mylonite from outcrop in bed of Swan River 0.8 km SSE of Mt Mambup. White porphyroclasts are strained and granulated quartz, groundmass is a fine mixture of silica and epidote with a little fine white mica parallel to the foliation. Chlorite is also locally present. University No. 74901. Width of field 4.75 mm. Plane polarized light. F.—Artifact from sandy area, Walyunga, Grid Reference 40640743 (locality 11). White porphyroclasts are strained and granulated quartz, groundmass is a fine mixture of silica and epidote with a little fine white mica parallel to the foliation. University No. 74904. Width of field 4.75 mm. Plane polarized light.



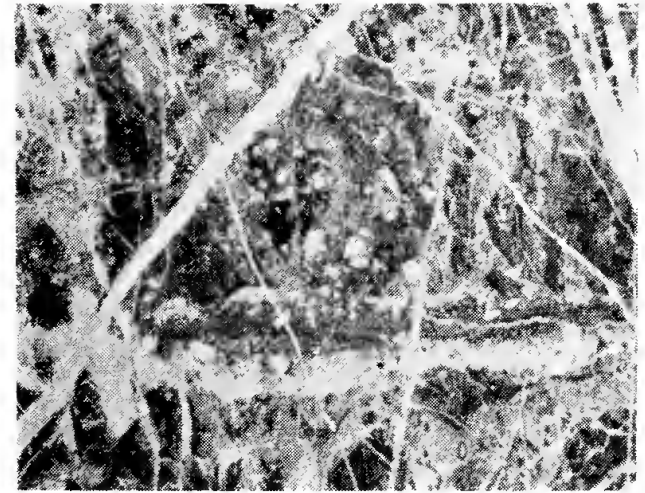
A



B



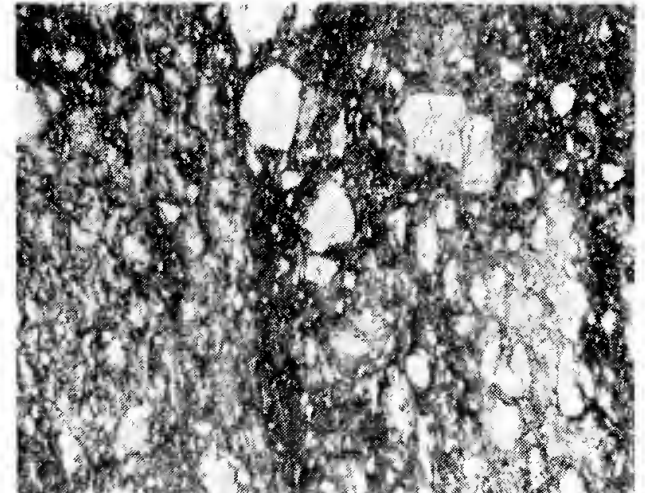
C



D



E



F

volcanic rocks, but it can scarcely be doubted that these textures arise from the cataclasis and neomineralization of Archaean granitoid. The tendency for the mylonitic flakes in areas of the Perth Basin north of the Swan River to increase in frequency toward Gingin and Walyunga shows that the sources could have been in mylonitic rocks of the Walyunga area, or in counterparts along the strike of the Darling Fault Zone towards Mogumber. There may have been other sources of mylonitic rock for sites south of the Swan River.

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6.—The history of two coastal lagoons at Augusta, Western Australia

by E. P. Hodgkin¹

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Abstract

The Deadwater and Swan Lake are two small lagoons which form appendages to the estuary of the Blackwood River near its mouth. Neither was a part of the estuary when the first white settlers arrived in 1830; Swan Lake was then a fresh-water lake with a stream to the estuary and the Deadwater is not shown at all on early maps. The Deadwater now has the characteristic form of a coastal lagoon that has developed as the result of diversion of the river mouth parallel to the shore behind a wave-built barrier on a prograding coast. The mouth is known to have migrated some distance eastwards during the 1930s and the river then flowed through what is now the Deadwater. The bar closed for the only time on record in 1945 and was reopened near its original site. This left the Deadwater as a coastal lagoon behind low dunes and the coastal alignment is now almost identical with that of the 1830s.

Introduction

This enquiry into the origin of the Deadwater and Swan Lake at the mouth of the Blackwood River has arisen out of a study being made for the Environmental Protection Authority of

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Western Australia into all aspects of the estuarine ecosystem (Hodgkin, 1976). These two lagoons have been added to the estuary in this century and are now a significant part of it, at least from the biological point of view. It is of considerable interest to understand how this came about, to know whether the events described were the result of natural processes or are attributable to human interference. Was the formation of the Deadwater a fortuitous event caused by vagaries of short term climatic change or was it caused by human activities? Is it evidence of a prograding coastline with an excess of mobile sand?

The following history has been pieced together from a few documents, from old maps and air photographs, and from the sometimes conflicting accounts given by local inhabitants of what happened 30 to 50 years ago.

The catchment and the estuary

The Blackwood River is the largest river of the south west, with an estimated average annual discharge of $1\ 057 \times 10^6 \text{ m}^3$, more than twice that

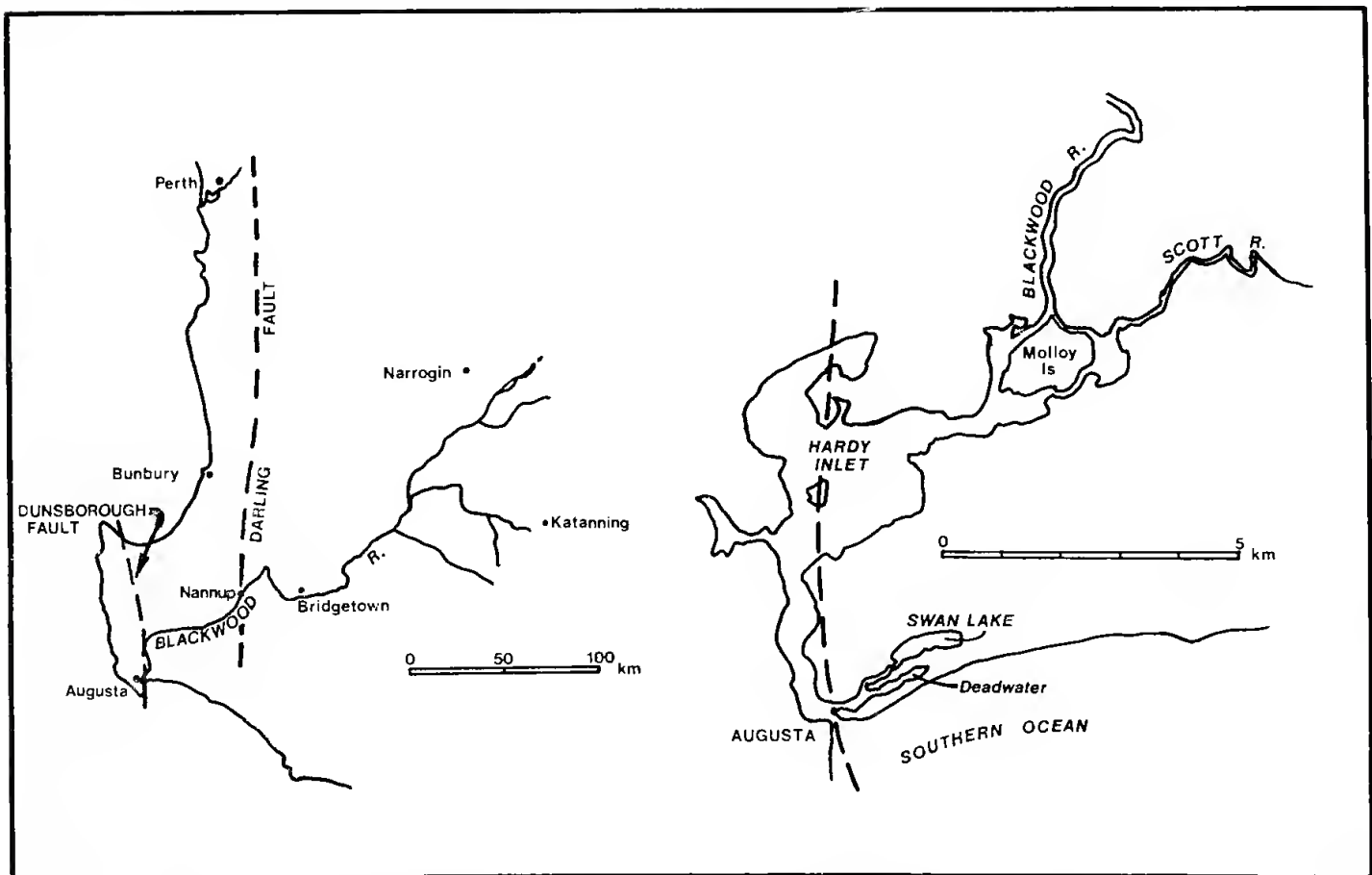


Figure 1.—Locality map and map of the Blackwood River estuary.

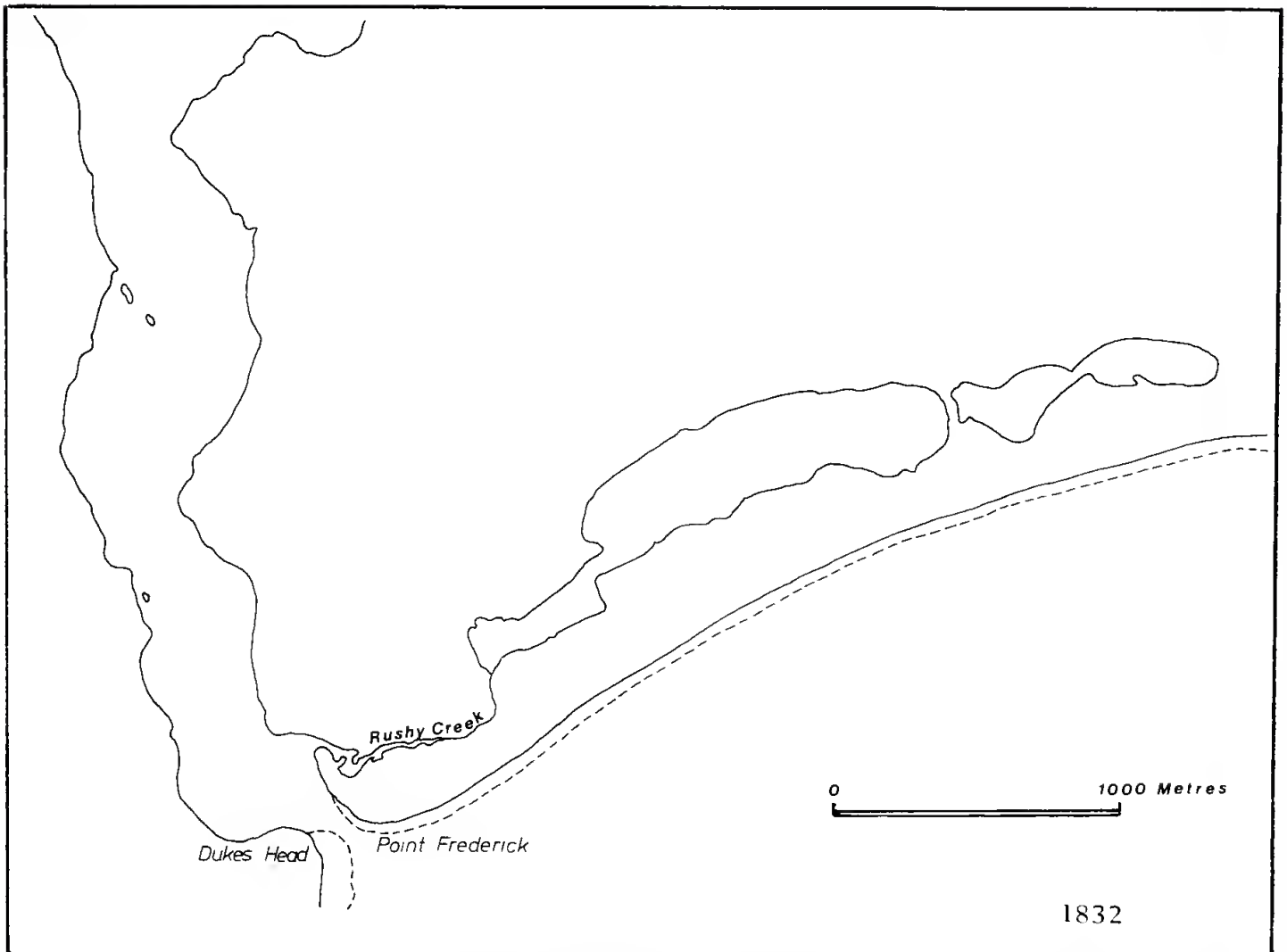


Figure 2.—Tracing from map dated 1832-4-8. This and the subsequent figures have all been reduced to the same scale. Broken lines outline sand banks.

of the Swan River with its larger catchment. Floods have resulted in discharge rates in excess of 480 m³/sec (Public Works Department, Western Australia, 1972). Flow is extremely seasonal with 97.5% of river runoff occurring during the six months June to November (as measured at the nearest gauging station). In consequence the estuary is fresh throughout in winter and brackish to marine in summer, often with extreme stratification of the water body.

Tides though small (maximum daily range about 0.6 m) are little damped in the estuary proper and strong tidal currents flow in and out of the two lagoons. The Deadwater is stratified in winter, surface water may be fresh and that below the level of the sill about half sea water salinity.

The Dunsborough Fault runs north-south through the estuary (Fig. 1). To the west of this is the Naturaliste-Leeuwin ridge of Precambrian rocks while to the east there are Mesozoic sediments of the Donnybrook Sunland and Quaternary sands of the Scott Coastal Plain where three old shore lines are recognised parallel to the present coast (Lowry, 1967). The estuary is 42 km long; the greater part is a tidal river 50 to 100 m wide and about 5 m deep

which discharges into the small, very shallow, Hardy Inlet with a deep channel to the mouth and bar. The mouth is sheltered from the predominantly westerly winds in winter by the Leeuwin ridge, but is exposed to strong southeasterly winds in summer.

1830

Early maps and paintings by Thomas Turner make it clear that when Captain Stirling and the early settlers came to the Blackwood in May 1830 the mouth of the river was where it is now. The first map, dated 1832-4-8 by Hillman, Turner and Edwards represents an accurate survey of the lower part of the estuary. On this map (Fig. 2) Dukes Head and Point Frederick and their associated sand banks have much the same form they have now. To the east of the mouth the shore line was where it is now.

Unfortunately there is no indication of the nature of the shore and it can only be assumed that then as now there were low dunes. The large Swan Lake had its present size and shape and a smaller lake extended about 1 km further east. A small winding stream, Rushy Creek, flowed from the lake to the estuary near its mouth. There was no Deadwater.

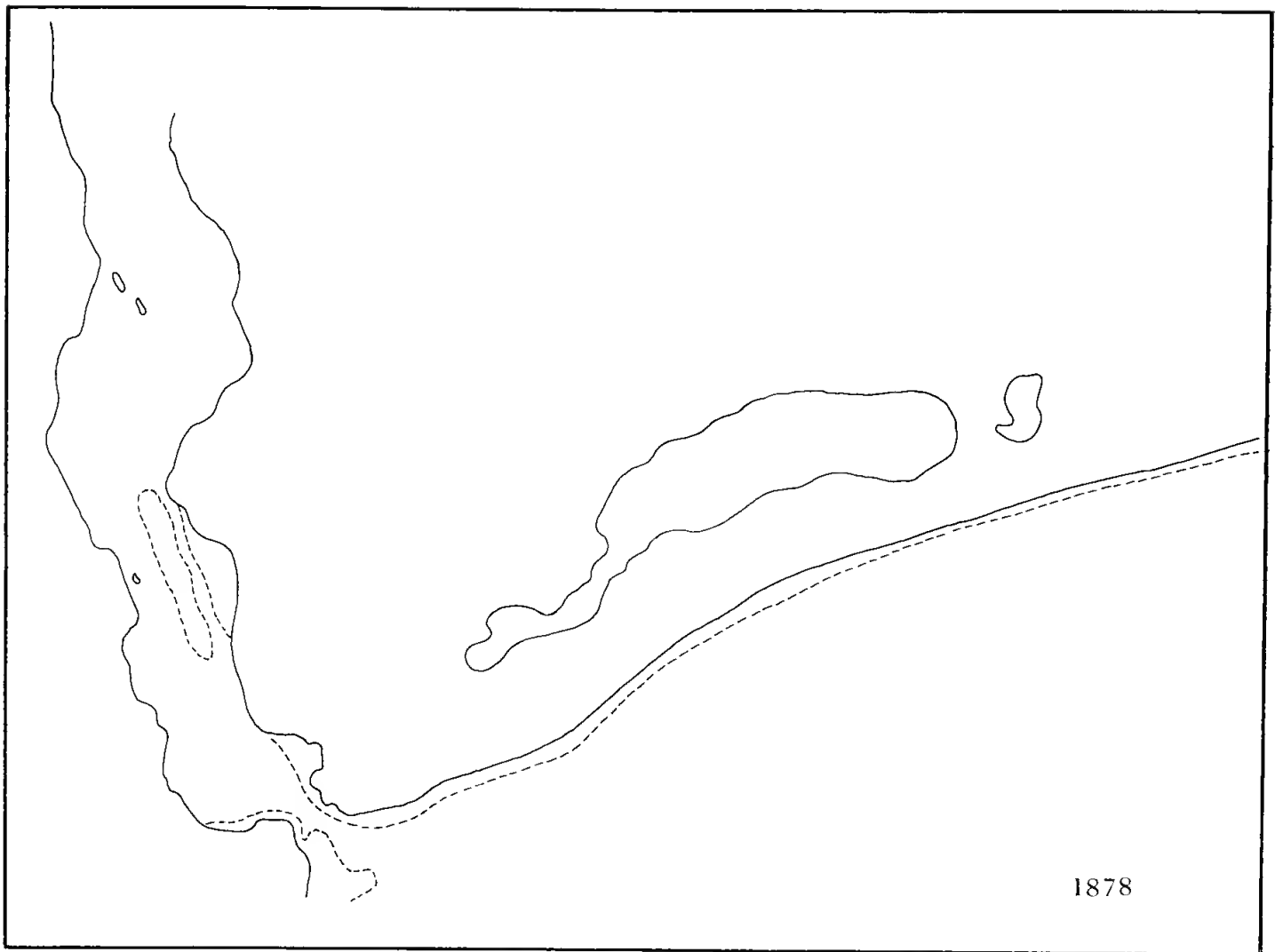


Figure 3.—Admiralty chart dated 1878.

1878

The Admiralty Chart (Fig. 3) only shows the coastal features in detail, as is usual in these charts. Again the mouth and shore line are depicted with essentially their present form. Low dunes are shown in what is now the western end of the Deadwater.

A "Townsite" plan dated 1899 appears to show considerable erosion of Point Frederick, but it is difficult to match this plan to other maps and photographs.

1925

A detailed hydrographic survey of the channel part of the estuary (Public Works Department, Western Australia, 23962) again shows the mouth with much the same form as in 1830 (Fig. 4). A low sandy patch extends 150 m east from Dukes Head and the mouth has moved slightly east at the expense of Point Frederick which has retreated about 100 m. The eastern shore line is unbroken; there is nothing to show where Rushy Creek discharged. The survey was made in April and the mouth of the creek was probably blocked with sand.

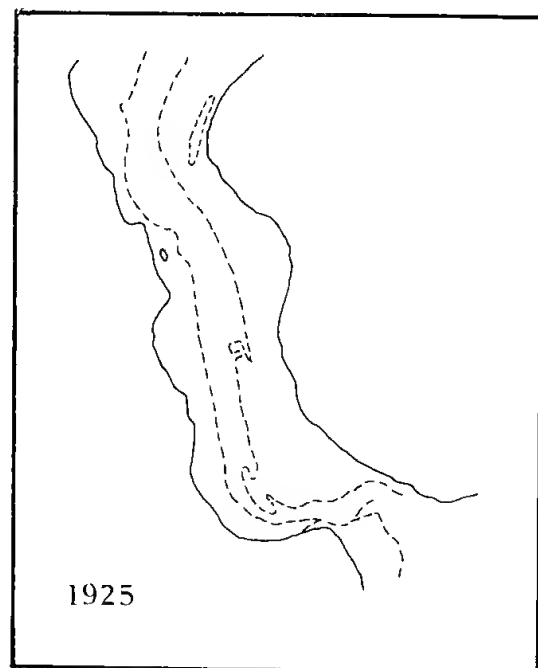


Figure 4.—Public Works Department, Western Australia, chart dated 1925.

1929

By this date: "the bar has so silted up that getting into or out of it from the Bay is a matter of impossibility" and "The mouth of the Blackwood is fast being blocked by a sand bar a few chains in width ..." (Letters on Fisheries Department file 165/21). There is no indication where the mouth was at this time.

1933

Now "the opening to the sea is about a mile east and each year sees it moving further eastward, the rate of movement has been fairly rapid, the present distance of about a mile being covered in the last twelve years" (letter from Augusta-Margaret River Shire, 29/4/1933). The letter petitions the Minister for Works to make a survey and re-open the old entrance, because of shallowing of the bar and an adverse effect on the fishing industry.

1943

Between 1933 and 1943 the mouth did not in fact move much further east; movement seems to have ceased when the mouth came to a big dune about 2.5 km from the old mouth. An air

photo taken 20/11/1943 (Fig. 5) shows the river flowing in a channel 100 to 200 m wide through what is now the Deadwater to the new mouth. Between this and the sea there is a sand spit 200 to 300 m wide that extends from Dukes Head to the new mouth.

It is clear from the correspondence and from the recollection of local residents that between 1925 and 1930 the sand round Dukes Head built out eastward as a broad spit and that Point Frederick retreated, in spite of an attempt to stabilise it with marram grass about 1927 or 1928. By 1930 the spit was sufficiently consolidated for people to drive along it in trucks and fish from them into the estuary. Light planes landed and took off on the spit and the perilously short landing strip was reportedly about opposite the present entrance to Swan Lake from the Deadwater; a photograph dated 1st January 1931 shows a Tiger Moth plane on the spit close to the then mouth. The air photo shows that the spit was wider than the present beach ridge and the shore line about 100 m seaward of its position today, or in 1830. Scattered vegetation grew on the western half but this was probably only pioneer plants such as *Arctotheca populiifolia* which colonise open sandy shores.

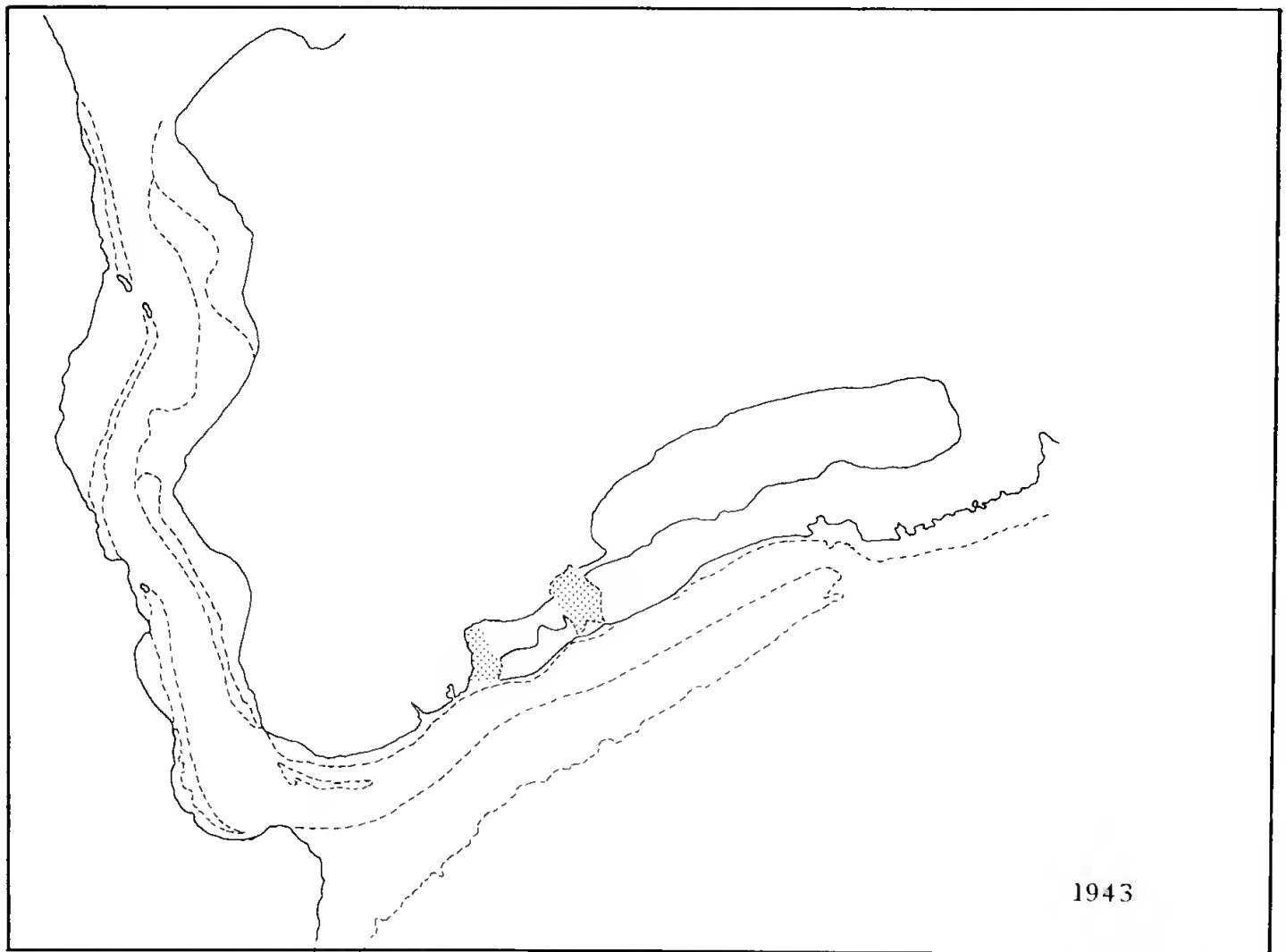


Figure 5.—Tracing from air photo of 1943. Stippled areas: bare sand, thought to be the result of attempts to block the creek.

There is no evidence that the bar ever closed during this period, though it was evidently very shallow. There were continual complaints from fishermen both because the passage was dangerous and because the bar was believed to obstruct the entry of fish. Whatever the condition of the bar in summer a considerable volume of water flowed through the new channel and mouth in winter keeping them scoured out.

1945

The events of this year are told in an article in the West Australian newspaper by Noel M. Brazier, dated 14th July 1945 and entitled: *Opening the Blackwood, how the river reached the sea again.*

"By the middle of March this year the water of the Blackwood River was barely flowing over its long sand bed where it entered the sea. The whole landscape of the river mouth had altered from what it was some 54 years ago; the new mouth had been diverted from its then course to about one mile east.

"For some years small round sand hills had filled the previous outlet of the river and continued east for nearly a mile ...

"By the end of March the river mouth had silted up; strong winds from the sea had raised the outlet some 3 ft. The river was completely shut off from the sea; fishing was bad. Seeing the danger to the low-lying land adjacent to the river Keith McWhae now permanently residing there, took his instruments out to find the easiest place to let the water out. He decided the best place was close to the natural outlet of over 50 years before.

"The people were anxious and appealed to the Government. Two engineers came down and agreed with Mr. McWhae but they said no men could be spared to do the work. The river had now risen some 4 ft. and the camping ground was flooded.

"The work must be done—or where would the water rise to? So a team of men started to work at the selected spot—and some of the sand hills were fairly high. Yet they got the water through in a small stream; the trouble did not end there. The sand hills began falling in; ... But three men stuck it out for five days, when the strength of the river suddenly began to break through. They had succeeded.

"A huge gap, 100 yards wide and many feet deep, was torn through the cut and in a few hours had lowered the height of the river some 4 ft. The troubles of the mouth were over. The cost in wages was less than £18. The fish from the sea can now reach the river; again the Blackwood will become a good fishing ground, and the friendly porpoise sport around".

Local residents still recall the spectacular out-rush of river water that spread as far as St. Alouarn Island 9 km from the mouth and carried with it fishermen's nets which had been set in the estuary.

The Public Works Department did in fact prepare a plan (Public Works Department, Western Australia, 23962 dated 24/5/1945) for a channel 325 m long across the bar.

The locality sketch shows "high sand hills" where the mouth is now and the proposed channel is marked about 400 m east of this where the highest point on the bar was about 1.5 m above sea level. This was probably the "selected spot" referred to above.

It would be interesting to know the actual date on which the bar was breached. River flow data, as recorded at Nannup 140 km upstream, show that even in May flow had increased little above the low summer levels and it was only in mid-June that the river began to flow strongly. Fortunately 1945 was a wet winter with the greatest river flow recorded in the 17 years for which there are records (Public Works Department, Western Australia, Water Resources Section, 1972) and the river scoured out for itself a good entrance which has never again closed.

1955

Air photos taken 23/5/1955 and 3/12/1955 (Fig. 6) show a shore alignment which is almost identical with that of 1830; the mouth has returned to its previous position and both Dukes Head and Point Frederick have essentially the form and dimensions shown on the 1830 map and that of the present time. The spit is now a narrow dune with a steep seaward face and with well established vegetation, except at the eastern end. There, where the mouth was in 1943, the dune appears lower and has only sparse vegetation. The 1943 river channel is now the Deadwater. At its western end there is a broad, shallow bar of mobile sand with a well defined deep channel to the river mouth. The eastern end has already silted up, though apparently still not vegetated.

1975

The only significant differences between conditions in 1955 and those of the present time are the full development of the fore dune along its whole length and establishment of vegetation on it.

Rushes are well established at the eastern end of the Deadwater and the bar at the western end has consolidated and carries some vegetation. A narrow channel keeps open to the north of the bar, and tends to scour its northern shore.

Interpreting the changes

There have undoubtedly been considerable changes in the estuary and coastline during the Holocene and the Swan Lakes may be attributable to this period; however the close similarity between present topography and that of the period of 1830 to 1925 suggests that this is a stable form for the mouth and coastline at the present time. The events of 1925 to 1945 may have had purely natural causes. It has been suggested that a series of dry years allowed the bar to silt up in summer and so forced the river to erode its way eastward during reduced winter flows. The rainfall record gives little support

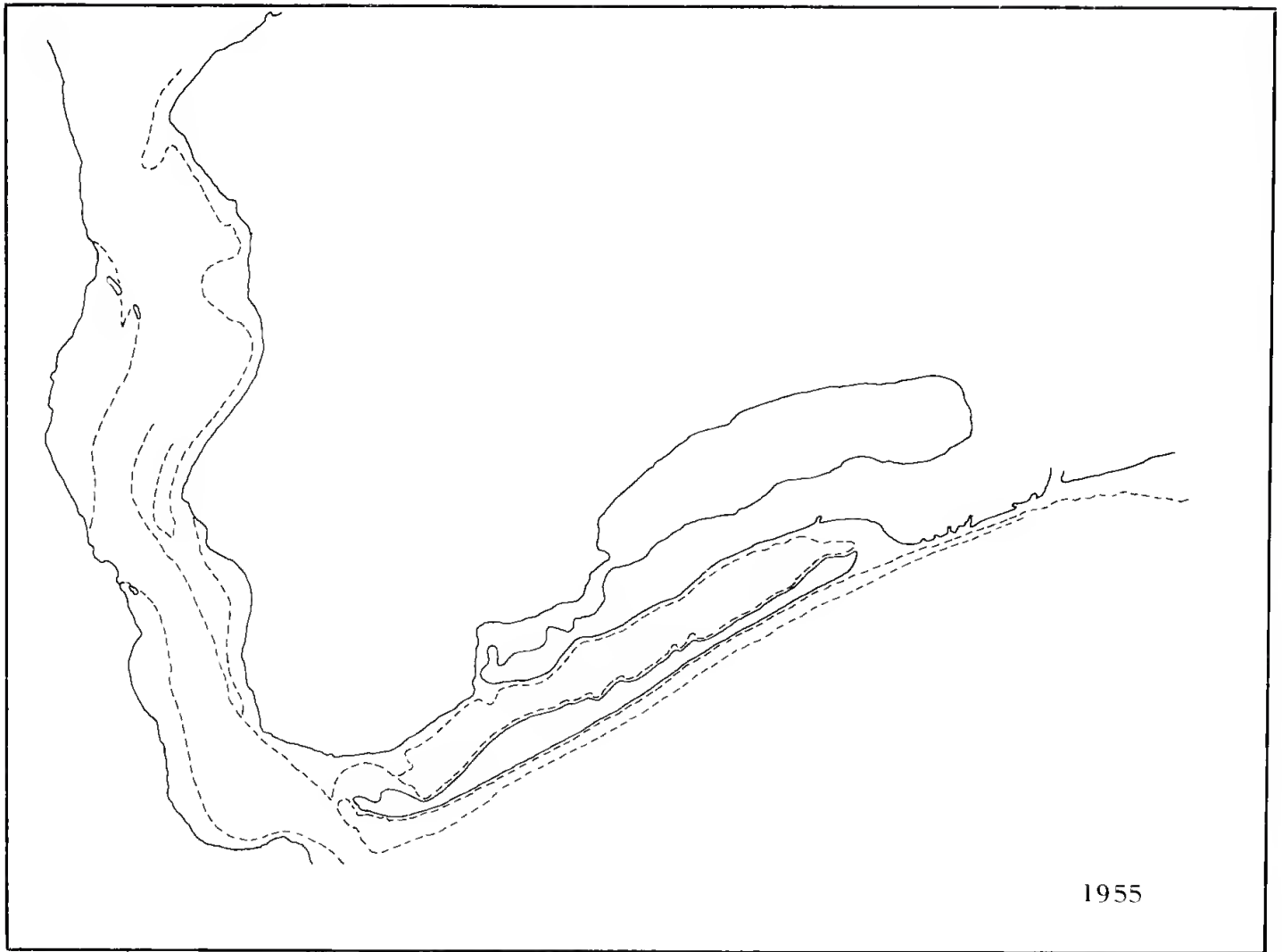


Figure 6.—Tracing from air photo of 1955.

to this explanation; 1925 was indeed a very dry year, but the following year was one of floods and the next eight years all had above average rainfall. Stormy seas may have cut back Point Frederick and transferred the sands to Dukes Head. There was just such a shift early in 1974 and continuation of such a process over several years could be expected to deflect the path of the river and increase the rate of erosion of Point Frederick. Alternatively growth of the spit may have been precipitated by human activities such as destruction of the vegetation on the east bank and consequent mobilisation of the sand; a big fire is said to have gone through the Deadwater area in the early 1920s. A number of possible hypotheses could be advanced.

The following explanation is proposed as best fitting the evidence available. Information additional to that recorded comes from members of the Ellis family who have owned property to the east of the Inlet since the turn of the century, and from various residents of Augusta.

Much of the land east of the Inlet was, and still is, used for grazing cattle and this includes the Deadwater area. This area provided good grazing behind the fore dunes; it would have been an inter-dune depression at the level of the

water table, separated from Swan Lake by low dunes and swampy ground as it is now. Rushy Creek flowed through this, draining fresh water from the lake to the estuary as shown on the 1832 map (Fig. 2). The lake floor then, as now, must have been below sea level. Wave action would have closed the mouth of the creek with sand each summer; no opening is shown on the chart surveyed April 1925. Water level built up in the lake in winter draining out slowly through Rushy Creek, and in spring the Ellis family cut through the sand bar releasing the water in order to take advantage of good grazing round the lowered lake; this is said to have been done each year for several years, and probably caused scouring of the creek.

Eventually some time in the 1920s failure of the sand bar to close allowed sea water to flow back into Swan Lake when there were unusually high tides. The 1943 air photo appears to show a later attempt to close the creek in two places between Swan Lake and the Deadwater. The salt water would have killed vegetation in the lake and flooded low-lying swampy ground between it and the fore dune killing vegetation here too. Add to this destruction of dune vegetation by fire on Point Frederick and the stage

was set for natural processes to take over; for Point Frederick to erode, for the mouth to migrate eastwards, and for a substantial sand spit to build out from Dukes Head.

What would have happened if a channel had not been cut through in 1945? Water level would have built up until before long the river would have broken through at the weakest point of the spit, perhaps where the cut was made, but perhaps again at the eastern mouth. In the latter event the sand spit might eventually have consolidated, a dune formed on it, and the river continued to flow through the Deadwater channel, but with the bar tending to close each summer because of reduced tidal exchange. How long this essentially unstable condition would have persisted it is impossible to say. The fact that after 1945 mouth and coastline rapidly reverted to their original condition suggests that there was not the necessary reservoir of mobile sand to permit the 1945 topography to consolidate and for a dune to build up on the spit.

Conclusion

On the evidence presented it is concluded that the changes to the river mouth which took place during the decade 1925 to 1935 were precipitated by quite small scale human interference: cutting the bar at the mouth of Rushy Creek to drain Swan Lake and possibly burning the fore dune. Natural forces took over and built a substantial sand spit, a spit which diverted the course of the river and forced it to gouge out a new channel that carried the mouth 2.5 km eastwards until halted by high dunes. The Deadwater formed when the sand of the spit was remobilised following the reopening of the original mouth in 1945. This sand formed a bar which closed the connection of the diverted river with the mouth, leaving only a small tidal channel; some of it probably contributed to the shallow bank of mobile sand in the inlet opposite Seine Bay; it silted up the eastern end of the Deadwater; it regenerated Point Frederick and the fore dunes

to the east and returned the coastline to an alignment very close to that of 1830. There is no evidence of any net gain or loss of sand to the system.

The Deadwater is silting up slowly and, left to itself, it might eventually return to the 1830 condition. Tidal currents tend to keep its mouth open, but bars form both inside and outside this and there have already been requests to have a channel dredged through the mobile sand. Damage to the fore dunes on Point Frederick by beach buggies has been blamed for erosion of the point in 1974, but whether this is sufficient by itself to cause changes of the scale of those of 1925-1935 to be repeated is speculation only. The point has since largely regenerated though it will be some time before the vegetation is re-established. However, it is clear that there is a situation of uneasy balance in which quite small changes to the natural environment may precipitate major movements of the poorly consolidated sands near the mouth of the river.

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7.—The environment of deposition of the Wooramel Group (Lower Permian), Lyons River area, Carnarvon Basin, Western Australia

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Abstract

Studies of the Wooramel Group, comprising the Moogooloo Sandstone and the Billidee Formation, in the Lyons River area indicate that the environment of deposition of the Moogooloo Sandstone was a temperate to cold, shallow marine environment, perhaps deltaic. Sedimentation was rapid, with abundant reworking of sediments and steady, fairly strong currents, possibly tidal in part. Conditions changed in late Moogooloo time with the development of euxinic conditions with periodic influxes of sand.

The overlying Billidee Formation is believed to have been deposited in shallow water near-shore conditions, with occasional subaerial exposure. Fairly strong currents flowed to the north during deposition of the sandstones. Stagnant anaerobic conditions prevailed during the deposition of the carbonaceous shales. There was rapid alteration between aerobic and anaerobic conditions. The deposition of the *Edmondia* band was marked by a minor marine transgression.

Modern sedimentary analogues are discussed.

Introduction

This paper presents the results of a study of the environment of deposition of the Wooramel Group (Lower Permian) in the eastern Carnarvon Basin. In the area studied (Fig. 1) the Wooramel Group comprises the Moogooloo Sandstone conformably overlain by the Billidee Formation.

No previous work has been published dealing with the depositional environments of the Moogooloo Sandstone or the Billidee Formation, except for the brief comments made by Condon (1954, 1967).

The base of the Wooramel Group is at the sharp change in lithology from fossiliferous calcareous sediments (Callytharra Formation) to arenaceous sediments largely devoid of fossils. The top is at the change in lithology, commonly gradational, from arenaceous sediments to dominant lutite sediments.

In the area mapped, the Wooramel Group comprises the conformable sequence of the Moogooloo Sandstone and the Billidee Formation. The Moogooloo Sandstone, the lower unit, overlies the Callytharra Formation, either conformably or disconformably. The Billidee Formation is overlain unconformably by the Coyrie Formation (Byro Group). The age of the Wooramel Group is Artinskian because of its position between the Callytharra Formation, of late Sakmarian-early Artinskian age, and the Artinskian, Byro Group.

Moogooloo Sandstone

In the Lyons River area, the Moogooloo Sandstone is the basal formation of the Wooramel Group.

The Moogooloo Sandstone consists of red, brown and white, fine- to coarse-grained orthoquartzite, subordinate subarkose (feldspathic sandstone) and orthoconglomerate. Minor interbedded silty shale is present in the upper part of the formation. The petrology has been described by McGann (1974).

In the Moogooloo Sandstone, sedimentary structures give the best clues to the environment of deposition.

Cross stratification

Cross stratification is common in the Moogooloo Sandstone with sets ranging in height from 2 cm to 3 m. A subdivision into small-, medium- and large-scale cross stratification (Conybeare and Crook 1968) is used.

Medium-scale.—Medium-scale cross stratification, which is the most common type of cross stratification in the formation, ranges from 60 mm to 2 m. The average height of a set is about 33 cm. A coset comprises from one to four individual sets. The maximum dip is 30°. The medium-scale cross stratification is of Allen's (1963) Omikron class, formed, he believes, by migration of trains of large-scale asymmetric ripple marks with essentially straight crests. This type of ripple is found in channels or in the open sea at depths many times the wave-ripple height, but still in shallow water.

Large-scale.—Trough cross stratification is the most common type of large-scale cross bedding. The large-scale cross beds are isolated sets bounded above and below by "massive" fine- to medium-grained orthoquartzite. The maximum dip is 32° and the average dip is 16°.

The large-scale cross stratification is of Theta type (Allen 1963), which is believed to be scour and fill structures formed in a shallow water environment.

Small-scale.—Small-scale (less than 6 cm) cross stratification, although not common in the Moogooloo Sandstone, is present within small, essentially symmetrical ripples of amplitude less than 3 cm. The cross stratification is tabular, solitary and lithologically homogeneous. The small-scale cross stratification is probably Lambda type (Allen 1963), formed by a migration of small-scale straight-crested ripples in a shallow water environment.

Small-scale ripple-drift cross lamination is present in one specimen. Walker (1963) suggests that this type of cross lamination is produced by a steady current and abundant sediment supply.

The azimuth of 152 foresets was measured, one to approximately every 500 m². The vector mean is N 3° E, with a high variance of 8 440 (standard

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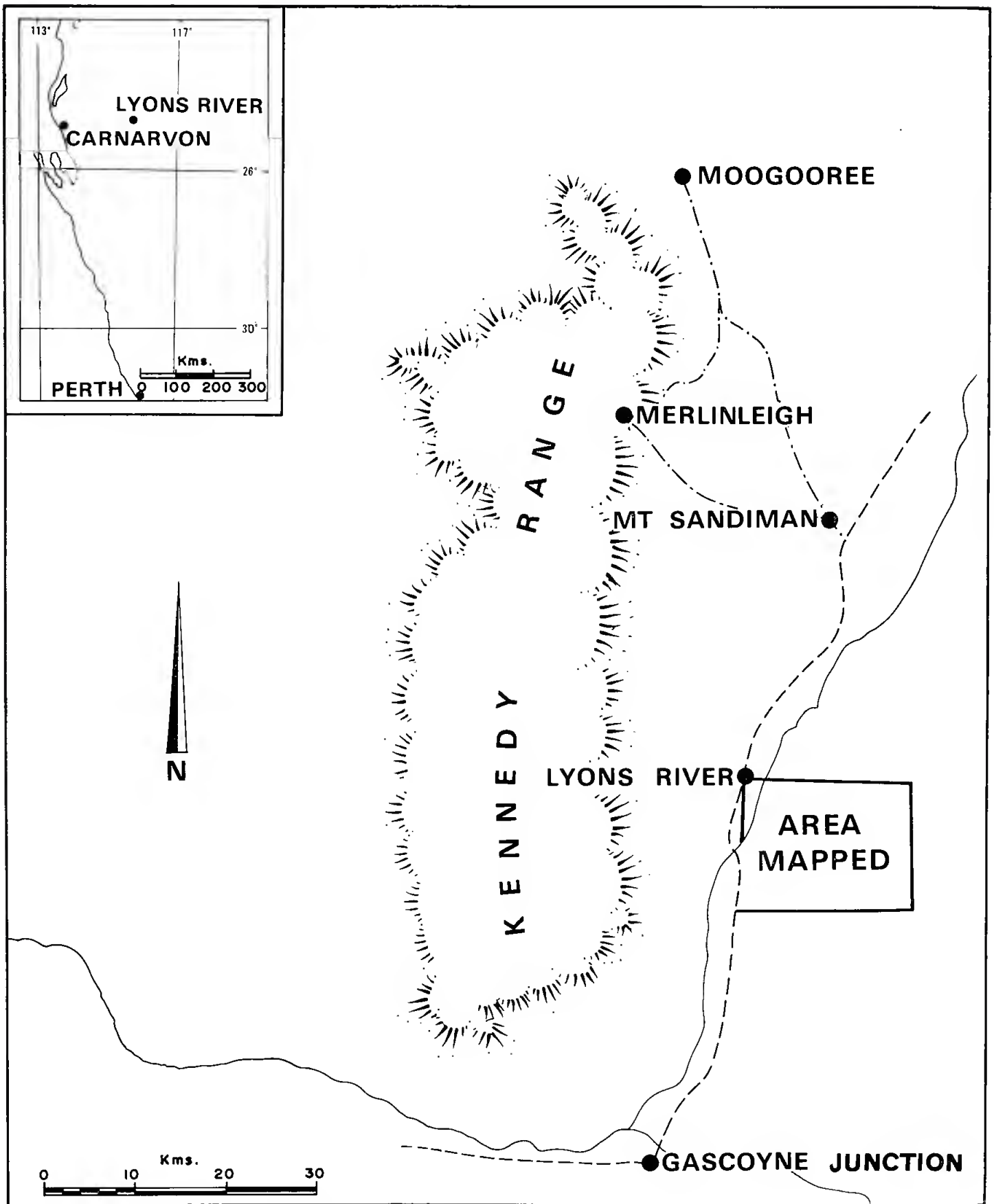


Figure 1.—Locality plan.

deviation of 92°). The results are summarized in Fig. 2. The dominant current flow is towards the north with a subordinate flow towards the south.

Ripple marks

Slightly asymmetric ripples are the only type recognized in the area studied. The ripples are of an amplitude ranging from 1 cm to 5 cm with a wave length between 10 cm and 1 m.

Slightly asymmetric ripples suggest an environment of deposition above wave base in a shallow, relatively open sea.

Slump structures

Two distinct types of slumping are observed in the Moogooloo Sandstone.

Slumping within cross stratified sets.—The foresets of some medium-scale cross stratified sets are distorted. This distortion ranges from minor folds on the foresets to folds where the foresets are parallel to the lower bounding surface. The upper surface of the set is everywhere erosional, indicating that the deformation was penecontemporaneous with deposition. The deformed sets are confined to particular horizons. Jones (1962) presents five possible causes of this type of deformation, the most acceptable in the present instances being surface thrusting generated by currents while the sand is still in a plastic state.

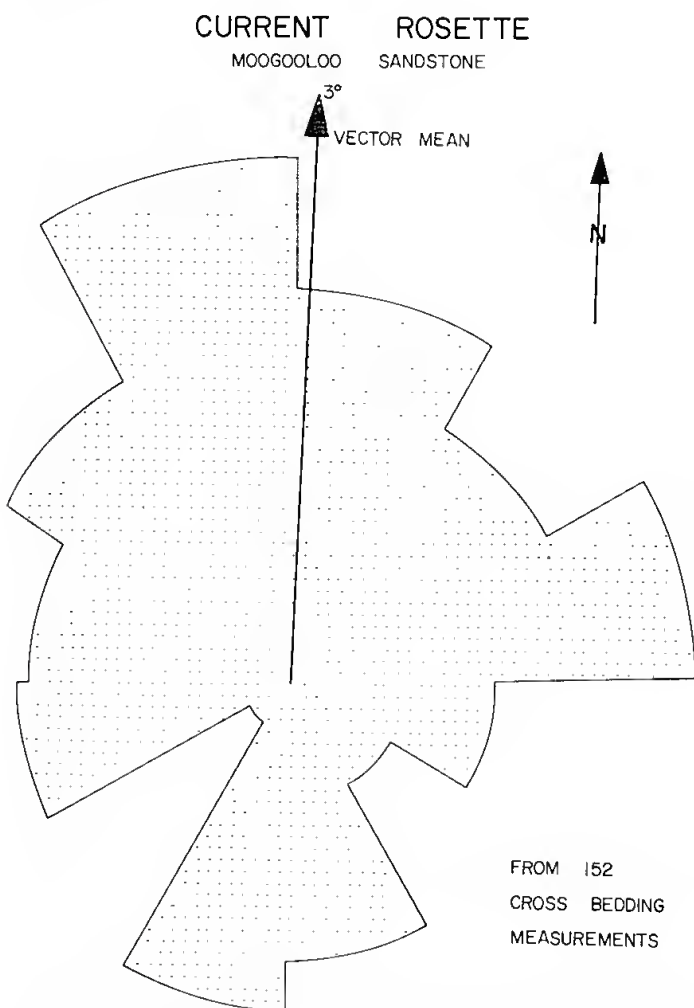


Figure 2.—Current rosette, Moogooloo Sandstone.

“Normal” slumping.—“Normal” slumping is present in plane bedded fine- to medium-grained sandstones as minor folds which do not persist vertically, and is often in the same general horizon as the slumping within cross-stratified sets.

Shale clasts

Two types of shale clast are present, both restricted to stratigraphically variable beds which persist for up to 300 m. Both are present only in fine- to medium-grained orthoquartzites.

The most common type of shale clast consists of scattered plates of grey fine-silt to clay-sized material roughly parallel to the bedding. The plates are about 2.5 cm in diameter and less than 3 mm thick.

A second type consists of tear or ellipse shaped silty-clay clasts about 11 cm long and 4 cm high.

Fossils

Indeterminate brachiopods, bryozoans and bivalves have been found sporadically in the formation throughout the basin. Despite an active search, however, only fossil wood was found in the area mapped.

Trace Fossils.—Tracks are present only in the upper part of the Moogooloo Sandstone, where they are extremely common. The tracks are confined to particular horizons. They consist of smooth, slender, circular tubes about 1 cm in diameter. In places, the tubes, which are essentially straight, interpenetrate, but they do not branch. At least one species of *Palaeophycus* Hall 1847 is represented. The affected beds are extensively ferruginized.

Osgood (1970) believes that *Palaeophycus* tracks were produced by worms and the lack of distinct pattern indicates that they were predators, probably in a shallow water environment.

Environment of deposition

From the data accumulated in this investigation it is possible to construct an environment of deposition for the Moogooloo Sandstone.

Cross stratification types and ripple marks suggest shallow waters with the depositional surface above wave base. Shale clasts indicate subaerial exposure or near-shore marine conditions (Conybeare and Crook 1968, p. 20).

Palaeocurrent data indicate that the palaeoslope was towards the north, the high variance indicating that the slope was of low angle. Tidal currents could be the main factor controlling the subordinate south-trending current. Sunborg (1956, cited by Lauff 1967) has indicated that currents of approximately 0.3 m/sec. would be necessary to move the average sized grain (0.3 mm). Obviously current strengths were greater at the time of deposition of conglomerates and coarse-grained sands. The high degree of winnowing of the sands suggests that the current was not intermittent, but persisted over long periods.

Mineralogical and textural maturity, as indicated by the low proportion of labile minerals, good rounding and sorting, suggests that considerable reworking has taken place (McGann

1974). A high-grade metamorphic or granitic provenance is indicated.

The virtual absence of fossils is probably due to a combination of continual reworking, attrition and abrasion, leading to almost complete breakdown of fossil grains. This reworking was probably combined with rapid sedimentation which would have two effects, the first being to produce an environment unfavourable to all but a few fossil groups. The second effect would be to "dilute" skeletal remains with abundant terrigenous clastic material. The overall result is that fossils remain only in isolated patches, probably representing more sheltered parts of the environment. The sparse fossils that are present, including *Palaeophycus* sp., indicate a shallow marine environment. The abundance of fossil wood indicates proximity to land and is often diagnostic of deltaic conditions (Shepard 1964).

The climate was temperate to cold, as inferred from palynological evidence obtained from a shaly unit just above the Moogooloo-Billidee contact. There is no evidence to suggest that climatic conditions changed greatly between Callytharra and Moogooloo time. The climate in Callytharra time is interpreted as cool (Teichert 1941).

The environment of deposition changed somewhat in late Moogooloo time with the deposition of gypseous carbonaceous silty shale interbedded with coarse-grained orthoquartzite containing *Palaeophycus* sp. This genus is indicative of shallow water conditions, and thus the interbedded carbonaceous shale was also deposited in shallow water. A stagnant environment was responsible for low oxidation potentials, which resulted in the high proportion of carbonaceous matter in the shale. Influxes of coarse-grained sand, deposited in aerobic conditions (as indicated by *Palaeophycus* sp.) periodically interrupted the euxinic environment.

When considering the environment of deposition of the Moogooloo Sandstone, the large outcrop area with uniform gross lithology (Teichert 1952) must be taken into account, and only a sedimentary model that is laterally extensive can be considered analogous to the conditions in Moogooloo time.

In summary, the available evidence indicates a shallow nearshore marine environment, perhaps deltaic, with rapid sedimentation, abundant reworking and steady, fairly strong currents, possibly tidal in part. Conditions changed in late Moogooloo time with the development of euxinic conditions with periodic influxes of sand.

Comparison of the Moogooloo Sandstone with recent analogues is handicapped by the lack of detailed work done on modern terrigenous sediments. Fisher *et al.* (1969) briefly describe the Gulf of Papua delta, naming it as the type example of a destructive, tide-dominated delta. The facies present in this model are analogous with the facies present in the Moogooloo Sandstone. The bulk of the formation—the orthoquartzite suite—is thought to represent the tidal sand-bar facies, the textural and mineralogical maturity, together with the lack of fossils and the sedimentary structures all being produced

in a predominantly marine environment with extensive reworking by tidal currents, and to a lesser extent, by waves. The conglomerate in the Moogooloo Sandstone may represent tidal channel facies, the channels running between sand bars. A shaly prodelta facies is not seen in the formation.

In late Moogooloo time, euxinic conditions gradually became prevalent, probably by the development of barrier bars with a complementary lagoonal-estuarine system. Periodic influxes of coarse sand, perhaps land derived, were introduced into the euxinic environment. The change to shallow water conditions could have been produced by a minor regression or, more likely, by normal building up of the delta platform as sediment accumulated.

Condon (1954) considered that the Moogooloo Sandstone was the product of slow deposition, caused by a major transgression on to a stable shelf. Major transgression may not have been necessary, however, as the underlying Callytharra Formation was laid down in a deep shelf environment, and the Moogooloo Sandstone represents a delta prograding on to this shelf. Thus, no major change in sea level is necessary to explain the Callytharra and Moogooloo facies.

Billidee Formation

The Billidee Formation consists of orthoquartzite and calcite-cemented sandstone (some fossiliferous) and gypseous, carbonaceous silty shale.

Only one unit in the Lyons River area persists throughout the area mapped. This unit is an easily identified calcite-cemented sandstone with locally abundant bivalves. The unit is named the *Edmondia* band, after the large bivalve which is characteristically present.

As with the Moogooloo Sandstone, in the Billidee Formation, sedimentary structures are useful in reconstructing the environment of deposition.

Cross stratification is common in the sandstone units, but poor outcrop makes detailed examination impossible. Both large- and small-scale cross stratifications are present, large-scale being by far the most abundant.

The average height of large-scale cross stratification is about 60 cm and the maximum dip is 30° (average for 42 readings is 19°). The only type observed took the form of single troughs. Small-scale cross stratification is present as cosets containing up to four sets, the height of each set being about 3 cm. The lower bounding surface is erosional, and the foresets are probably trough shaped. The small-scale cross stratification is the Nu type of Allen (1963), probably formed from the migration of trains of linguoid small-scale asymmetrical ripples in shallow water.

The azimuth of 96 foresets was measured, one to approximately every 200 m². The vector mean is N 16° W with a variance of 3 650 (standard deviation of 59.7°). The results are summarized in Fig. 3. The dominant current direction was towards the north.

CURRENT ROSETTE

Billidee Formation

Fossils

The fossils previously reported from the Billidee Formation are:

Bivalvia:
Nuculopsis (Nuculanella) sp.
Nuculana sp.
Oriocrassatella sp.
Aviculopecten sp.
Schizodus sp. cf. S. kennedyensis Dickins
Stutchburia n. sp.

Gastropoda:
Mourlonia (Pseudobaylea?) n. sp.?
Macrochilina sp.
Warthia sp.
Pleurotomaria sp.
 Bellerophonitid

Ammonoidea:
Propinacoceras sp.
Neocrinites sp.

Brachiopoda:
Neospirifer sp.
Aulosteges sp.
Strophalosia sp.
 Chonetid
 Productid

Crinoidea:
Calceolispongia sp.

An indeterminate bryozoan was also reported.

In the area mapped, fossils were found only in the *Edmondia* band (except for a highly calcified bivalve lower in the formation). The fauna is impoverished in species and in the number of individuals, and is dominated by bivalves.

Poorly preserved *Edmondia sp.* is common, as broken, disarticulated valves, distributed sporadically throughout the calcite-cemented sandstones. *Oriocrassatella sp.* is locally abundant, as disarticulated, and often broken, valves. Other bivalves present are *Schizodus cf. kennedyensis* and *?Nuculopsis sp.* The gastropods *Warthia sp.* and *Mourlonia sp.* are also present. Some phosphatic cylindrical fragments up to 6 cm long were collected, and tentatively identified as fragments of arthropods. One *Stenopora sp.* was seen in thin section. *Stenopora sp.* has not previously been reported from the Billidee Formation.

Silicified fossil wood (*?Araucaria*) is common, and is distributed randomly throughout the sandstone units of the formation.

Palynology.—A carbonaceous shale sample (University of Western Australia sample no. 65501) yielded a rich but not very diverse nor well-preserved assemblage dominated by *Sulcatisporites potonie* (Lakhanpal, Sah and Dube). The other pollen grains are mainly disaccate, nonstriate or monosaccate. The forms present are:

Sulcatisporites potonie (Lakhanpal, Sah and Dube)
Leiotriletes directus (Balme and Hennelly)
Protohaploxyptinus limpidus (Balme and Hennelly)
P. sp. cf. P. amplus (Balme and Hennelly)
Platysaccus leschiki Hart
Microbaculispora tentula Tiwari
Acanthotriletes tereteangulatus (Balme and Hennelly)
Limitisporites sp.
Florinites eremus (Balme and Hennelly)
Apiculatisporis sp.
Cordaitina janakii Potonie and Sah
Neoraistrickia ramosa (Balme and Hennelly)
Veryhachium trispinosum Deunff.

Balme (personal communication) states that this assemblage is typical of early Artinskian coal-bearing sediments from the Perth and Collie

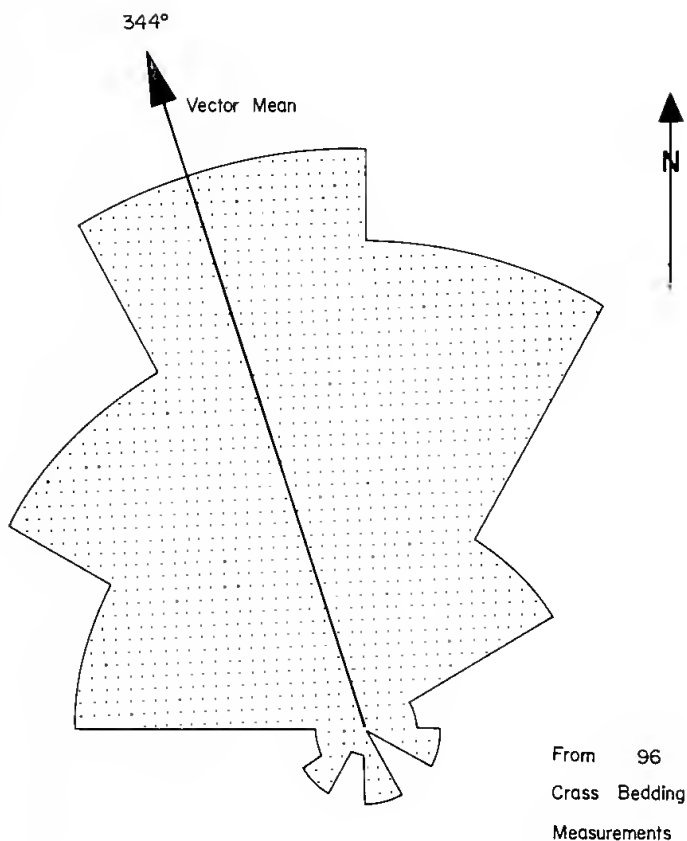


Figure 3.—Current rosette, Billidee Formation.

Rare symmetric, small-scale ripples were observed in fine-grained orthoquartzite. Shale clasts are abundant in the Billidee Formation, occurring in beds traceable for up to 500 metres. The clasts are essentially planar grey mudstone plates about 3 cm in diameter and about 3 mm thick, and are oriented parallel to the bedding.

Vertical ferruginized tubes are common in the *Edmondia* band. The presence of a central, more ferruginized, column suggests that they are root casts and not burrows. One specimen in the *Edmondia* band shows well-developed root casts in a clayey lime mud. The casts are about 1 cm in diameter and are infilled with detrital grains supported by ferroan calcite cement. The area surrounding the cast is extensively ferruginized, probably resulting from oxidation of organic matter. The root casts are cut by a number of collophane "tabulae", which penetrate the carbonate mud, where they bifurcate. The tabular form of the veins indicates that they are probably desiccation cracks, infilled with collophane. A ferruginized clay horizon, about 4 mm thick, is present. It is believed to represent a fossil soil horizon. The carbonate mud contains many sparry ferroan calcite patches up to 1 mm long and 0.02 mm wide. These patches are thought to represent root hairs that have rotted out, the voids being infilled with sparry ferroan calcite. Marine fossils are closely associated with the root casts.

Basins. It is identical with those from the Irwin River Coal Measures (northern Perth Basin) and the lower coals at Collie.

In the Carnarvon Basin, similar assemblages are seen in the Coyrie Formation and also the Keogh and One Gum Formations (formations of the Wooramel Group).

The assemblage is unlike the synchronous Poole Sandstone of the Canning Basin, which contains a diverse pteridophyte suite and a more varied gymnosperm pollen, leading Balm to believe that the Billidee Formation was probably deposited in a cooler climate than the Poole Sandstone.

Spores and pollen grains completely dominate microplankton, with only one specimen of *V. trispinosum* observed.

Environment of deposition

From a study of field relations, petrology, sedimentary structures, fauna and flora it is possible to assemble the following evidence concerning the environment of deposition of the Billidee Formation:

(a) Water Depth: The rapid horizontal and vertical variation in lithofacies indicates rapidly changing conditions during deposition. Such conditions would only be expected from a shallow water environment; deep water environments produce much more monotonous and laterally persistent lithofacies.

The dominance of spores over microplankton suggests nearshore, thus probably shallow water, conditions.

The association of probable root casts with dessication cracks suggests that shallow water plants, subaerially exposed at times, were present during deposition. Shale clasts also indicate subaerial exposure or nearshore conditions (Conybeare and Crook 1968).

The *Edmondia* band marks a change to slightly deeper water conditions, with the marine influence on sedimentation becoming more noticeable.

(b) Currents: Essentially unidirectional currents, towards the north, were responsible for the deposition of the cross stratified sands. Tidal currents were probably not significant. Current strengths were strong enough to transport and break bivalve valves, and are estimated at about 30 cm/sec, using the chart of Sunborg (1956, quoted in Lauff 1967). Currents were probably responsible for winnowing much of the clay from the sands. During deposition of the carbonaceous shales, currents were slight, because anaerobic conditions could only be maintained with minimal circulation.

Dickins (1963) believes that *Oriocrassatella* sp. favoured a silt-free environment. Apart from this, however, no evidence is available concerning water turbulence.

(c) Biota: Conditions favourable for abundant organisms were not present during deposition of the lower part of the formation, although some broken shell material is believed to have been present on deposition, and subsequently destroyed by pressure solution.

During deposition of the *Edmondia* band, conditions were favourable for the deposition of "shell banks", as Dickins (1963) believes this was the life habit of *Oriocrassatella*. The growth of shell banks indicates a favourable combination of salinity, temperature, substrate, etc. Conditions were also favourable, during deposition of the *Edmondia* band for boring organisms.

The reason why abundant brachiopods and bryozoans are not present in the Billidee Formation is not clear, but Dickins (1963) states, without reasons, that abundant brachiopods and bryozoans are almost never found together with the molluscan association present in the formation.

The close association of probable root casts and marine fossils indicates that the plants may have been halophytes, possibly filling the same ecological niche (shallow brackish-marine water with some subaerial exposure) as modern mangroves.

Abundant pebbles, up to 14 cm in diameter, are scattered randomly throughout the *Edmondia* band, in fine- to medium-grained calcite-cemented sandstones. The scattered distribution of these pebbles cannot be explained by "normal" sedimentation, and probably burrowing organisms were responsible for reworking coarse-grained beds and distributing the pebbles evenly throughout the member. This same process may also have been responsible for destroying primary lamination, as outlined by Ginsburg (1957).

(d) Regional Controls on Sedimentation: The heavy mineral assemblage suggests that the provenance of the sandstone is similar to that of the Moogooloo Sandstone—that is, from granitic or high-grade metamorphic rocks.

The strong south to north current trend suggests a strong palaeoslope towards the north. The lack of slump structures, however, indicates that the surface of deposition was essentially flat.

The formation thickens towards the north. The significance of thickening down the apparent palaeoslope (i.e. to the north) is not known, and a regional study of the Billidee Formation would be necessary to produce any meaningful conclusions.

Slow subsidence during deposition may have been necessary to produce the thickness of sediments present in the formation.

(e) Substrate: During deposition of the *Edmondia* band, the substrate must have been soft, because Dickins (1963) believes that *Edmondia* sp. was a burrowing form. The bottom was also probably soft during deposition of the organic muds.

Lime muds formed in some sheltered areas with low influx of terrigenous debris. The mud may have been partially stabilized by plants.

The wide distribution of shale clasts, together with the scattered distribution of burrowing bivalves (obviously resulting from transport), indicates that the substrate was actively eroded by currents.

(f) Salinity: Ladd *et al.* (1957) have described deposition of gypsum in organic muds in salinities as low as 9‰. Thus, high salinities can-

not be inferred from the abundant gypsum in the shales. Hypersaline conditions may have been necessary, however, for the deposition of gypsum interbedded with orthoquartzite.

(g) Climate: Palynological evidence indicates that the climate was cool, and that no significant climatic change occurred between Callytharra and Billidee time.

(h) Oxygen Supply: The carbonaceous shales were developed in anaerobic conditions (Pettijohn 1957, p. 363). Pyrite indicates local reducing conditions. This pyrite could have been formed within the mud, as outlined by Van Straaten (1951).

In summary, the environment of deposition of the Billidee Formation was shallow water (with some subaerial exposure), fairly strong, essentially unidirectional currents during the deposition of the sandstone, with stagnant anaerobic conditions during the deposition of carbonaceous shale. There was fairly rapid fluctuation between aerobic and anaerobic conditions. The deposition of the *Edmondia* band was marked by a minor marine transgression. The substrate was soft during deposition of the *Edmondia* band. Burrowing bivalves were common, as were *Oriocrassatella* sp. "shell banks".

Comparison of the Billidee Formation with likely modern analogues shows that deposition was probably in an environment similar to the lagoonal bays of central Texas (U.S.A.), described by Shepard and Moore (1955) and by Ladd *et al.* (1957). The bays are separated from the ocean by a string of barrier islands. In these bays are found all of the facies present in the Billidee Formation, arranged in a similar pattern, with rapid interfingering of sands and shales. The bays cover a large area (210 × 24 km). Three distinct facies are outlined by Shepard and Moore. These facies are (moving inland): the beach facies, the bay facies and the marsh-river facies. The majority of the Billidee Formation is believed to represent the bay facies. The *Edmondia* band is thought to represent the beach and lower bay facies, these facies having migrated over the underlying bay facies as a result of a slight transgression.

The conditions and facies present in one of these bays (Hynes Bay) are believed to be closely analogous to conditions and facies in Billidee time, and are quoted in part (from Ladd *et al.* 1967, p. 619, 620):

"Hynes Bay measures 5 by 2½ miles and has a maximum water depth of 4 feet ... A sample of the bottom mud dried to a very dark slightly waxy clay with scattered bits of shell and some sand grains ... averaging 0.25 mm in maximum diameter ... also ... plates of gypsum (selenite) averaging 0.5 mm in diameter ... A rich concentrate of Foraminifera shells ... together with some pelecypods were recovered from the bottom. In areas ... the bottom was clean hard sand under 2 feet of water. One fairly large *Rangia* was the only living mollusk recovered. The sand was fine grained but poorly sorted, consisting largely of grains of glassy quartz up to 0.25 mm in maximum diameter ... together with the shells of smaller foraminifers, ostracodes and worn fragments of mollusks ..."

Salinities of 9‰ are the highest reported from Hynes Bay. This is apparently high enough for the deposition of gypsum. Wood fragments are common in the sand lithofacies. Small streams drain into the bays, supplying detrital material for the sand bodies.

Oyster and mussel bioherms are developed in the lower-bay facies. The typical form of these bioherms is a low mound. Many of the larger bivalves and gastropods are bored. The bioherms are believed to correspond to the *Oriocrassatella* sp. "shell banks" in the *Edmondia* band.

The dominant palaeocurrent direction, from south to north, is interpreted as resulting from periodic currents initiated by streams entering the enclosed bays. The thickening of the formation away from the streams (i.e. towards the north) could have been caused by influx of sand from (or over) the barrier islands and into the enclosed bays. This type of sedimentation has been described by Van Straaten (1951, cited in Lauff 1967) from the Ems estuary.

Condon (1967) believes that the deposition of the Billidee Formation followed a marked change in environment from that of the Moogooloo Sandstone. In the area mapped, however, the contact is gradational, with gypseous carbonaceous shale present in both formations. The upper Moogooloo Sandstone is believed to represent a lagoonal environment similar to the environment of deposition of the Billidee Formation.

Condon (1967, p. 98) also states "The siltstone members of the Billidee Formation were deposited in moderately deep water (perhaps 50 fathoms or more) whereas the arenaceous members were deposited in shallow water (indicated by invertebrate trails and burrows, and ripple marks) ..." He goes on to postulate rapid fluctuation of relative sea level, produced in part by tectonic movement and partially by eustatic sea level changes.

The arguments in favour of a shallow water origin for the shale (and siltstone) units of the formation are:

(a) the shale units are laterally impersistent, a feature that would not be expected from shales deposited in water over 90 m deep. Such shales would be expected to outcrop in traceable beds, over large strike distances, as outlined by Rich (1951).

(b) near the Moogooloo-Billidee contact, thin shale beds are interbedded with lenses of orthoquartzite, containing the shallow water trace fossil *Palaeophycus* sp. The rapid alternation between shale and shallow water orthoquartzite indicates shallow water conditions.

(c) the palynological assemblage (almost complete lack of microplankton) indicates a near-shore, probably shallow water, origin for the shales.

Thus it seems that the shales and the sandstones are all part of a shallow water sequence, and no relative change in sea level is necessary to explain the facies present.

There is no evidence to support Condon's (1967) idea that the depositional surface had high topographical relief, thus influencing sedimentation in Billidee time. The lack of slump structures in the area mapped indicates that the surface of deposition was fairly flat.

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8.—An indigenous term for the Western Australian sandplain and its vegetation

by J. S. Beard¹

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Abstract

Sclerophyll shrublands which characterise the vegetation of countries with a Mediterranean climate are variously termed maquis, macchia, chaparral and fynbos. Western Australia has not enjoyed a similar native term. It is shown that in the Aboriginal Nyungar language of the South-west there was a word Kwonkan (gwong-gan) variously spelt Guangan, Quangen, Gongan, Quoncken and Quonkan by authors, meaning sandy country with an open, scrubby vegetation. This "sandplain" vegetation is not a physiognomic or floristic unity but consists of at least two plant formations. None the less the formations are all sclerophyll shrubland and possess a unity in contrast to forest, woodland and steppe. The introduction into common usage of a term spelt kwongan is suggested.

Introduction

In those countries of the world which enjoy a typically Mediterranean climate—mesothermal, with winter rain and summer drought—much of the vegetation consists of sclerophyll shrublands which are to a large extent physiognomically similar. Local terms exist for this vegetation which have come to be widely known and have even passed into common usage. In the Mediterranean area itself such a term is maquis in its French and machia in its Italian form, both from a Corsican dialect word meaning "wild, bushy land" (American College Dictionary, Barnhart and Stein, 1961 ed.). In California the corresponding term is chaparral, an application of a Spanish term for a formation of evergreen oaks, from chaparro, an evergreen oak (same authority). South Africa uses fynbos, the Afrikaans name for certain species of *Leucadendron* and the vegetation in which they are dominant.

The Sandplains

Southwestern Australia is another Mediterranean region and analogous plant formations are widespread mainly on the so-called sandplains, but there is no corresponding indigenous nomenclature in common use. Diels (1906) originated the term Sand-Heide which was translated sand heath by Gardner (1942).

The Aboriginal name Wodjil (Main 1967) is not defined by that author but describes a thicket of shrub-sized Casuarinas which is one only of the formations of the sand plain, while Beard (1969) proposed the terms heath, scrub-heath and broombush thicket for various of these. None is universally applicable.

It now appears that an Aboriginal word can be found which will have general application.

In "The Drummonds of Hawthornden" (Erickson 1969, p. 37) where the author is describing

correspondence between the botanist Drummond and Sir William Jackson Hooker we find the following:

"In July he (Drummond) continued by describing the Avon valley and the Guangan. The latter was a sandplain that lay to the north and east of the Toodyay Valley. 'Guangan', he explained to Hooker, 'in the native language means sand, but I mean by it the open sandy desert which commences about 80 miles E.N.E. of Fremantle and is known to continue in the same direction for 200 miles.'"

This word appears in G. Fletcher Moore's "A descriptive vocabulary of the language in common use amongst the aborigines of Western Australia" (1842 and 1884, p. 29) as Gongan, said to mean "A sandy district. The easiest road, or usual path, or mountain pass to a place". The word thus appears to convey the sense of open country and an easy route to travel.

What is evidently the same word has been found in the annotation to a herbarium specimen referred to *Adenanthos terminalis* R.Br. collected by the botanist Preiss, cited by Lehmann (1844). This reads "In planitie arenosa Quangen, Victoria. Herb. Preiss No. 795." In this case Victoria means the Victoria Plains district of Western Australia, not the Colony (now State) of Victoria. Preiss 795 is actually *A. drummondii*, a Western Australian species (Nelson 1975). This was drawn to the writer's attention by Mr. C. Nelson who had come upon the reference in the course of monographing the genus *Adenanthos*.

The same word apparently also crops up in 1894 in a letter from J. P. Brooks, a settler near Israelite Bay, to the botanist F. von Mueller which was published by the latter in *Proc. Austral. Assoc. Adv. Sci.* 6: 561-9. The letter gives a vivid and detailed description of the Israelite Bay district and includes the information that

"The character of the country is locally termed 'Quowcken' or sandplain. The meaning attached to this word 'Quowcken' by the Aboriginal natives is simply an open plain without timber and would equally apply to clear, grassy plains; whereas a European only applies it to these extensive scrubby plains, thus giving it a special significance".

Nelson (1974) used the spelling Quonkan after discussion with Mrs. Crocker, an elderly resident at Balladonia Station who remembered J. P. Brooks and had a life-long connection with the

¹ 16 Fraser Road, Applecross, Western Australia, 6153.

district. Mrs. Crocker thought that quowcken was mis-spelt and should read quonken. It is suggested that as Brooks' letter was handwritten it may have been difficult to decipher, and indeed his name appears as Brooke in the published letter.

Modern authority in this matter may be found in "The Aboriginal Languages of the South-West of Australia" (Douglas 1968) where page 73 lists the word Kwonkan (gwong-gan) with the English equivalent "plains country". Kwonkan is a phonemic transcription while gwong-gan is an equivalent in a "modified alphabet" used by Douglas to enable non-linguist readers to read out items. As the Nyungar language spread across the South-west from Geraldton to Esperance and maybe even to Eucla it is likely that the word was widely known and that the variant spellings Guangan, Gongan, Quangen, and Quowcken (or Quoncken) are all attempts to symbolise dialect variants of the same word (W. H. Douglas, pers. com.). As English spelling is not properly phonetic it is often difficult to decide how an author intended a transcribed word of this nature to be pronounced. It seems probable that Drummond intended Guangan to be pronounced Gwong-gan (cf. quantity, and the Western Australian quandong, common name for *Santalum acuminatum*), and that Freiss' Quangen should be expressed as Kwong-gan. There is thus little real difference between the various renderings of the word.

If one were to attempt to standardise for common usage it would be necessary to adopt a form which could be readily comprehended and did not appear uncouth, and Kwongan is suggested. There is precedent for the Kw combination in a number of place names in the South-west, e.g. Kwolyin, Kweeda, Kwobrup.

The meaning of kwongan

We have thus a word, but what exactly does it mean? The various definitions make it clear that kwongan means a type of country, just as maquis does. "The character of the country is locally termed 'Kwowcken'" (Brooks). The various definitions all agree essentially on the meaning. The country is sandy (a sandy desert, a sandy district, a sandy plain) and is open without timber-sized trees but with a scrubby vegetation. It consists of plains in an Australian sense of open country rather than in a strict sense of flat country—though much of the open country is also flat.

Sandy "plains" of this nature are very common in South-western Australia where they most commonly appear as relics of a Tertiary land surface coated with laterite which may either be present at the surface or covered with varying depths of sand. According to the detailed accounts of the vegetation which have been published for the eastern half of the South-west, (Beard 1969, 1972 a-e, 1973 a-b) there are two principal plant formations in the kwongan, scrub heath and broombush thicket. These were defined (Beard 1969) as

Scrub heath: a mixed, stratified, partly open shrub assemblage with Proteaceae and Myrtaceae prominent, found on leached sands.

Broombush thicket: a less diverse single-layered very dense shrub assemblage consisting mainly of *Casuarina*, *Acacia* and *Melaleuca* species, found on shallow sandy soil underlain by lateritic ironstone and gravel, or by unweathered granite.

The kwongan therefore does not contain or consist of one plant formation with which it may be equated. None the less both the sand heath and the broombush thicket are sclerophyll shrublands and possess a certain unity when contrasted with woodland and forest or steppe and succulent steppe communities. In this broader sense it is possible to speak of a kwongan vegetation in Western Australia.

Other names of botanical interest

The following Aboriginal names in the Nyungar language of botanical interest are listed by Douglas (1968).

- kwatinj (gwardin)—Figface, *Macarthuria australis*.
- manat (mangard)—Jam, *Acacia acuminata*.
- mut (murd)—a mallee tree, scrub country.
- palak (balag) or pol (borl)—Blackboy, *Xanthorrhoea*.
- tjarilmari (djaril'mari)—forest country.
- warilj (waril')—mallee tree.
- wont (wornd)—white gum tree.

In mut we can recognise Moort, the common name for *Eucalyptus platypus*, and in wont, Wandoo, the common white gum *Eucalyptus wandoo*. In tjarilmari we have perhaps the root of Jarrah (*E. marginata*). Warilj is perhaps related to Morrell (*E. longicornis*) or Yorrell (*E. gracilis*). Wodjil mentioned in this paper from Main 1967 is perhaps related to watjan, fire.

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The Royal Society of Western Australia Incorporated

Constitution and Rules and Regulations

Constitution

1. The scientific society known as "The Royal Society of Western Australia Incorporated" (hereinafter referred to as "the Society") has the objects purposes and powers hereinafter mentioned.

Objects, purposes and powers

2. To promote and assist in the advancement of science.

3. To print and publish, or join in printing and publishing, one or more journals, periodicals, books, newsletters or other documents relating to science.

4. To promote, produce and hold, or join in promoting, producing and holding meetings, lectures and exhibitions in furtherance of any objects of the Society.

5. To found, subsidize or contribute to, for the benefit of any institutions or persons, scholarships, grants, prizes, or monetary or other rewards in connection with all or any of the objects or purposes of the Society.

6. To acquire by purchase, lease, exchange, hire, or by way of loan or otherwise, any real or personal property in furtherance of any objects of the Society.

7. To invest, sell, lease, hire, mortgage, charge, lend, surrender or otherwise dispose of, or deal with all or any part of the assets or property, real or personal, of the Society, or to borrow money and grant security therefor and to liquidate, redeem or discharge any obligations undertaken in furtherance of any objects of the Society.

8. To improve, develop or extend all or any of the property or rights of the Society, also to build, erect or alter any buildings or erections, and to furnish, fit up, and maintain the same and provide fittings, equipment and appliances.

9. To amalgamate, co-operate or affiliate with any other society, association or body having objects wholly or in part similar to those of this Society.

10. To protect or assist in protecting the interests or rights of any member or members of the Society.

Rules and Regulations

Membership

11. The Society shall consist of members divided into the classes hereinafter mentioned, and the members who are, have been or may be duly elected as members of such respective classes shall have the rights and privileges hereinafter specified as appertaining to such respective classes, subject always to the due and

punctual payment of the annual subscription or other sum hereinafter provided to be paid by the respective members of each class, namely—

(a) Ordinary Members: An Ordinary Member if financial shall have the following rights and privileges:—

(i) To be present and to speak and vote at Ordinary, Special or Annual General Meetings of the Society, to vote in postal ballots conducted by the Society, and to attend excursions, meetings, lectures or other activities arranged from time to time by the Society.

(ii) To be eligible for election as a member of the Council hereinafter referred to and also to any office or position in the Society.

(iii) To submit to the Council for consideration for publication papers prepared by any such member on any scientific subject.

(iv) To submit to the Council for consideration for publication on behalf of authors not resident in Western Australia, papers written by such authors on any scientific subject.

(v) To receive the Journal of the Society.

(vi) To receive other publications or documents issued by the Society, upon such conditions as the Council may from time to time determine.

(vii) To borrow books, periodicals, papers, or other documents belonging to the Society, subject to the approval of the Council.

(viii) To propose or second candidates for admission as Ordinary, Associate or Student Members of the Society.

(ix) With the previous approval or assent of the Council or President, or duly appointed chairman or leader of any meeting held by the Society, to introduce visitors. Such visitors shall not be entitled to vote at any such meeting or excursion, but may express opinions on any matter under discussion at the invitation of the chairman or leader.

(x) To propose or second any Honorary or financial Ordinary Member for election to Council.

(b) Associate Members: Persons elected as Associate Members shall be entitled to attend and speak at general meetings, excursions and other activities conducted by the Society, but shall not be entitled to vote at any meeting, and if any such member should vote, then that vote shall not be counted. Associate Members shall be entitled to submit papers for publication, to receive publications or documents issued by the Society at a price fixed by the Council from time to time and subject to the approval of the Council, may borrow books, periodicals or other documents belonging to the Society,

but shall not be entitled to be proposed for, or elected to, any office in the Society, nor to propose or second others for membership or office in the Society.

(c) Student Members: The Council may, on application to be made each year in such form it may require, admit as Student Members, persons under the age of twenty five years who are undertaking formal studies in Western Australia. Student Members shall have the same rights and privileges, and shall be subject to the same restrictions, as Associate Members.

(d) Honorary Members: The Society at its Annual General Meeting in any year may, on the recommendation of the Council, admit as Honorary Members persons distinguished in Science or as patrons thereof, but only in so far as the number of such members shall not at any time exceed twenty five. Honorary Members shall have the same rights and privileges as Ordinary Members, but without liability for any subscription.

(e) Honorary Associate Members: The Society at its Annual General Meeting in any year may, on the recommendation of the Council, admit as Honorary Associate Members persons interested in science, but only in so far as the number of such members shall not exceed twenty five. Honorary Associate Members shall have the same rights and privileges, and be subject to the same restrictions, as Associate Members, but without liability for any subscription.

(f) Corporate Members: Corporate membership may be made available by the Council to organizations under such terms and with such rights and privileges as the Council may determine.

12. Every person desirous of becoming an Ordinary or Associate Member of the Society shall make application in the form prescribed from time to time by the Council and shall be proposed by an Ordinary or Honorary Member of the Society and seconded by at least two other Ordinary or Honorary Members of the Society, to each of whom the applicant is known personally. Each application shall be accompanied by the subscription applicable to the class of membership sought and shall be lodged with one of the Secretaries. Each Ordinary and Honorary Member of the Society shall be informed of the application forthwith by such means as the Council may from time to time determine. The Council shall accept or reject each candidate at a meeting of the Council held not less than one month and not more than six months after issue of advice of the candidate's application to the Ordinary and Honorary Members. Ordinary or Honorary Members wishing to object to admission of any candidate shall communicate their objection and the reasons for it to the President within one month of the issue of such advice. The President shall investigate any such objection and shall report the results of his investigation to the Council, but shall not reveal the identity of the Ordinary or Honorary Member lodging such objection. The Council shall consider the President's report, and shall determine by vote

to admit or not admit the candidate to the class of membership sought. Admission shall be made by a two thirds majority of those Council members present and voting.

13. The Secretary shall inform each candidate of his admission or non-admission to the class of membership sought. Upon admission, each Ordinary or Associate Member shall receive a copy of the Society's Constitution and Rules and Regulations. His membership shall be deemed to apply to the whole of the financial year in which he was admitted so that, subject to their availability, he shall be entitled to receive all publications and documents issued during that year to all members of his class.

14. Every member of the Society, of whatever class, shall be bound to observe and perform, and not commit any breach of, the Rules and Regulations of the Society from time to time in force.

15. Every member shall notify the Secretary in writing of the address to which he may desire notices or communications to be forwarded to him, and shall from time to time notify in writing any change in such address. If any member shall fail to give such notification he shall have no claim against the Society for publications or notices of the meetings or other activities of the Society; no meetings or other proceedings shall be invalidated by reason of any such member not having received such notice.

16. Any member, on paying to the Society all subscriptions or moneys owed by him and returning all books, papers, manuscripts, or property of the Society which may have been borrowed or received by him, may resign his membership by giving notice in writing to the Secretary of the Society; and any member ceasing by resignation, death, or otherwise to be a member of the Society shall not, nor shall his representatives have any claim upon or interest in the funds or property of the Society; but nothing herein contained shall prejudice the right of the Society to recover any moneys owing or property of the Society borrowed, held, or received by such member at any time.

17. Any member whose subscription may be in arrears for a period of at least two years shall, on a resolution of the Council being at any time thereafter passed, be declared to be no longer a member and thereupon shall cease to have the rights and privileges to which he may have been entitled; provided always that nothing herein contained shall prejudice the right of the Society to recover from such member all moneys or subscriptions due, owing, or payable by him up to the date of such termination of his membership, and also to recover all books, papers, manuscripts, or property belonging to the Society which may be held or have been received by such member at any time.

18. Every member in the respective classes of membership in the Society shall use his best efforts to promote the objects of the Society and shall not do or commit any act, deed, or

thing which may be deemed by the Council to be prejudicial to the interests of the Society.

19. The Council may, by an affirmative vote of two thirds of its total membership, remove or suspend from membership or expel any member of the Society without being required to assign any reason for such action. Notice of such removal, suspension, or expulsion, shall be sent by registered post to the last known address of the member concerned within seven days after the decision of the Council. Any member against whom such decision of removal, suspension, or expulsion shall be made, shall be entitled to appeal to a Special General Meeting of the Society by notice to be forwarded by him in writing, addressed to the Secretary within two months after the date of such removal, suspension, or expulsion, stating in such notice the grounds of appeal. It shall be the duty of the Council to summon a Special General Meeting of the Society for the purpose of considering any such appeal, and of hearing statements by any Member of the Council or by the member who may have been removed, suspended or expelled, and if a majority of the members present at such meeting uphold the decision of the Council, then the decision of the Council shall be confirmed, but if such majority shall uphold the appeal, then the decision to remove, suspend, or expel such member shall be set aside. No such member shall be entitled to exercise such right of appeal after the expiration of the said period of two months. In the event of any such removal, suspension, or expulsion taking effect, the member concerned shall remain liable for all moneys or subscriptions due or payable by him as at the date of such removal, suspension, or expulsion, and for the return of all property belonging to the Society.

Subscriptions

20. The subscription for each ordinary membership shall be set from time to time on recommendation of Council and approval by a resolution passed by a two-thirds majority of Ordinary Members voting at any Ordinary or Annual General Meeting of the Society, of which at least twenty eight days notice has been given, and in which notice the proposed alterations have been specified.

An Ordinary Member, whose subscription is not in arrears, may at any time compound for the subscription for the current year and for all future years during the life of such member on payment of a fee of:

(a) twenty years subscription at the rate of the current year or

(b) such sums as will, together with the annual subscriptions already paid, make a total equal to thirty years subscription at the rate for the current year.

21. Associate Membership shall not be more than 60% of the Ordinary Membership rate.

22. Student Membership shall not be more than 20% of the Ordinary Membership rate.

23. The financial year of the Society shall be from the first day of July in each year to the thirtieth day of June in the following year.

24. All subscriptions shall be payable in advance and shall become due on the first day of July in each year. Any member whose subscription is unpaid three months after the due date in any year shall be deemed to be not financial.

Management

25. The management of the business and affairs of the Society shall be vested in a Council consisting of a President, two Vice-Presidents, Treasurer, two Secretaries, Librarian, Editor, Immediate Past President and eight Ordinary or Honorary Members of the Society.

26. All members of the Council shall be elected annually at the Annual General Meeting of the Society to be held on a date normally in July at a place to be decided by the Council. For the purpose of such election, the Council then in office shall submit at an Ordinary or Special General Meeting held not less than one calendar month before the Annual General Meeting, a list of names of Honorary or financial Ordinary Members proposed by the Council for election for the ensuing year and shall appoint a Returning Officer. Any Ordinary or Honorary Member present at such Ordinary General Meeting shall be entitled to propose another financial Ordinary or any Honorary Member to hold any position on the Council, and if such nomination be duly seconded and if the candidate nominated has signified his willingness to accept office if elected, then the name of such nominee shall be added as a candidate. Further, any Ordinary or Honorary Member of the Society may lodge with the Returning Officer within seven days after that Ordinary or Special General Meeting, preceding the Annual General Meeting, a nomination in writing in favour of any financial Ordinary or any Honorary Member for any position on the Council. Such written nomination shall be seconded by another Ordinary or Honorary Member, and shall carry a statement by the candidate nominated as to his willingness to accept the office if elected. Upon receipt of such nomination, the Returning Officer shall add the name of the nominee as a candidate for the Council.

27. If the number of members duly proposed for election does not exceed the number of vacancies for the various offices, the Chairman of the Annual General Meeting shall declare the persons nominated as duly elected. If the number of nominations for any office exceeds the number of vacancies, an election shall be held and the results ascertained by preferential ballot. For the purpose of such election, a ballot paper containing the names of all persons duly proposed for all contested positions on the Council shall be prepared by the Returning Officer and sent to all Ordinary and Honorary Members. Such members desirous of voting shall cause to be delivered to the Returning Officer such ballot papers, duly completed in

accordance with any instructions on voting procedure before the formal opening of the Annual General Meeting. The Annual General Meeting shall appoint at least two scrutineers, who shall examine the procedures of the Returning Officer in his counting of votes and who shall report the results of his count to the Chairman of the Annual General Meeting. Such Chairman shall announce the result of the ballot at the Annual General Meeting or at the next Ordinary or Special General Meeting of the Society.

28. All members of the Council shall be eligible for re-election, and each Council duly elected shall hold office until results of the next annual election are announced at an Annual or Ordinary or Special General Meeting or otherwise communicated to the Society.

29. Any casual vacancy in the Council may be filled by resolution of the Council, and any member so appointed shall hold office until the next annual election of Council. Any vacancy not filled at the annual election shall be deemed a casual vacancy.

30. The Council may define the duties of the two Secretaries and may add any distinguishing word to the title of one or both Secretaries in accordance with the nature of the duties to be performed.

31. The Council shall meet at least once in each month from February to November inclusive in each year (unless otherwise decided by Council), at such times and places as may be appointed by the President or in his absence, by one of the Vice-Presidents, and due and sufficient notice shall be previously sent to each member of the Council.

32. A quorum for a meeting of the Council shall be the President or one of the Vice-Presidents, a Secretary who may be specially appointed for that meeting, and four other members of the Council, and no business shall be transacted at any Council meeting unless such quorum is present.

33. If any member of the Council (including holders of offices) shall fail to attend three consecutive meetings of the Council without satisfactory explanation or reason, or without leave of absence having been first granted to him, then the position or office of such member may by resolution of the Council be declared vacant, and on passing of such resolution he shall cease to be a member of Council and holder of any office to which he may have been elected.

34. The Council shall present at each Annual General Meeting a report giving a review of the work of the Society during the preceding year and some details and information with regard to its progress and affairs, and shall publish this report.

35. The Council may appoint a Committee of such number as the Council may decide to consider and make recommendations on any subject on which the Council may require advice provided that such Committee include

at least one Council Member. Each Committee so appointed shall be reviewed at regular intervals to be determined by the Council.

36. The Council may from time to time make, alter, and repeal by-laws to enable it more effectually to carry out the management of the affairs of the Society, and to regulate the conduct of members and assist in the protection of its property, and for such purposes as may be calculated to advance the welfare of the Society, provided that such changes are not inconsistent with these Rules and Regulations.

37. The Council, without limiting its general powers of management and carrying on the business and affairs of the Society, may exercise and do all things necessary except such as may be required or directed to be exercised by General Meetings, including power to appoint and remove all or any officers, assistants, employees, or others deemed by the Council to be necessary in connection with the work of the Society, and that with or without remuneration and upon such terms and conditions as the Council may think fit. The Council may also delegate all or any of its powers or authorities to any committee or sub-committee from time to time, and may pay all or any expenses or liabilities incurred from time to time and take any steps or proceedings which may be deemed desirable for the purpose of carrying out or securing the fulfilment of any of the objects or purposes of the Society.

President and Vice-Presidents

38. The duties of the President shall be to preside at all meetings of the Society and Council, and regulate all the proceedings therein and generally to execute or see to the execution of the Rules and Regulations and by-laws of the Society. In the case of an equality of votes at any meeting, the President or Vice-President or member presiding shall have a casting vote in addition to a deliberative vote.

39. In the absence of the President from any meeting of the Council, his place shall be filled by one of the Vice-Presidents. In the absence of the President from any other meeting or excursion of the Society, his place shall be filled by one of the Vice-Presidents or by an Ordinary or Honorary Member of the Society elected as Chairman or leader by the Ordinary and Honorary Members there present.

Duties of Officers

40. The Secretaries shall conduct correspondence, cause notices of meetings to be sent out, keep adequate records of all meetings and other activities of the Society, and generally perform such duties as are usually assigned to persons holding such office and comply with the directions, requests, or instructions issued from time to time by the Council.

41. The Treasurer shall keep a correct record of all receipts and disbursements, including subscriptions and all moneys received for the benefit of the Society, and shall pay those moneys forthwith to the credit of the Society

at its bankers. It shall be the duty of the Treasurer to pay all accounts passed by the Council. No moneys shall be withdrawn from the bank account except by cheque signed by any two of a group of three which shall include the President, Treasurer and another member of the Society so authorized by the Council. The Treasurer shall cause the books of the Society to be posted regularly, and shall bring his books to balance as on the thirtieth day of June in each year, or on such other date as the Council may from time to time decide.

42. The Treasurer shall annually submit to an Auditor or Auditors all books and accounts kept by him in connection with the affairs of the Society, made up to the date last mentioned. The Society shall, not later than its Ordinary General Meeting immediately prior to the Annual General Meeting, appoint some person or persons to be Auditor or Auditors, but if such Ordinary General Meeting shall fail to make such appointment, then the Council may appoint an Auditor or Auditors.

43. It shall be the duty of the Auditor or Auditors of the Society to submit a written report each year on the financial affairs of the Society through the Council to an Ordinary, Special or Annual General Meeting of the Society.

44. The Librarian shall maintain records and generally manage the books, periodicals and documents of the Society according to the directions of the Council.

45. The Editor shall supervise the production and distribution of the Society's Journal and such other publications as the Council may direct.

46. Other members of the Council shall assist in the general management of the Society according to the needs which may arise from time to time.

Ordinary General Meetings

47. Ordinary General Meetings of the Society shall be held at 8 p.m. on the third Monday of the months March to June and August to December inclusive in each year, unless the Council determines otherwise, but at least three Ordinary General Meetings shall be held in each financial year. Notice of each Ordinary General Meeting shall be sent to all members of each class. A quorum for an Ordinary General Meeting shall be seven Ordinary or Honorary Members personally present. Conduct of an Ordinary General Meeting shall be at the discretion of the President or Chairman elected by such meeting.

Annual General Meetings

48. The Annual General Meeting of the Society shall, unless the Council determines otherwise, be held on the third Monday of July in each year at a time and place determined by the Council. Notice of each Annual General Meeting shall be sent to all members of each class at least one calendar month before such meeting.

49. The proceedings of the Annual General Meeting, unless otherwise determined by the Council, shall be as follows:—

- (a) Presentation of the minutes of the previous Annual General Meeting.
- (b) Reading of nominations of candidates for Council, appointment of scrutineers, and counting of votes.
- (c) Presentation of the Annual Report of the Council.
- (d) Presentation of the Balance Sheet, Statement of Accounts and (if available) Auditors' Report.
- (e) Report (if available) of the scrutineers on the ballot and declaration of the results by the retiring President.
- (f) Address by the retiring President.
- (g) Installation of the new President.
- (h) Any other business of which notice may have been given or agreed by the meeting to be considered.

50. A quorum for transaction of business at an Annual General Meeting shall be seven Ordinary or Honorary Members of the Society personally present.

Special General Meetings

51. Special General Meetings of the Society may be called by the Council whenever it may deem such meeting expedient, or on the requisition of ten Ordinary or Honorary Members made in writing to one of the Secretaries and specifying the purpose for which the meeting is required. Upon receipt of such requisition, that Secretary shall call the meeting within not less than seven days nor more than twenty eight days. Notice of such meeting shall be sent to all members of each class. The Chairman of the meeting shall be the President or a Vice-President or, in their absence, an Ordinary or Honorary Member elected by the meeting.

52. A quorum for a Special General Meeting of the Society shall be seven Ordinary or Honorary Members personally present.

The Journal of the Society

53. The Society shall publish a Journal at least once a year, in which papers communicated to the Society during or before that year may be printed. The Journal shall be printed in such form as may be decided by the Council.

54. Every paper intended to be published in the Society's Journal must be sent to the Editor for consideration by a Publications Committee appointed by the Council. The Editor shall be Chairman of the Publications Committee.

55. The Publications Committee shall obtain an expert opinion from any person or persons it may select as referees to judge the suitability of any paper for publication. The Committee shall communicate to the Council the Committee's recommendation on whether or not a paper submitted for publication should be accepted for the Society's Journal.

56. It shall be the duty of the Council to decide, on the recommendation of the Publications Committee, whether or not a contribution shall be accepted for publication.

57. All papers accepted for publication must be read or otherwise communicated at an Ordinary, Annual or Special General Meeting prior to publication. The Council shall decide if a paper shall be read in full, in abstract, or taken as read.

58. Publication in the Society's Journal shall be available to all categories of members and to non-members resident outside Western Australia. Papers by non-members resident outside Western Australia shall be communicated through an Ordinary or Honorary Member.

59. The original copy of every paper accepted for publication by the Society, with its illustrations, shall become the property of the Society, unless the Council decides otherwise. Authors shall not be at liberty to publish elsewhere papers submitted to the Society for publication in its Journal, unless permission for doing so is given by the Council, or unless the Society fails to publish the paper in the Journal of the year in which it is accepted or of the succeeding year, or does not accept the paper for publication.

60. The published price of the Journal shall be fixed by the Council from time to time.

61. Offprints of papers shall be available to authors on such terms as shall be decided from time to time by the Council.

The Medal of the Royal Society of Western Australia

62. A medal shall be awarded by the Council every fourth year or at such other times or periods as the Council may from time to time decide for distinguished work in science connected with Western Australia. The Council shall appoint a Medal Committee consisting of five members of the Council to recommend a recipient of the medal.

Formation of Sections

63. Sections may be formed for the purpose of any particular branch of science. Any member of the Society may be enrolled as a member of one or more sections. Each section shall appoint a Chairman and Secretary, who shall

be approved by the Council. Sections shall not incur expenditure without first obtaining the approval of the Council. Any communication to a section may be presented subsequently at a general meeting of the Society.

Common Seal

64. The Common Seal of the Society shall be in the custody of the President or one of the Vice-Presidents, and the President or any one Vice-President shall respectively be authorized to use the same, and when required to be affixed to any deed, document, or writing, shall be so affixed by either the President or one of the Vice-Presidents and signed by him and countersigned by a Secretary of the Society.

Interpretation of the Constitution and Rules and Regulations

65. The Council of the Society shall be the sole authority for the interpretation of the Constitution and of the Rules and Regulations of the Society, and the decisions of the Council on questions of interpretation shall be final and binding on all members.

Alteration of the Constitution and Rules and Regulations

66. The Constitution or the Rules and Regulations or any of them may be amended, altered, enlarged or repealed from time to time by a resolution passed by a two thirds majority of Ordinary or Honorary Members voting in a postal ballot conducted by the Council. Notice of intention to conduct such a ballot shall be given with notice of an impending Ordinary or Annual or Special General Meeting of the Society and the proposed amendment or amendments shall be presented at that meeting at least one calendar month before the ballot is held.

Winding up of the Society

67. The Society may be wound up by a resolution to be passed by a four fifths majority of the Ordinary Members of the Society present and voting at a Special General Meeting summoned for such purpose, whereof at least twenty eight days notice shall be given. If a resolution to wind up be passed, all property and assets of the Society shall be disposed of or applied in such manner as may be decided at such meeting.

INSTRUCTIONS TO AUTHORS

Contributions to this Journal should be sent to *The Honorary Editor, Royal Society of Western Australia, Western Australian Museum, Perth*. Papers are received only from, or by communication through, Members of the Society. The Council decides whether any contribution will be accepted for publication. All papers accepted must be read either in full or in abstract or be tabled at an ordinary meeting before publication.

Papers should be accompanied by a table of contents, on a separate sheet, showing clearly the status of all headings; this will not necessarily be published. Authors should maintain a proper balance between length and substance, and papers longer than 10,000 words would need to be of exceptional importance to be considered for publication. The Abstract (which will probably be read more than any other part of the paper) should not be an expanded title, but should include the main substance of the paper in a condensed form.

Typescripts should be double-spaced on opaque white foolscap paper; the original and one carbon copy should be sent. All Tables, and captions for Figures, should be on separate sheets. Authors are advised to use recent issues of the Journal as a guide to the general format of their papers, including the preparation of references; journal titles in references may be given in full or may follow any widely used conventional system of abbreviation.

Note that *all* illustrations are Figures, which are numbered in a single sequence. In composite Figures, made up of several photographs or diagrams, each of these should be designated by letter (e.g. Figure 13B). Illustrations should include all necessary lettering, and must be suitable for direct photographic reproduction. To avoid unnecessary handling of the original illustrations, which are usually best prepared between $1\frac{1}{2}$ and 2 times the required size, authors are advised to supply extra prints already reduced. Additional printing costs, such as those for folding maps or colour blocks, will normally be charged to authors.

It is the responsibility of authors to adhere to the International Rules of Botanical and Zoological Nomenclature. Palaeontological papers must follow the appropriate rules for zoology or botany, and all new stratigraphic names must have been previously approved by the Stratigraphic Nomenclature Committee of the Geological Society of Australia.

Fifty reprints of each paper are supplied free of charge. Further reprints may be ordered at cost, provided that orders are submitted with the returned galley proofs.

Authors are solely responsible for the accuracy of all information in their papers, and for any opinion they express.

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The Royal Society of Western Australia Incorporated. Constitution and Rules and Regulations.



Editor: A. E. Cockbain

The Royal Society of Western Australia, Western Australian Museum, Perth

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OF
WESTERN AUSTRALIA

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9.—Lake Leschenaultia—an oligotrophic artificial lake in Western Australia

by R. P. Atkins¹, R. A. Congdon¹, C. M. Finlayson^{1, 2} and D. M. Gordon¹

Manuscript received 16 March 1976; accepted 14 September 1976

Abstract

Lake Leschenaultia is a semi-natural freshwater lake established in 1912 on the Darling Scarp 40 km from Perth. In contrast to natural lakes in the south-west of Western Australia, this body of water is deep, low in nutrients, and phytoplankton. The emergent macrophytes are restricted to the lake margin. The area is being developed for public recreation.

Introduction

Wetlands occupy a relatively small part of south-western Australia (Riggert 1966). Among them there is a large proportion of swamps, but there are few freshwater lakes and these are generally very shallow and restricted to the ancient dune systems of the coastal plain (McArthur and Bettenay 1960).

In contrast, Lake Leschenaultia, situated at Chidlow, 40 km east of Perth, and 49 km from the coast, is up to 9 m deep. This spring-fed, freshwater, artificial lake results from a dam built across Cookes Brook and completed in 1912 (Shipway 1948). The lake was used by the Western Australian Government Railways for watering of steam locomotives, and is now being developed for public recreation.

The lake (Fig. 1) is in a laterite basin in the Darling Scarp. It has an area of approximately 40.5 ha (Leggo, pers. comm. 1975), a capacity of 530 million litres and a catchment area of 168.78 ha (Morris, pers. comm. 1975). The bottom of the lake is covered by an organic sediment which becomes deeper and more peaty at the narrower south-western end. A preliminary account of Lake Leschenaultia and its vegetation was published almost 30 years ago (Gentilli 1948; Shipway 1948).

Detailed studies of the chemistry and vegetation of three coastal interdunal lakes are being made by the authors; they are Loch McNess, 50 km north of Perth at Yanchep, Lake Joondalup, 32 km north of Perth at Wanneroo (Congdon and McComb 1976), and Lake Monger in the Perth suburb of Leederville. The present investigation of Lake Leschenaultia was undertaken to provide comparisons with a different lake type, deep and presumably oligotrophic, in the same general climatic region. An artificial lake was chosen because no natural lake of this type is available.

Benthic and fringing plants

The dominant hydrophyte is *Nitella congesta*, which covers most of the bottom of the lake. In the shallower, narrow part of the lake *Pota-*

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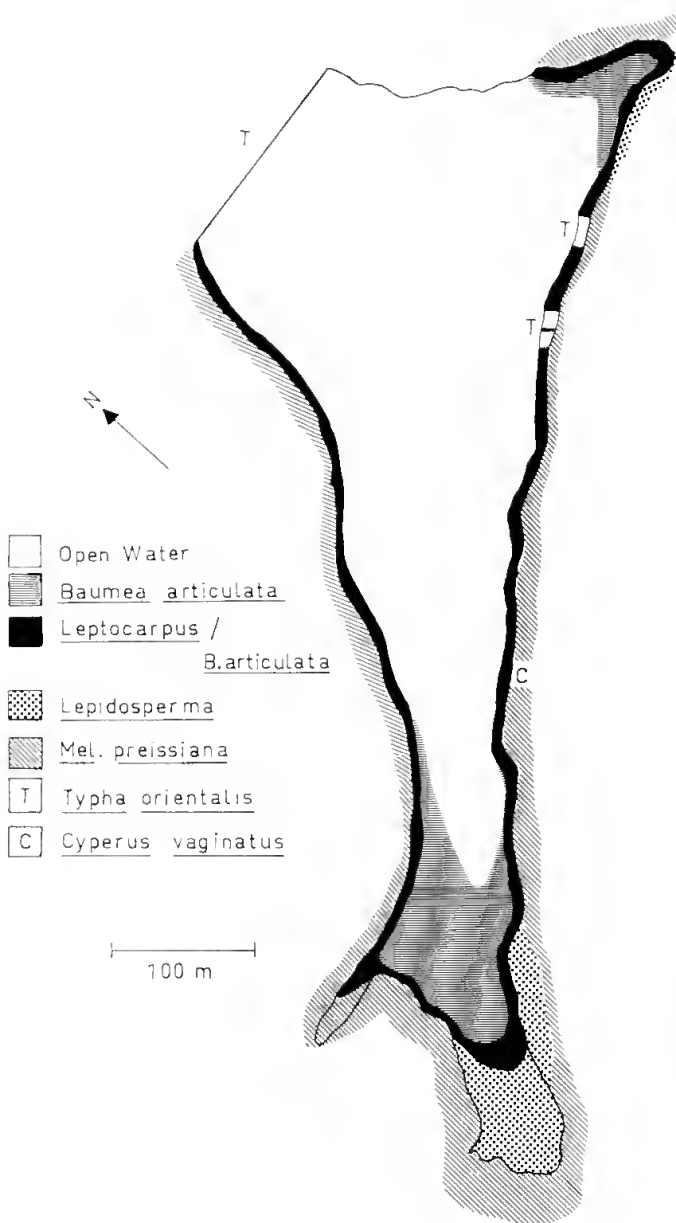


Figure 1.—The plant communities of Lake Leschenaultia.

mogeton tricarinatus becomes dominant. Other aquatic plants include *Villarsia albiflora* and *Triglochin procera*, which are found at the water's edge in very moist soil and in water up to several centimetres deep.

The fringing vegetation (Fig. 1) appears to have changed little since the descriptions of Gentilli (1948) and Shipway (1948). The dominant fringing macrophytes are *Baumea articulata* (presumably named *Juncus pallidus* in error in

the earlier papers) and *Leptocarpus aristatus*. *Baumea juncea* occurs sparsely at the north-western shore where the lake narrows and continues to the western end. There is one patch of *Typha orientalis* to the north of the dam wall, and three on the south-eastern shore, of which one is approximately 15 m x 5 m and two are approximately 5 m² and 10 m apart. There is one patch of *Cyperus vaginatus* about 10 m² on the south-eastern shore. The *Typha* and *Cyperus* appear to have colonized disturbed areas of the south-eastern shore.

Further back from the shoreline the monocotyledons *Lepidosperma angustatum*, *Restio megalotheca*, *Restio appianatus* and *Paspalum dilatatum* occur, together with the paperbark *Melaleuca preissiana* (*M. parviflora*). *Scirpus nodosus* is found at the south-western end and in patches along the south-eastern shore. *Hakea prostrata* is also found along this south-eastern shore.

The greatest abundance of species is found where there has been an accumulation of silt from the two major inflow streams at the south-western and eastern ends of the lake. *Baumea articulata* extends into water up to one metre deep at the eastern inflow. Other species found at these two sites are *Melaleuca preissiana*, *Eucalyptus rudis*, *Viminaria juncea*, *Acacia cyanophylla*, the sedge *Lepidosperma longitudinale*, and the insectivorous herbs *Drosera heterophylla* and *Polypompholyx* spp. The sedges and larger dicotyledons stabilize the silt which is discharged in these areas from the inflowing streams. Voucher specimens of the hydrophytes have been lodged in the Herbarium of the Department of Botany, University of Western Australia.

The surrounding forest is a *Eucalyptus marginata*—*Eucalyptus calophylla* association, with *Eucalyptus wandoo* present on the south-eastern and eastern sides of the lake. A road around the lake comes to within 10 m of the waterline on the north-western side, and 20-30 m on the south-eastern side. The vegetation appears more disturbed on the north-western side of the lake, where there is reduction in ground cover, marked by the presence of gravel deserts (Gentili 1948) and an increase in exotic species such as the thistle *Sonchus asper*.

Biological aspects of the open water

Phytoplankton

Water was collected from just below the surface at 4 sites on the lake, bulked, and the plankton in a one litre sub-sample concentrated by centrifuging at 2000 xg for 15 minutes. The supernatant was removed by suction and the residue resuspended and counted, using a counting chamber, (Gelman Hawksley Ltd., England) with a grid size of 0.0025 mm², and a depth of 0.1 mm. Eight replicates of 25 fields were scanned, i.e. 200 fields of view.

Plankton levels were extremely low and no measurable estimates per unit volume could be given, even though the method gave high levels for other lakes (Table 1). Species seen at very low frequency during the study, though not

necessarily within the grid, were *Lyngbya limnetica* Lemm., *Navicula* sp., *Spirogyra* sp., and *Pediastrum duplex* Meyen.

Table 1

Total counts and chlorophyll 'a' levels for Lake Leschenaultia and three coastal lakes in May 1975

Lake	Total Number/litre	Chlorophyll 'a' (mg/m ³)
Leschenaultia	< 6x10 ⁴	< 0.10
Monger	540x10 ⁴	1.58
Joondalup	2800x10 ⁴	3.94
McNess	55x10 ⁴	0.44

As an estimate of biomass along with these direct counts, chlorophyll 'a' per litre of lake water was determined, using a modification of the trichromatic technique of Richards with Thompson (1952). Again, the pigment extract gave absorbancy readings which were too low to be used for calculating pigment amounts. For comparison, the chlorophyll 'a' levels of three coastal lakes are included in Table 1.

Lake bathymetry and physico-chemical aspects

Depth soundings were made along two transects at 50 m intervals, measured with the buoy and float method described by Welch (1948). The transects were taken across the length and breadth of the lake. The results were transposed onto Figure 2, which is derived from an aerial photograph supplied by the Department of Lands and Surveys.

A comparative measure of light transparency was obtained with a 20 cm-diameter Secchi disk. pH was measured in the field using a portable meter (E 488, Metrohm Ltd., Herisau, Switzerland). Specific conductivity was measured on return to the laboratory with a conductivity meter (E 382, Metrohm Ltd., Herisau, Switzerland) and converted to a standard temperature of 18°C using the formula of Bayly and Williams (1973).

Table 2

Some physico-chemical characteristics of Lake Leschenaultia compared with Loch McNess, Lake Monger and Lake Joondalup for May 1975

	Leschenaultia	McNess	Monger	Joondalup
Maximum depth (m)	9.0	1.5	1.9	1.4
Secchi transparency (m)	4.2	100%	100%	0.8
pH	7.6	7.8	8.7	9.2
K ₁₈ (mS.cm ⁻¹)	1.13	0.45	0.85	1.76

Some basic physico-chemical parameters of the lake are presented in Table 2 and compared with the other lakes under study. Lake Leschenaultia has by far the greatest depth. It also has a high Secchi transparency for May 1975, and this transparency correlates with a low phytoplankton standing crop.

All the lakes are alkaline but Leschenaultia has the lowest pH. Monger, Joondalup and Loch McNess lie in the Spearwood dune system of calcareous sands overlying aeolianite (McArthur and Bettenay 1960), and this probably accounts for their higher pH values. Loch McNess lies in

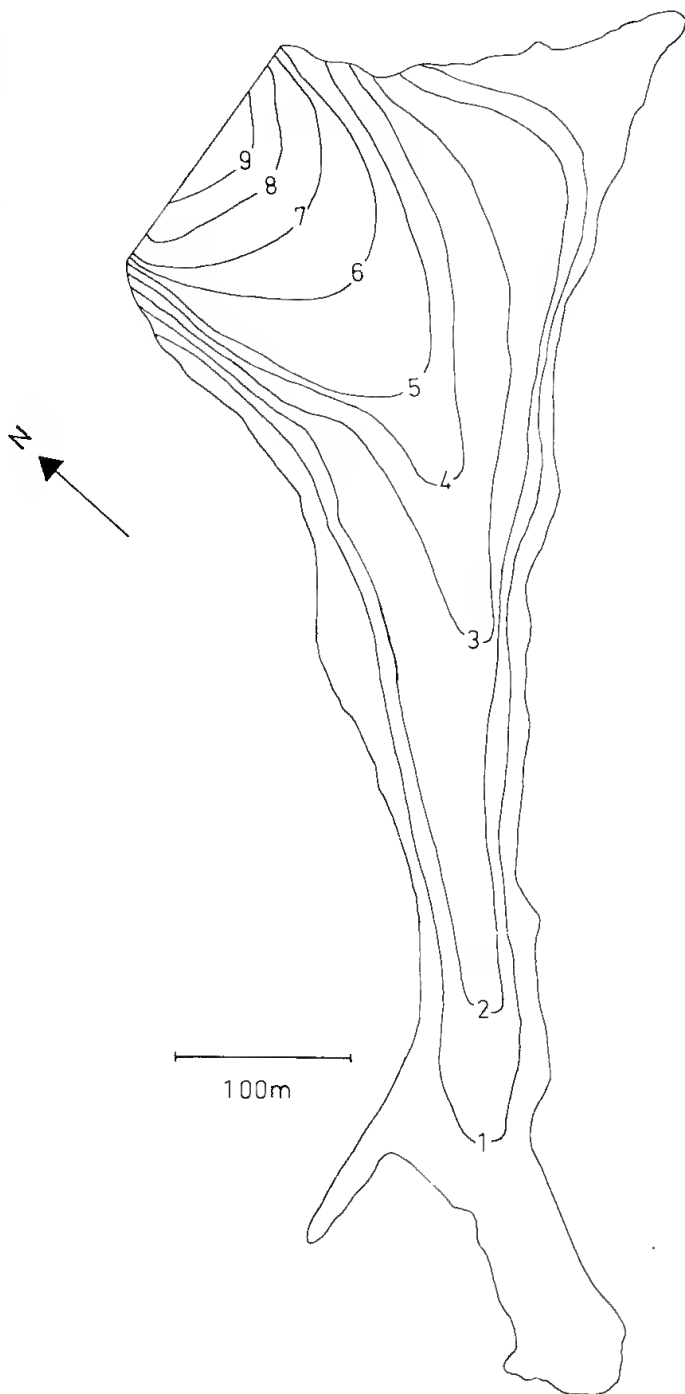


Figure 2.—Depth contours for Lake Leschenaultia. One metre intervals, recorded May, 1975.

close proximity to extensive fens (McComb and McComb 1967) which may contribute humic acids which would modify the pH.

The specific conductance of Lake Leschenaultia is relatively high compared with the other lakes, only being exceeded by Lake Joondalup. This is a reflection of the high ion levels (see below).

Dissolved oxygen

Oxygen was measured with an oxygen meter (YSI Model 51B, Yellow Springs Instrument Co., Yellow Springs, Ohio) calibrated by an air-saturation technique. This meter allowed compensation for temperature, air pressure and chloride concentration in the water. Readings

were taken at different depths in order to check for stratification. On one occasion oxygen levels at the same site were compared for surface water collected at midday, and at depth using the azide modification of the Winkler method (Anon. 1971) A Hales water sampler, described by Welch (1948), was used to collect the bottom sample. All samples were fixed in the field.

Results are given in Table 3. No stratification was observed for oxygen over depth. However, an oxygen profile taken during September at the same site as that in June, showed a significant difference between top and bottom oxygen levels. It would appear that an oxygen gradient may persist at certain times of the year.

Table 3
Oxygen levels in Lake Leschenaultia (mg/litre)

Depth (m)	June		September		
	°C	Dissolved oxygen		°C	Dissolved oxygen Meter
		Meter	Winkler		
Surface	14.2	8.8	8.7	14.6	10.5
1	14.0	8.8	....	14.2	9.4
2	13.8	8.8	....	14.2	8.4
3	13.6	8.8	....	13.4	6.6
4	13.5	8.8	....	13.0	5.6
5	13.4	8.8	....	13.0	....
6	13.4	8.8	8.7	13.0	5.2

Cation-anion balance

The ionic concentrations of most shallow lakes of the Swan Coastal Plain change seasonally with lake volume, which is in turn related to rainfall (Congdon and McComb 1976). Loch McNess may be an exception, in that the level is relatively constant seasonally, as the lake basin overflows (McComb and McComb 1967). Short term comparative studies between lakes must therefore take this effect into account.

Figure 3 gives the monthly rainfalls for the areas in which the four lakes lie. There is a very close relationship between the rainfalls of Perth (Lake Monger), Wanneroo (Lake Joondalup) and Chidlow (Lake Leschenaultia). The figures for Yanchep (Loch McNess) are not as closely correlated, but the same trends are apparent. Consequently, the ion levels in the lakes might well be meaningfully compared for a particular month.

The metallic cations were determined by atomic absorption spectroscopy. Chloride was determined potentiometrically using an automatic chloride titrator. Bicarbonate was determined by the double indicator method and sulphate by the turbidimetric method (Anon. 1971).

The ion levels are comparable to those found by Congdon and McComb (1976) for Lake Joondalup in May 1973. These levels are high compared with freshwater lakes throughout the world, although Australia possesses many athalassic saline lakes (Bayly and Williams 1973).

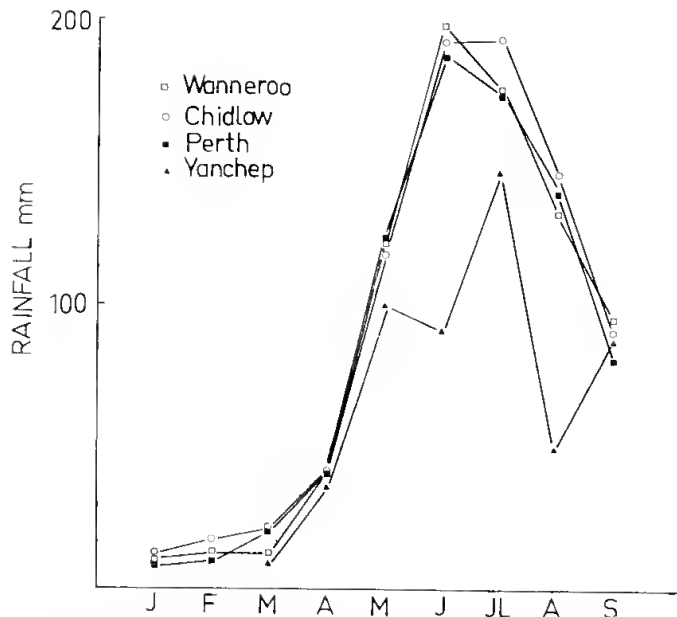


Figure 3.—Monthly rainfall figures for lake regions. (Yancheep figures courtesy of National Park's Board; others courtesy of Bureau of Meteorology.)

The order of dominance of the cations is $\text{Na} > \text{Mg} > \text{Ca} > \text{K}$ and that of the anions is $\text{Cl} > \text{HCO}_3 > \text{SO}_4$. This order is the same as in seawater but the percentage equivalence values are not closely correlated with those of seawater, being relatively low in Na and K, and relatively high in Mg and Ca (Table 4).

Lateritic profiles in the Darling Range show soluble salts stored in the pallid zone and these are released following clearing of native hardwood forests (Dimmock *et al.*, 1974). These salts are believed to have originated largely from long term atmospheric accessions in rainfall (Peck and Hurlle 1973). This may well be the source of the major ions in Lake Leschenaultia. The

derivation of ions from rainwater of oceanic origin has been postulated for coastal dune lakes of New South Wales and Queensland (Bayly 1964), Blue Lake in South Australia (Bayly and Williams 1964) and Lake Joondalup in Western Australia (Congdon and McComb 1976).

At the time of sampling there was no significant difference between the ionic composition of the surface water and water from 6.5 m, except for increased sulphate at depth. This is in accord with Mortimer's (1941-1942) results for aerated water over mud.

Silica

Reactive silicate was determined by the reduced β -silico-molybdate method (Major *et al.* 1972). There was little variation in silica level with depth (Table 5). Comparison with the range of silica levels for other freshwater lakes (Hutchinson 1957), indicates that values found here are relatively low. In considering a temperate, deep water lake, Mortimer (1941-1942) found silicate levels, under aerobic conditions, ranged from a few to 20 000-30 000 $\mu\text{g/litre}$ in Lake Windermere.

Presence of silica in lake water is generally correlated with diatom populations, which play a significant role in reducing silicate levels through direct utilization. Though it would be unwise to generalise from the May data to other seasons, it would seem reasonable to suggest that the levels found in Lake Leschenaultia are due to drainage patterns providing silica from silicate mineral decomposition, rather than from diatoms in the water, which were at very low numbers at the time of sampling.

Phosphorus

Water collected for total phosphorus determinations was frozen as soon as possible after collection. The samples collected for inorganic

Table 4

Major cations and anions found in Lake Leschenaultia in May 1975, with some data for seawater for comparison

Depth	Units	Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺	Cl ⁻	HCO ₃ ⁻	SO ₄ ²⁻
surface	mg/litre	194	2.8	11.7	38	380	30.5	4.5
	% meq/litre	69	0.5	5	25.5	95	4	1
6.5m	mg/litre	190	2.8	11.6	39	380	30.5	12.0
	% meq/litre	68	0.5	5	26.5	93.5	4.5	2
seawater ¹	g/litre	10.8	0.4	0.4	1.3	19.4	0.1	2.7
	% eq/litre	77.1	1.6	3.3	18	90.2	...	9.8

¹Figures for seawater taken from Parker (1972).

Table 5

Nutrient levels in Lake Leschenaultia and three other lakes on the coastal plain for May 1975

Lake	Depth	Nutrient ($\mu\text{g/litre}$)						
		Si	Tot P	PO ₄ -P	Org-P	NH ₃ -N	NO ₃ -N	NO ₂ -N
Leschenaultia	surface	274	10	8	2	11.4	61	13
Leschenaultia	6m	280	20	8	12	12.5	20	20
Monger	surface	..	21	<1	21	33.6	594	16
Joondalup	surface	..	38	2	36	14.8	813	33
McNess	surface	..	7	<1	7	4.1	813	12

(ortho) phosphate determination were placed in polyethylene bottles previously soaked in a KI/iodine mixture and determined by the single solution method (Major *et al.* 1972). Total phosphorus was determined by the same method after perchloric acid digestion. Surface and depth readings obtained for Lake Leschenaultia during May 1975 are given in Table 5 along with levels found in three other lakes.

Levels of phosphorus in Lake Leschenaultia were relatively low. Hutchinson (1957), in a review of a number of geographically-distinct lakes found in humid, temperate regions, noted uniform low concentration of total P in surface waters. Though within 80 km of Lake Leschenaultia the three coastal lakes, used for comparison, gave contrasting phosphorus levels. Lake Monger, a well established, shallow alkaline lake, sometimes subject to intense algal blooms and considered to be fairly eutrophic, gave total phosphorus readings during May which were similar to those for bottom water in Lake Leschenaultia. However, levels of phosphorus during this period were declining in Lake Monger and it is noteworthy that levels of 60-70 $\mu\text{g}/\text{litre}$ have been reported during this month in this lake in earlier years (Harris 1969). A similar trend was found for total phosphorus in Lake Joondalup, considered to be mildly eutrophic (Congdon and McComb 1976). Closer agreement was found between the values for Lake Leschenaultia and Loch McNess, the latter being the least disturbed and least productive of the coastal lakes.

Inorganic phosphorus comprised a significant part of total phosphorus in Leschenaultia, being 80% of total surface water phosphorus. Much of the phosphorus utilised by phytoplankton in lakewater is in this fraction. From the large amounts of $\text{PO}_4\text{-P}$ relative to total P, it is suggested that low phytoplankton numbers, and thus little utilisation of the phosphate fraction, may be responsible. This may be further borne out from comparison with the coastal lakes, where reduced orthophosphate levels occur where algal population numbers are significant.

Levels of organic phosphorus were higher at depth, though the orthophosphate fraction remained constant. Phytoplankton levels were minimal during May, and it can only be assumed that organic material was present at depth, derived from benthic or fringing plants.

Nitrogen

Inorganic nitrogen was determined by individually testing for ammonia, nitrate and nitrite. Ammonia was detected by the cyanurate method (Dal Pont *et al.* 1974). Nitrate was detected by an ultra-violet method which takes into account interference by organic nitrogen (Anon. 1971). The nitrite concentration was tested by a diazotisation method which involved coupling diazotised sulfanilic acid with naphthylamine hydrochloride (Anon. 1971).

Ammonia was found in similar concentrations at both depths (Table 5), but differences occurred in concentration of nitrite and nitrate. The nitrate was more concentrated at the surface. (The lower value of 20 $\mu\text{g}/\text{litre}$ may not be entirely accurate as the ultra-violet technique

has a recommended lower detection limit of 40 $\mu\text{g}/\text{litre}$ (Anon. 1971).) The level reported here is lower than that given by Shipway (1948) (10 mg $\text{NO}_3\text{-N}/\text{litre}$). As no information on the technique used to measure the early sample is available it would be unwise to draw conclusions from the comparison, as many nitrate methods have been found to be unreliable (eg. Vollenweider 1968). Nitrite was higher in the 6 m sample but the relatively minor role this element plays in the environment (Malhotra and Zanoni 1970) reduces the significance of this change.

Using inorganic nitrogen values for Lakes Joondalup, Monger and McNess (Table 5) it is possible to gain an indication of the relative trophic level of Lake Leschenaultia. The nitrite concentration places Leschenaultia between McNess and Joondalup and very similar to Monger, but as this compound is so transient in the environment, little emphasis should be placed on this comparison. The nitrate found is considerably lower than levels found in the other three lakes. As the level of nitrate in oligotrophic lakes rarely exceeds 1 mg/litre $\text{NO}_3\text{-N}$ (Bayly and Williams 1973), it seems reasonable to classify Lake Leschenaultia as oligotrophic, at least on this one occasion, on this basis. An attempt was made to read nutrient levels, as total P and inorganic nitrogen, onto tables classifying lakes into their trophic status. Using the table of Sakamoto (1966) (cited Vollenweider 1968), Lake Leschenaultia can again be classified as oligotrophic. Thus, from a consideration of nutrient levels (as N, P and Si), phytoplankton populations and physical state of the water using information for other lakes in the area, and information from the literature as a guideline, it is suggested Lake Leschenaultia be designated oligotrophic.

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10.—Poison plants in Western Australia and colonizer problem solving

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Abstract

Because of their leguminous seed pods, poisonous plants of the genera *Gastrolobium* and *Oxylobium* posed major problems for Western Australia's nascent pastoral industry. Not only did they cause considerable economic loss, but it took nearly twelve years for their lethal properties to be recognised. This delay is attributed here to the nature of these plants and to the confusion generated among colonists by the conflicting explanations offered by Dr Joseph Harris and the botanist James Drummond.

The process by which the toxic nature of these plants was established raises important theoretical implications about problem solving and hazard response in unfamiliar environments and throws light on colonizer adjustment. It is concluded that learning can be viewed as a progression along a generalization-differentiation continuum where generalization denotes the constraining effect of well established past behaviours and differentiation refers to a growing sensitivity and responsiveness to previously unfamiliar environmental stimuli.

Introduction

Any relocation in space will induce a period of active adjustment. Nowhere is this more evident, or more crucial than in pioneering situations. Here, people with diverse backgrounds, predispositions and expectations invariably encounter grossly unfamiliar and often extremely forbidding conditions which contain few of the elements which gave their former behaviour structure and cohesion. Yet, with the exception of Found's exploratory theorizing of incremental learning (Found 1971, p.139-141), colonizer adjustment has received little attention.

No attempt is made here to examine all types of learning evident in colonizer adjustment. Rather, the emphasis is placed on the problem solving activities associated with Western Australia's poison plants for these activities represented a deliberate attempt to decrease the disparity between the expected and actual outcomes of pastoral operations. This is a unique example but does have important theoretical implications. The paper is therefore structured into three parts which focus respectively on the nature of the problem, the sequence of events leading to its resolution, and the characteristics of problem solving behaviour evident in this sequence.

The problem in its context

Western Australia has more than 150 endemic plants capable of poisoning stock under some circumstances (Gardner and Bennetts 1956). Of these, the 32 toxic species of the genera

Oxylobium and *Gastrolobium* are the most widespread and lethal, less than 15 g being at times sufficient to kill an adult sheep (Aplin 1967). As partly indicated in Table 1, they constituted the major hazard for the nascent pastoral industry, losses from them exceeding combined losses from all other hazards including bushfires, floods, drought, aboriginal depredations and the attacks of native dogs. Stock losses were recorded as early as December 1830 and continued at a high level throughout the 1830s. They created the conditions of stress necessary for inducing accelerated learning and active problem solving (Festinger 1964; Heider 1958; Lewin 1938) but the cause of death was not positively confirmed until May 1841 (*Inquirer*, 26 May 1841; *Perth Gazette* (hereafter P.G.), 17 May 1841). Two factors, the nature of the problem, and the nature of the problem solvers, account for this slow resolution.

The nature of the problem

A recognition of the fact that the genera *Oxylobium* and *Gastrolobium* are members of the pea flowered family (Papilionaceae) is fundamental to understanding delays in identification. Shepherds believed their leguminous structure placed them among the more nutritious local fodder sources and deliberately sought them out. As the plants had not been previously encountered in Australia, there could be no warning of their lethal properties. To add further confusion, only 15 of the 59 species recognised by 1864 (Bentham 1864, p. 14-26, 96-207) have since been found to be toxic (Gardner and Bennetts 1956, p. 52-75). All species can be eaten, their palatability being greatest in the winter and spring months when toxicity is at a peak. These features alone sufficiently explain delays but they were exacerbated by the nature and effect of the toxic element.

The toxic agent of *Oxylobium* and *Gastrolobium* is monofluoroacetic acid, found elsewhere only in the gifblaar (*Dichapetalum cymosum*) of South Africa and the gidgee (*Acacia georgina*) of Queensland and the Northern Territory (Aplin 1967). More commonly known as the rabbit poison '1080' (its sodium salt derivative), fluoroacetic acid is odourless, colourless, tasteless, water soluble and extremely stable. When ingested, it converts by enzyme action into the toxic fluorocitric acid (Peters 1954). As shown in Table 2, only small dosages are required to produce fatal results. There is no known antidote. As its presence in nature was not demonstrated until 1943, settlers could not know of its existence.

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Table 1

Recorded stock losses from poison plants, 1833-1840

Date recorded	Details of mortality	Location	Remarks
(PG) 21 September 1833	Heavy stock losses: upwards of 100 sheep from 1 flock.	Upper Swan	
(PG) 19 October 1833	4 out of 6 bullocks. Dog eating one of the bullocks later died.	York Road	
(PG) 15 March 1834	21 sheep	Upper Swan—Scarp face	
(SD) 17 March 1834	300+ sheep, 5 cattle, 3 horses	King George Sound	
(PG) 16 August 1834	40 sheep, 6 goats	Upper Swan	
(PG) 11 April 1835	55 out of 66 goats	York Road	} Very dry season with the result that many flocks were moved to the inland pastures of the Avon Valley. Total sheep numbers were then less than 4 000.
(PG) 16 May 1835	93 sheep, 13 goats, 6 bullocks	York Road	
(PG) 20 June 1835	15 sheep	York Road	
(PG) 14 November 1835	8 out of 10 bullocks	York	
(PG) 26 November 1836	130 sheep out of 300	Williams district	} Exceptionally dry season which persisted until the winter of 1842
(PG) 4 August 1838	56 sheep out of 239	Williams district	
(PG) 20 November 1838	Major losses of cattle	Williams district	
(PG) 7 July 1839	Major losses of all stock throughout the colony.		} Mortality associated with the overland movement of imported stock from King George Sound to the Avon Valley.
(PG) 28 March 1840	250 sheep and 12 cattle out of 750 sheep and 54 cattle.	Kojonup district	
(PG) 27 June 1840	63 sheep out of 600. Other losses were even greater.	Road from King George Sound to the Avon Valley	
(PG) 10 October 1840	33 out of 180 sheep	Upper Swan—Scarp face	
(INQ) 7 October 1840	Total flock of 180 sheep	York	
(PG) 5 December 1840	All of Craigie's flock (c.500) 304 of Tapson's flock 118 of MacDonald's flock	Kojonup district	

Source: *Perth Gazette* (shown as PG); *Inquirer* (INQ); *Spencer Diary* (SD).

Table 2

Toxicity of sodium fluoroacetate (50% mortality)

Animal	Dosage (a) (mg per kg of body weight)
Dog	0.066
Sheep	0.25
Pig	1.0
Horse	1.0
Kangaroo	8.0 (b)
Pigeon	9.0
Frog	300.0

(a) All dosages were administered orally.

(b) This figure is for 100 per cent mortality. Dosage for 50 per cent mortality is not available.

Source: Department of Agriculture, Western Australia, n.d., *Sodium fluoroacetate: A resume of the available literature dealing with the poisoning of human beings and animals (mimcod)*.

Most English poisonous plants, by contrast, are cyanogenetic, or contain poisonous, sometimes narcotic, alkaloids. With the exception of foxglove (*Digitalis purpurea*), their poisonous qualities were suggested through their acrid taste and the foetid smell of their sap and bruised leaves. These characteristics settlers were well aware of and it is not surprising that attention first centred on a number of cyanogenetic plants, particularly the blind grasses (*Stypandra imbricata* and *S. grandiflora*) which induce a range of symptoms similar to those induced by *Oxylobium* and *Gastrolobium* (Gardner and Bennetts 1956, p. 79-82), and the narcotic Woodbridge poison (*Isotoma hypocrateriformis*), a member of the lobelia family.

The rarity of fluoroacetic acid naturally is matched by its variable toxicity, variations depending on the species, its location, and the time of the year (Aplin 1967). These variations, in turn, induce a wide range of symptoms from

mild agitation, partial paralysis and blindness, to a violent, convulsive death (Carne, Gardner and Bennetts 1926). This feature most perplexed colonists because several conditions closely corresponded to already known stock diseases, particularly 'hoove', 'staggers', and 'blood striking', all of which were caused by an inability to digest over-rich herbage (see Wilson 1852, v. 2, p. 684-6). In addition, not all animals were equally affected (Table 2). Sheep and goats appeared most susceptible, followed by cattle. Horses had a high resistance (Landor 1847, p. 379-380) which was enhanced by their greater body weight. The relative immunity of local fauna was most perplexing. The botanist James Drummond consistently refused to accept that York Road poison (*G. calycinum*) had poisonous properties for he had observed pigeons feed on the seeds of the plant with immunity (P.G., 5 December 1840).

Problem solvers

While pastoralists were extremely anxious to identify the cause of mortality, and while they were deeply involved in the poison debate, they generally deferred to the superior knowledge and expertise of Joseph Harris, a surgeon with veterinary experience, and James Drummond. Similarly, the Agricultural Society took little direct action although it did provide a forum for discussion and debate. As a consequence, although their initial expertise was only marginally superior, Drummond and Harris emerged as the major authorities and the key problem solvers. That they held strongly divergent views greatly added to the confusion surrounding stock deaths.

Harris was convinced that stock died from 'blood striking' (P.G., 21 September 1833). His conclusions were derived from detailed patho-

logical evidence and his knowledge of English stock diseases but there were other considerations. Apart from being Drummond's rival for prestige and influence, Harris was concerned that the colony's already bad reputation would be further degraded by reports of high stock fatalities. This attitude, first expressed in September 1833 (P.G., 2 September 1833), was maintained throughout the 1830s with the result that unfavourable evidence was unconsciously suppressed.

Drummond, by contrast, early suspected plants because of the similarity of the vegetation associations in localities where deaths were reported (P.G., 19 October 1833; 5 December 1833). Drummond's approach involved the isolation, identification, description and testing of suspected species (P.G. 3 February 1838) but was slow to produce results for he began by isolating plants similar to those known to be toxic in England. So convinced was Drummond of the beneficial nature of all legumes that the pea-flowered shrubs of *Gastrolobium* and *Oxylobium* were only examined after all other alternatives had been examined and rejected (P.G., 24 August 1838; 5 December 1840).

Learning sequence

The discovery of poison plants was largely a result of trial-and-error procedures. Although existing knowledge and conceptual structures pointed to several lines of enquiry, the conflicting explanations offered by Drummond and Harris made the initial task one of definition. Extinction of established learning was a necessary concomitant. Until the problem had been defined, there could be no effective attempts at its solution. Learning was not characterized by steady increments. Rather, it progressed in spurts, these corresponding with 'crisis states' or periods of considerable stress. Consequently, the record of stock losses shown in Table 1, even though these are incomplete, identify the major periods. Greatest concern and most active problem solving were associated with those areas and time periods where mortalities posed serious threats. That there should be periods of relative quiescence indicates that settlers in established areas had learned to live with the threat of poison and avoid it, and suggests that improvised techniques, determined by trial-and-error, compensated for detailed knowledge and understanding.

Attempts at definition

Major concern was first expressed in the winter of 1833. Two factors induced this. Firstly, sheep which had previously been pastured on the alluvial flats along the Swan and Canning Rivers were now being grazed on the edge of the Darling Scarp (Moore 1884, p. 210). Here, they came in contact with Champion Bay poison (*G. oxylobioides*) and prickly poison (*G. spinosum*) and fatalities increased rapidly. This was sufficient cause for alarm as it is unlikely that total sheep numbers then exceeded 3 000, but these fatalities seriously interfered with the intentions of a number of settlers to increase

their flock size to the point where they could profitably begin wool production (P.G., 18 May 1833). Harris was requested to outline the symptoms of and treatment for 'blood striking' at the September meeting of the Agricultural Society (P.G., 21 September 1833, 28 September 1833).

Harris' statement failed to dispel fears for within a month Bland, the government stock-keeper, requested Drummond to examine the vegetation in an area where a number of separate fatalities had been recorded. Drummond found nothing of significance but suspected a mineral spring (P.G., 19 October 1833). Harris, who was also consulted, was adamant that the richness of the vegetation was responsible. In this he was supported by a number of settlers who were most perturbed that plants were already being thought to be poisonous (P.G. 26 October 1833).

Further debate was initiated in the following March when Brockman lost 21 sheep (P.G., 15 March 1834). Although he originally consulted Harris (P.G., 21 September 1833), he now seriously doubted that 'blood striking' was the cause because more sheep were affected than could be expected and dogs died after eating the meat of infected carcasses. Most importantly, deaths occurred when grass was dry and scarce whereas, in England, they occurred when pastures were abundant and green (P.G., 22 March 1834). His argument was given added force by an anonymous correspondent in the *Perth Gazette* who pointed out that the presumably rich herbage was "long, stringy, spiry grass, suddenly drawn up by the warm forcing sun, and thus brought forward unnaturally" (P.G., 2 August 1834).

Now under strong attack, Harris suggested that the Agricultural Society contact the sister society in New South Wales for its opinion of the disease and its recommended treatment (P.G. 10 May 1834). The reply, published in the *Perth Gazette* on 16 August, was of no value for the full circumstances of the disease were completely unknown outside Western Australia. In his accompanying commentary, Harris admitted some uncertainty about the cause but insisted that the antidotes he proposed, namely bleeding and saline purging, were quite adequate. Therefore there was no cause for alarm (P.G., 16 August 1834).

His optimism seemed justified as fatalities again subsided. They flared up again with increased severity early in 1835 following the general movement of sheep from the coast to the inland pastures of the Avon Valley surrounding York, 80 km to the east (P.G., 8 November 1834, 6 December 1834, 10 January 1835). This had been precipitated by the excessively dry winter of 1834 (P.G., 16 May 1835; Moore 1884, p. 243-248) but, until the road from Guildford to York was completed in October 1835 (P.G., 10 October 1835), stock had to traverse the lateritic-capped hills, broad, sandy slopes and swampy lowlands of the western plateau, over the greater part of which grew luxuriant stands of Champion Bay, York Road and prickly poisons. Stock losses were general (P.G. 4 Novem-

ber 1835). It may have been rough justice but the most severe losses were experienced by Harris. On one crossing, he lost 93 sheep, all 15 goats and 2 bullocks. Nevertheless, he maintained his original position (P.G., 16 May 1835).

Avoidance

The combined and disastrous impact of this new outbreak led to the formulation of effective techniques of avoidance. By June 1835, it was suggested that losses could be substantially reduced by "a careful attention to folding at night, and a fast driving by day, except on the burnt ground, where the herbage is generally young and sweet" (P.G., 20 June 1835). Techniques were further evolved by November when Trimmer advocated a strong application of stock salt prior to departure and muzzling while en-route (P.G. 14 November 1835). By the following June, Bland argued that most effective preventative was the hand feeding of stock for two days prior to departure and then throughout the journey (P.G., 4 June 1836). With the adoption of these practices, fatalities again subsided, the trend being hastened with the clearing of established camp sites along the completed York Road. Once in the Avon Valley, stock were relatively secure because the poisonous plants were restricted to the rugged and rocky hill tops and the sand plain well to the east (Aplin 1967).

Resolution

The excessively dry conditions beginning at the end of 1837 precipitated further outbreaks in widely separated localities as sheep and cattle spread in search of pasture. The considerable anxiety these generated increased the possibility that an effective solution would be found as suspicion was now strongly centred on the poisonous rather than the nutritive qualities of the vegetation. Even Harris was forced to conclude that blind grass may have been the cause of death of sheep he moved to his son's grant on the Williams River in November 1836 (P.G., 26 November 1836). Earlier, Bland had concluded that one of the *Gastrolobiums* was responsible for he had seen sheep feed on these before going blind or dying (P.G., 4 June 1836). Whitfield had come to a similar conclusion (Erickson 1969, p.54). However after careful examination, Drummond stated that none was harmful. Woodbridge poison was the cause of death (P.G., 3 February 1839). His evidence, presented in the *Perth Gazette* on 10 February 1839, seemed irrefutable. Woodbridge poison was a member of the lobelia family (*Lobeliaceae*) and this was widely known to contain noxious attributes. He had noticed that no wild animals ate it but an examination of the area in which sheep and goats recently died revealed that a considerable amount had been consumed. The results of a post-mortem examination seemed conclusive: the contents of the stomach smelt very like the plant and had the same acrid odour so common in English poisons.

Drummond's findings did not allay fears for losses continued at a disastrously high level. The autumn of 1839 was the driest yet experi-

enced and was succeeded by an abnormally dry winter (P.G., 7 July 1839, 5 October 1839). The drought seriously interfered with attempts to establish an overland stock route from King George Sound to the Avon Valley, and, on one trip, Eyre lost over 250 sheep and 54 bullocks (P.G., 28 March 1840). An acrimonious debate ensued between Drummond, Harris and their supporters, all of whom reverted to their original positions (P.G., 24 March 1839, 28 April 1839, 5 October 1839, 11 April 1840) and this notwithstanding the fact that Harris lost 63 sheep on his trip north from King George Sound (P.G., 27 June 1840).

Matters were brought to a head by the rash of deaths in the newly opened Kojonup District. Here, during September and October 1840, three flocks numbering more than 900 sheep were almost totally destroyed (P.G., 5 December 1840; *Symers Papers*, 5 September 1840). Drummond was consulted and administered a potion from Woodbridge poison. This gave negative results (*Inquirer*, 17 March 1841). Influenced by one of the shepherds, he reluctantly tried York Road poison but, having failed to prove his initial hypothesis, departed for Williams before the results were known. The sheep died the following afternoon (*Government Gazette*, 25 December 1840; P.G., 5 December 1840, 26 December 1840).

When he arrived at Williams, Drummond was contacted by Harris' son who was extremely perturbed by the continuing fatalities in his flock. Close examination of the area where the sheep had been feeding revealed the presence of York Road poison. The evidence now seemed overwhelming for, not only was this poison common throughout the Kojonup District, but Drummond had earlier observed it alongside the York Road where fatalities had been particularly heavy. Tender young branches were collected, made into a drench and given to a healthy goat. It died within 14 hours (P.G., 21 November 1840, 5 December 1840).

The matter was not yet resolved, however. Harris reluctantly accepted his son's and Drummond's evidence but refused to accept that more than one species was involved or that York Road poison was widely distributed, (P.G., 19 December 1840). His view was influenced by a desire to defend the pastoral properties of the Kojonup District. In this he had several supporters including the German botanist Preiss, recently arrived in the colony, who insisted that "leguminous plants are particularly suited for the food of animals and the human race". To prove his point, he drank a wineglass of diluted fluid extracted from the leaves of York Road poison (*Inquirer*, 17 March 1841). Suffering no ill-effects, he recommended the plant to stock holders as "the very best thing they could cultivate as artificial food for stock" (quoted in Erickson 1969, p.59).

To resolve all doubts and end the confusion, the Agricultural Society requested Drummond in May 1841 to demonstrate the toxic properties of the plants he had identified. All three test animals died within four hours. Three dogs also died after feeding on the entrails of the poisoned sheep. Harris was now fully convinced

and agreed that "the plant is a most powerful poison". He knew no antidote (*Inquirer*, 19 May 1841; P.G., 17 May 1841).

Extended learning

Further experiments on 13 August 1841 confirmed these findings and led to the search for an antidote (P.G., 14 August 1841). Within a week it was reported that washing soda may be beneficial (P.G., 21 August 1841). A considerable hiatus followed which suggests that identification of the cause substantially reduced settlers' concern (see P.G., 22 January 1842). A repetition of the May 1841 experiment twelve months later produced negative results and led Drummond to conclude that toxicity was greatest from the beginning of new growth until the onset of the summer drought. January through to May could be considered the quiescent period (*Inquirer*, 18 May 1842). The range of poison plants was now extended to include rock poison (*G. callistachys*) and box poison (*O. parviflorum*) (P.G., 14 May 1842). Heart-leaved poison (*G. bilobum*) growing in the south and particularly around King George Sound was already under suspicion (*Inquirer*, 23 December 1840; P.G., 5 December 1840).

With Drummond's positive identification, fatalities rapidly diminished and it became common practice for shepherds to carry branches

of known or suspected species to aid in their identification. Where belts of poison had to be traversed, stock were driven in haste and were frequently muzzled. Main roads were gradually cleared of poison to a distance of a chain (20 m) on each side (Erickson 1969, p. 60). When moving stock into unfamiliar areas, it became usual to send out scouting parties to identify and mark poison outcrops (P.G., 8 October 1842). On established properties, aborigines were temporarily employed in grubbing out poison plants in exchange for a ration of tobacco and flour.

The rate at which toxic species in areas settled by 1850 were identified, summarized in Table 3, is particularly revealing. The obvious conclusion to be made is that the commonest and most toxic species were among the first to be identified. River poison (*G. forrestii*), the major exception, has a restricted location on the rivers of the south coast. Of these, only the Kent and Hay Rivers were stocked before 1850 and then by small flocks grazed mainly on the upper reaches. Similar conclusions may be made for Stirling Range (*G. velutinum*), hook-point (*G. hamulosum*) and berry (*G. parvifolium*) poisons, all of which grow in rugged, hilly country or poorly grassed sandplains. The late discovery of the low toxicity poisons is almost self explanatory, but, in addition, crinkle leaf (*G. villosum*) and runner (*G. ovalifolium*) poisons grow along

Table 3

Toxic Species of *Oxylobium* and *Gastrolobium* present in areas occupied by 1850

Species	Toxic category	Maximum (a) toxic reading (ppm)	Date toxic effect determined	Date of first detailed description (pre 1864)
Box poison (<i>G. parviflorum</i>)	High level of toxicity (more than 1 000 ppm)	2 500	1842	1841
Heart-Leaf poison (<i>G. bilobum</i>)		2 650	1841	1829
Rock poison (<i>G. callistachys</i>)		1 000	1842	1844
Cluster poison (<i>G. bennettsianum</i>)		1 350	1841(b)	....
River poison (<i>G. Forrestii</i>)		1 200	1926	....
Champion Bay poison (<i>G. oxylobioides</i>)	Medium level of toxicity (more than 100 ppm)	1 050	1841(b)	1841
Sandplain poison (<i>G. microcarpum</i>)		600	1841(b)	1839
York Road poison (<i>G. calycinum</i>)		400	1841(b)	1841
Prickly poison (<i>G. spinosum</i>)		400	1901	1841
Berry poison (<i>G. parvifolium</i>)		300	1910	1841
Gilbernine poison (<i>G. rotundifolium</i>)		150	1841(b)	1843
Hook-Point poison (<i>G. hamulosum</i>)		100	1920	1843
Stirling Range poison (<i>G. velutinum</i>)		300	1921	1853
Woolly poison (<i>G. tomentosum</i>)		n.a.	1955	....
Crinkle-Leaf poison (<i>G. villosum</i>)		Low toxicity (less than 30 ppm)	n.a.	1900	1841
Runner poison (<i>G. ovalifolium</i>)	n.a.		1910	1841
Bullock poison (<i>G. trilobum</i>)	n.a.		1921	1841

(a) Parts per million of the toxic radical in terms of air dried plant material.

(b) No real distinction was made between Champion Bay, York Road, Sandplain, Cluster and Gilbernine poisons because of their basic similarity. The toxic effect of all was effectively demonstrated by Drummond's experiments with Champion Bay poison (*G. oxylobioides*) in May 1841.

Source: Bentham 1864, v.2, p. 14-26 and 96-107; Gardner and Bennetts 1956, p. 40-77; Aplin 1967-71; Erickson 1969, p. 61-122.

the ground. Both were suspected in the early 1840's (Landor 1847, p. 380), but, perhaps because of their prostrate growth form, these suspicions were rejected. The thorny, unpalatable hardness of the leaves of both prickly and bullock poison (*G. trilobum*) explain their late identification as poisonous plants.

The second and more important conclusion is that there was no general knowledge transfer from one harmful species to others within the genera. Otherwise, all presently known toxic plants would have been quickly classified for, with the exception of crinkle leaf and runner poisons, all toxic species are easily recognised by the similarity of their growth form, leaf arrangement, and the shape, colour and arrangement of the flowers. Certainly cluster poison, Champion Bay poison, sandplain poison and gilbermine poison were identified when encountered but their similarity with York Road poison is very close indeed, clear distinctions only being possible when the plants are in flower.

That transfer was minimal indicates that no general framework for identification had yet been determined. To this extent, learning was still at a trial-and-error stage. It is possible, however, that this is indicative of an unwillingness to extend the range of harmful plants, and reflects the attitudes earlier adopted by Harris and others.

Learning characteristics

Three features of the learning sequence above are of particular significance in understanding the colonization of unfamiliar environments, namely: the role of problem solvers in a pioneering community; the relationship between a problem's difficulty and the rate at which it is resolved; and the characteristics of problem solving in pioneering situations..

The role of problem solvers

Although Curti (1957, p. 417-440) has demonstrated that individuals rather than formalized institutions are the key problem solvers in pioneering communities, neither Drummond nor Harris initially knew more about the poison problem than other colonists. They developed their competence through community pressure. Three factors account for their eventual dominance; they had superior knowledge in appropriate areas; they were able to isolate possible causes and solutions, and, as fellow pastoralists, they were viewed as status equivalents. They had credibility because they also suffered severe stock losses and were able to transmit their conclusions through informal channels. The deference of pastoralists was not complete, however, for they clearly reserved the right to question conclusions when these differed from their own views. Drummond and Harris were used to isolate causes and solutions but pastoralists were the final arbiters. This process minimized their own efforts while maximizing Drummond's and Harris' expertise and, as such, is an important modification of Found's observation that 'man attempts to optimize some utility while minimizing his own effort' (Found 1971, p.129).

The time factor in problem solving

The learning sequence indicates that the tempo of effective learning is not continuous but does accelerate up to the point where a solution is determined. This is a basic characteristic of all problem solving for much initial learning centres on definition and this is often surrounded by considerable confusion. Following definition, problem solvers are able to formulate and test hypotheses and are in a position to reject unsatisfactory solutions or reinforce those which seem suitable. Although new hypotheses may be added, there is a progressive decrease of possible alternatives. With resolution, there is a rapid diversification leading to both the solution of attendant problems and the development of compatible operational procedures. It must be emphasised, however, that problems can be effectively avoided before solutions are defined. This must seriously complicate attempts to identify adaptive processes for what may often be considered problem solving is, in reality, avoidance. That both are in response to stress levels adds a further dimension.

Colonizer problem solving

Problem solving is far from simple. Gagné (1970, p.36-69, 214-236) sees it as the apex of an eight-layered hierarchy which ranges from signal learning (essentially Pavlovian conditioning) at the base through stimulus-response connections where the learner acquires a precise response to one or more discriminated stimuli to concept development (common response to a general class of stimuli) and rule or principle learning where causal links between stimuli are clearly established. Problem solving requires competence in most of these learning types.

While the Gagne model identifies the stages of most learning situations, not all levels are applicable to the poison problem. The key problem solvers already had well developed learning patterns including single and multiple discriminations, chaining and associations, and, in the case of Harris, clearly established rules regarding the relationship between vegetation and stock deaths. What was critical was that these lower orders of the learning hierarchy had been developed in another and quite dissimilar environment and were thus inadequate. Because of this inadequacy, they had to be transformed or, more correctly, extinguished and replaced until they were compatible with the new environment. This was a major inhibitor of the learning rate.

The process of transformation may best be discussed by reference to the Lewinian concept of 'life space' (Lewin 1946, p.239-40). Lewin views behaviour as a function of the life space which is the product of a person's interaction with his environment and is essentially the known physical and psychological environment of that person as derived by his whole pattern of behaviour in a specific environmental setting. As the life space is highly structured, behavioural directions are well defined. When relocation occurs, a new and unstructured life space is imposed because there has been a complete change in the environmental component. The

individual is initially confused because of the lack of definite orientations but he institutes a learning sequence whose purpose is the *differentiation* of unstructured areas in the new life space (Lewin, 1942).

A similar viewpoint is expressed by Gerritz (1969) in his discussion of the effects arising from gross shifts in the maintaining environment. When the maintaining environment (analogous to Lewin's life space) is changed, the individual 'will bring to a new environmental setting . . . behavioural systems that have been maintained (and possibly acquired on the basis of) the stimuli in the setting from which he had come. It follows . . . that initial behaviour in response to the stimuli in the new setting will be a function of the similarity of those stimuli to the stimuli that controlled behaviour in the earlier context' (Gerritz 1969, p.119). If the new context is markedly dissimilar, severe constraints will be imposed on behaviour until the behaviour that does take place provides 'the basis for a new adaptive learning in connection with the stimuli available in the new setting'.

Both Lewin and Gerritz hold the view that relocation induces confusion and inhibits responsiveness to environmental stimuli. Yet, it is quite apparent that initial responses in Western Australia were quite pronounced and were accompanied by a degree of confidence that later responses did not have. Reference to Harris' assertion that stock died from 'blood striking' effectively demonstrates this point. That this was erroneous is irrelevant as it was not seen to be so. This example suggests that, in pioneering situations at least, differentiation is preceded by another process which can be termed *generalization*.

Generalization may be viewed as the process of interpreting and reacting to newly encountered environmental stimuli from the standpoint of already learned behaviour. Its dominant characteristic is the blanket application of well defined rules formed from past experiences as these are expressed through preconceptions. As such, it is essentially a function of factors internal to the individual. As well as established knowledge and preconceptions, these factors will include motives, goals and expectations. There is little observable interaction with (cognitive responsiveness to) external stimuli. It is only when blanket generalizations prove unsatisfactory that the search for the appropriate relationships between stimuli (differentiation) begins.

As suggested by the Gerritz quote above, differentiation refers to the process where specific relationships between environmental stimuli, both internal and external to the individual, are determined. It must be seen as a function of actions centred on the resolution of specific problems or the definition of particular behavioural orientations, and clearly involves an internal (nature of the problem solver) external (nature of the problem) dichotomy. That is, differentiation requires interaction between the problem solver and those environmental stimuli

relating to the problem, the amount of interaction and hence differentiation increasing as learning progresses towards the point of ultimate resolution. This cannot be viewed as a purely perceptual or even more broadly cognitive process for affective components are also influential. As evidenced by Drummond's attitudes towards legumes, these are frequently inhibiting. Confidence levels may also inhibit (Found 1971, p.134). It is also apparent that when stress reaches a critical threshold all differentiation ceases and behaviour is characterized by avoidance.

From the preceding discussion, it is reasonable to postulate that all learning in colonizing situations progresses from the point where blanket generalizations are made to increasingly selective differentiation, both processes being embedded in a cognitive-emotional-motivational matrix. That no true separation of these components is possible is the problem facing all analyses of adaptive learning.

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11.—Foraminifera of Hardy Inlet, southwestern Australia

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Abstract

Total foraminiferal faunas were examined from 18 samples from Hardy Inlet and a nearby beach as part of a much broader study of the Blackwood River estuary under the auspices of the Department of Conservation and Environment.

Several regimes can be identified on the basis of foraminifera and these correspond closely with geomorphic and hydrological regimes.

Faunas in the upstream part of the tidal river regime are dominated by *Ammonia beccarii* although diversity and foraminiferal number are low.

The delta faunas and those from the tidal river near the delta are dominated by agglutinated forms, although again, diversity and foraminiferal number generally are low.

Lagoon faunas are dominated by species of *Ammobaculites* and diversity and foraminiferal number, while still low, are higher than in samples from farther upstream.

River mouth, beach and Deadwater faunas are abundant and very diverse with typical shallow marine faunas dominated by *Elphidium-Discorbis-Cibicides*.

Swan Lakes fauna is dominated by ostracods. The foraminiferal fauna is dominantly *Ammonia-Elphidium*.

Introduction

Foraminifera constitute a group of skeleton-producing protozoans with a long geological history. Several important summaries of the biology and classification of this important group have been prepared, the most significant being those by Cushman (1948), Glaessner (1945) and especially Loeblich and Tappan (1964). The distribution of recent foraminifera has been the subject of several reviews in recent years and important contributions have been made by Phleger (1960) and most recently by Murray (1973).

For many years, the study of the distribution of living foraminifera has been related to the needs of oil exploration companies for reconstruction of past environments. To this end, foraminifera of the Gulf of Mexico and nearby areas have been studied in great detail (see Walton 1964; Seiglie 1970 *et seq.*, Phleger 1951, 1955 etc.).

More recently there has been a tendency to study distributions of these organisms in man-made or man-affected situations (e.g. Bandy, Ingle and Resig 1964, *et seq.*) although the use of foraminifera for documenting changes due to pollution is in its infancy (Schafer 1970). The Hardy Inlet is a relatively small area and could prove an ideal test case for changes due to mining if mining is undertaken in the area.

In Australia, little has been published on distribution of foraminifera from the major river systems but Albani (1968, *et seq.*) and colleagues have made significant studies in New South Wales. Apthorpe (1974) has recently studied foraminifera from the Gippsland lakes of Victoria. McKenzie (1962) has made the only study in a comparable area from Western Australia. Work is proceeding on a similar study of Swan River foraminifera.

Methods

This report is based on an examination of 17 box core samples from within the Hardy Inlet and Swan Lakes and Deadwater. In addition, a single beach sand sample was taken immediately south of Deadwater to compare the oceanic and saline lake faunas. Rose Bengal staining of samples was attempted but the attempt can only be regarded as a failure. The results are based on total faunas only.

Most samples were taken on 29 June 1974 when the Hardy Inlet proper was approximately at a winter condition. Later sampling at Station 9 (See Figure 1) was done to detect any difference between winter and summer distribution patterns. Localities and locality parameters are shown on Figure 1 and on the distribution charts. Also shown on Figure 1 are the sample localities which form part of a broader Hardy Inlet study (See Imberger and Agnew, in press). It was hoped that these sample localities could be used for the study of foraminifera but not all foraminiferal study sample stations are coincident with the standard localities.

The results given here are by no means the final study that could be made of the Hardy Inlet foraminifera but give only a preliminary estimate of their distribution. Longer term studies at many more stations are needed.

Samples represent the surface 1 cm from the top of each box core sample which was bottled, washed over a 100 μ m sieve, and examined.

Physical conditions in Hardy Inlet

Physiographic units of the Hardy Inlet

Hodgkin has identified a series of physiographic units which are detailed by Imberger and Agnew (1974). They are as follows: tidal river, lagoon, channel, Deadwater and Swan Lakes, and mouth and sea bar. Throughout this report, these units will be used and are shown on Figure 3A.

The lagoon of Hodgkin can be divided conveniently into two regions for this work. The dominant one is the true delta of the Blackwood-

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Scott system which has a classic delta shape with well marked distributary channel pattern. One of these distributaries has been accentuated by dredging. The remainder of what was defined originally as lagoon will be referred to as lagoon proper.

To the units documented by Imberger and Agnew (1974) must be added oceanic beach,

which is here represented by a single sample (18).

Reliability of salinities, bathymetry etc.

Detailed measurements of salinity (Figure 2) for Hardy Inlet have been made so far at short intervals over only one year (Imberger and Agnew, in press) so it is not certain that the

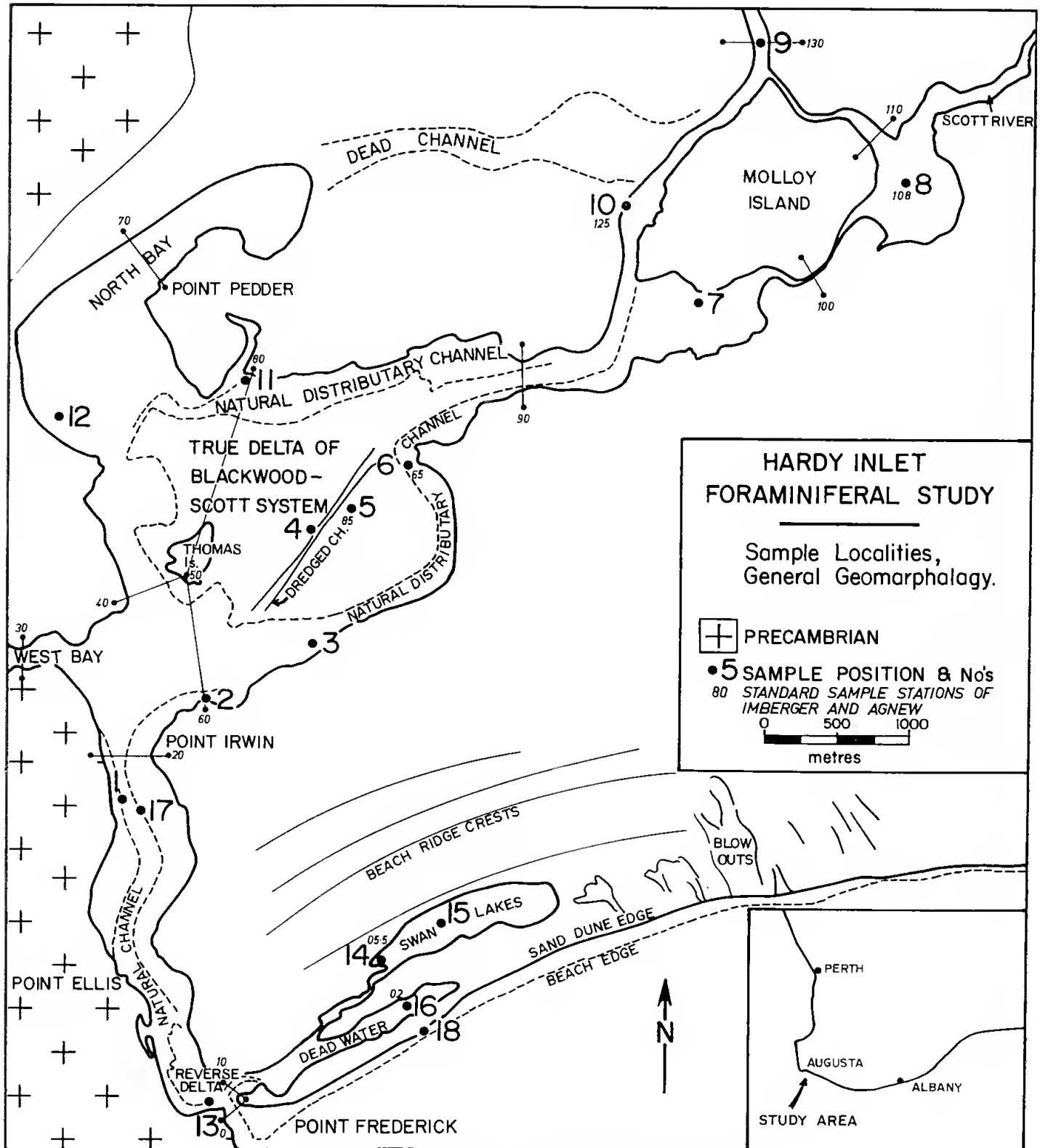
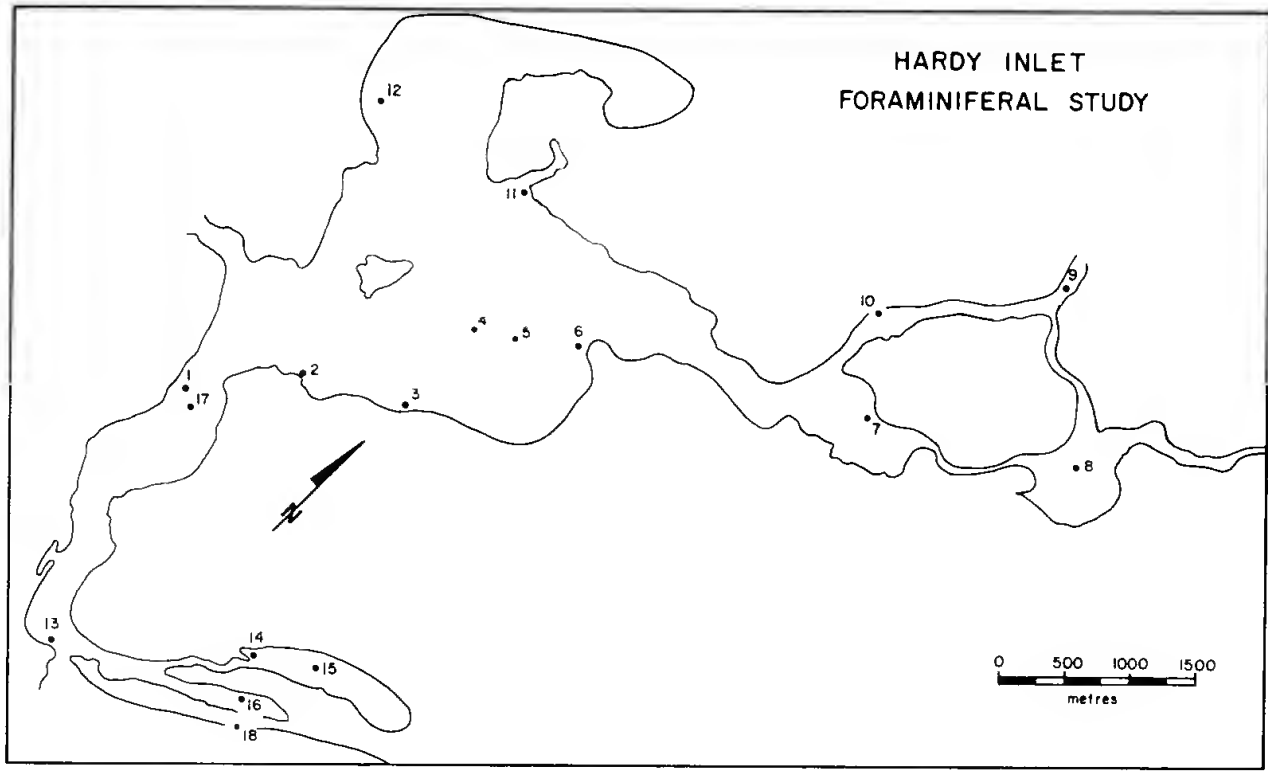
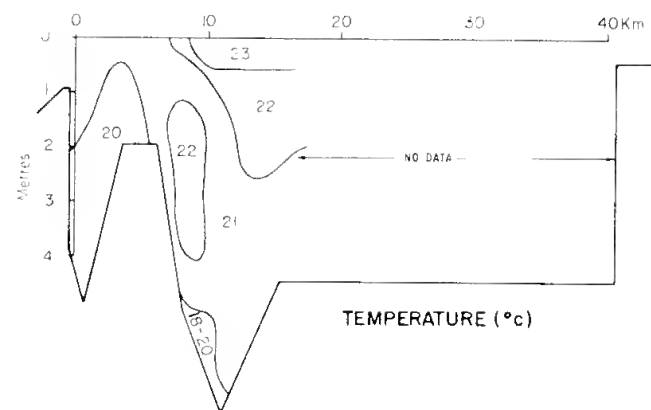
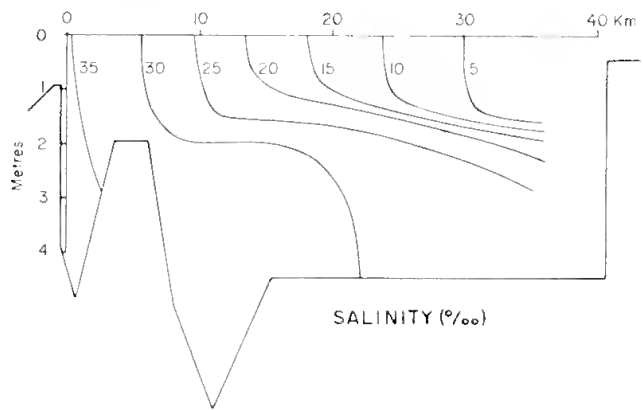


Figure 1.—Locality and geomorphology diagram.



SUMMER



WINTER

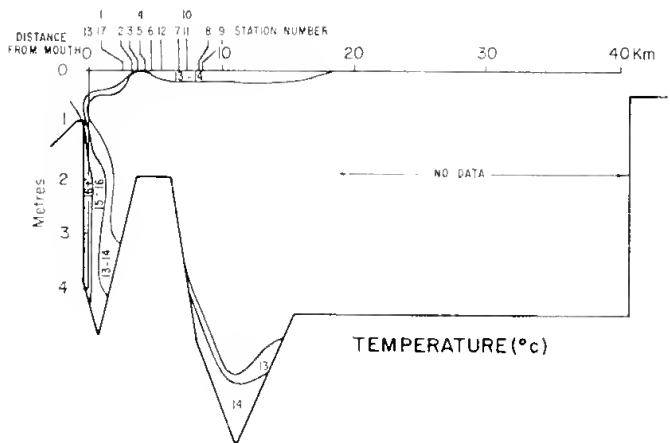
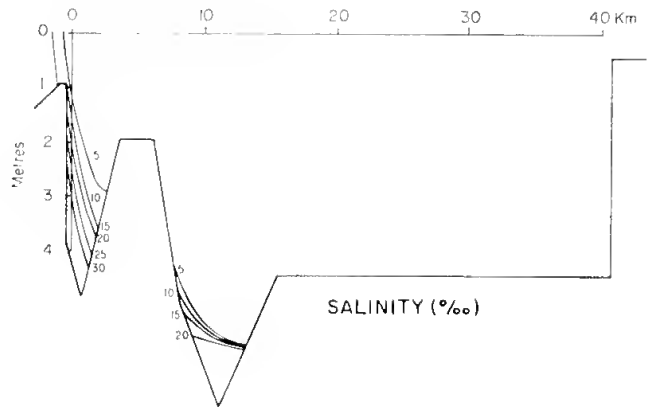


Figure 2.—Summer and winter salinity and temperature, Hardy Inlet.

figures given here are typical, although there is no reason to think that they are not. Virtually the entire system is at a salinity of less than 5 ‰ in typical winter pattern. The summer pattern is less uniform with surface salinity decreasing at approximately 1 ‰ per km upstream from the mouth.

It is noteworthy that the true delta of the Blackwood-Scott system acts as a shallow barrier between a deeper, more fluvial, channel upstream, and shallower lagoon proper and channel downstream. As a result of the barrier, a deeper level salt wedge may become stranded in the tidal channel upstream. This is discussed

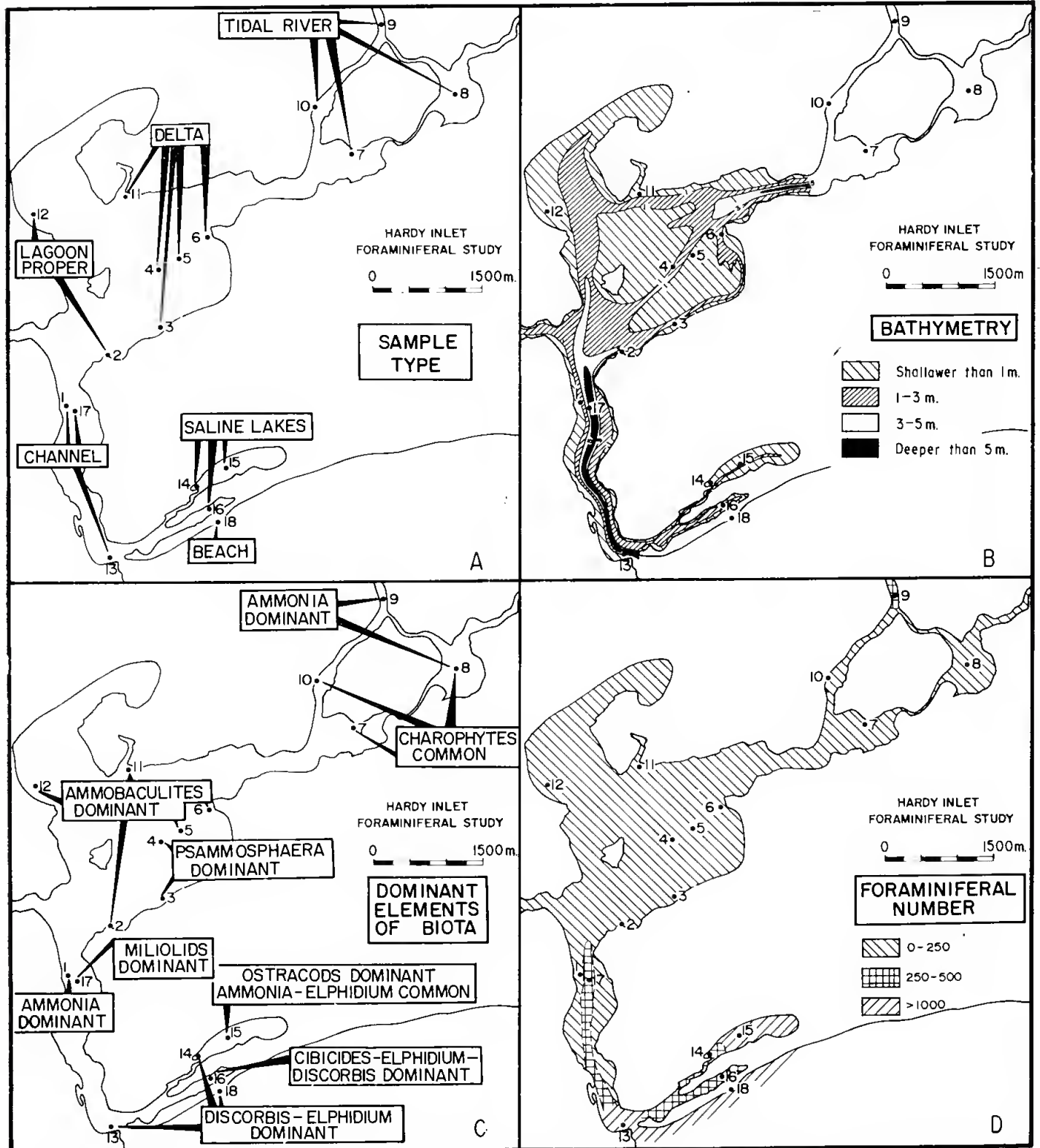


Figure 3.—Parameters of foraminiferal distribution; A. sample type; B. bathymetry; C. dominant elements of biota; D. foraminiferal number.

further by Imberger and Agnew (in press) and is shown in the salinity diagrams (Figure 2).

Final bathymetry maps are not available and Figure 3B is based on preliminary data taken by the Public Works Department.

Water movement is not yet well known but the information so far available is contained in Imberger and Agnew (in press). According to them, tidal variation has a maximum of about 1 m and is "normally not sufficient to break up any salt wedge system that may have formed".

In winter, water temperatures (Figure 2) in the river fall to about 12°C when the ocean outside the mouth is warmer, perhaps as low as 15°C. The contrast is between cooler, low salinity surface runoff and the warmer oceanic water. In summer the situation seems more complex. The ocean water, at 20°C, is cooler than the river water which is the converse of the winter condition.

Figure 2 purports to show the summer and winter salinity and temperature conditions. The bottom profile of the river is diagrammatic and is based on similar figures prepared by Imberger and Agnew (in press). 29 June 1974, the date of the first sampling, is taken as representing winter conditions although Imberger and Agnew (pers. comm.) suggest that in the full winter condition, no salt wedge is preserved north of the delta. 21 March 1974, is taken as typical of summer although there is the possibility that full summer maximum temperatures are a little above those shown on the figure.

Sample details

The distribution of all species identified is shown on Figure 4 which also shows several other features of the samples studied. They are: *Distance* from the inlet mouth which in a general way corresponds with decrease in salinity. *Setting* which reiterates the classification shown on Figure 3A. *Water depth* at times of measurement. *Number of specimens* actually separated during the study. *Foraminiferal number* which is simply the number of specimens of foraminifera which can be expected from each gram of dry sediment. These figures are shown diagrammatically on Figure 3D. *Fisher's Index* which is an index of the diversity of the foraminiferal fauna (See Murray 1973). This figure must be regarded as very tentative because of the small specimen numbers studied. The number in each square is the number of specimens of the species recovered from the sample. Figure 3A shows the samples grouped according to environment.

Tidal river samples

The Tidal river regime is represented by four sample stations, 9 and 10 in the Blackwood River and 7 and 8 in the Scott River.

Station 9 (Location 130 of Imberger and Agnew, in press). This is the farthest upstream sample examined and is the deepest sample taken.

Sediment: The sediment at this station consists of very fine grey mud, which when sieved is found to be composed almost completely of ovoid faecal pellets. The organisms responsible were not identified and the pellets are identical with those so abundant in the lagoon of the Swan River. Nowhere else in the Hardy Inlet are these so prominent.

Salinity: The winter salinity is less than 5‰ and in summer there is a weak halocline separating 20-25‰ above 2 m from 30‰ and over below. At the time of winter sampling (29 June, 1974), there was a very marked halocline at 5.5 m separating salinity of 2‰ above from 29‰ below.

Station 10 (Location 125 of Imberger and Agnew).

Sediment: Fine angular quartz sand with minor mud.

Salinity: Similar to station 9 except that summer salinities may be marginally higher.

Station 8 (Location 108 of Imberger and Agnew).

Sediment: Fine dark mud with angular sand.

Salinity: Winter salinities are less than 5‰. Summer values are about 30-35‰.

Station 7

Sediment: Fine angular quartz sand with dark, fine mud admixed. The calcareous foraminifer *Ammonia beccarli* shows some dissolution effects (see plates) which indicate a pH significantly below 7 for some time of the year at least.

Salinity: Values would not differ significantly from those at Station 8.

Lagoon samples

A.—Blackwood-Scott Delta

Station 6 (Location 65 of Imberger and Agnew).

Sediment: Poorly sorted angular fine quartz sand and considerable black mud.

Salinity: Winter—less than 5‰. Summer—30-35‰.

Station 5 (Location 85 of Imberger and Agnew).

Sediment: Fine quartz sand with some heavy mineral and minor mud.

Salinity: Winter—less than 5‰. Summer—30-35‰.

Station 4 Interdistributary sand.

Sediment: Muddy angular and rounded fine quartz sand.

Salinity: Winter—less than 5‰. Summer—30-35‰.

Station 3 Mouth of interdistributary channel.

Sediment: Muddy angular quartz sand with minor heavy mineral.

Salinity: Winter—less than 5‰. Summer—30-35‰.

Station 11 (Near Location 80 of Imberger and Agnew)—broad distributary channel.

Sediment: Muddy, fine to medium angular sand with common heavy mineral.

Salinity: Winter—less than 5‰. Summer—30-35‰.

B.—Lagoon proper

Station 12

Sediment: Poorly sorted angular quartz sand.

Salinity: Winter—less than 5‰. Summer—30-35‰.

Station 2 (Location 60 of Imberger and Agnew).

Sediment: Clean angular quartz sand.

Salinity: Winter—less than 5‰. Summer—30-35‰.

Channel samples

Station 1 Sand flat on edge of main channel.

Sediment: Admixture of dark grey mud coarse angular quartz sand and minor shell material.

Salinity: Winter—less than 5‰. Summer—35‰.

Station 17 Main channel.

Sediment: Black mud with common faecal pellets, foraminifera, ostracods and sponge spicules.

Salinity: Winter—Surface—less than 5‰. Below halocline—5-30‰.

Station 13 Edge of mobile sand bar (part of reverse delta).

Sediment: Well sorted calcareous sand.

Salinity: Winter—surface—less than 5‰, but sometimes varying with the tides. Summer—35‰ +

Saline lakes

The saline lakes—Swan Lakes and the Dead-water—are saline for a much longer part of the year than the rest of the Hardy Inlet system. As they are so shallow and as water access is only via very narrow channels, they have some features unique in the system. Although it is not properly documented, it is probable that they are slightly warmer than the waters in the rest of the study area. A figure of 4°C warmer than the water in Hardy Inlet itself has been mentioned (R. Lenanton, pers. comm.). Because of these factors a slightly hypersaline condition exists in part of the summer.

STATION NUMBER	9	10	8	7	6	5	4	3	11	12	2	1	17	13	15	14	16	18
Distance(km) from Inlet mouth	8.5	7	8	6.5	4.5	4	4	3.5	7	5	3	2.5	2.5	0	2	1.5	1.5	1.5
Setting	Tidal River			Delta					Lagoon		Channel		Lakes		Beach			
Water Depth (m)	7.5	1	1.2	1.5	1.5	1.5	0.7	1.2	1.2	1.2	0	1	5.5	1.2	0.5	0.3	1.5	0
Number of specimens	94	36	11	38	42	11	2	48	27	55	86	48	92	146	55	56	125	182
Foraminiferal Number	300	18	3	13	27	7	1	4	13	25	14	8	500	1200	1000	500	270	2500
FISHER'S INDEX	<1	-	-	-	-	-	-	c.2	-	c.2	<2	c.3	12	6	<5	c.10	11	10
SPECIES	<1	-	-	-	-	-	-	c.2	-	c.2	<2	c.3	12	6	<5	c.10	11	10
<i>Protoschista findens</i>	1	7		4				1		1	6							
<i>Ammonia beccarii</i>	89	6	10	4	1	3	1	10	6	5	3	38			15			
<i>A. tepida</i>	4												4		4			
<i>Ammobaculites agglutinans</i>		7	1	18	8			3	18	18	22	4						
<i>A. sp.1</i>		16			33	6		10	3	29	50							
<i>Bathysiphon sp.1</i>				1														
<i>Psammosphaera sp.</i>				11		2	1	22				3						
<i>Miliammina fusca</i>								1				2	1					
<i>Trochammina inflata</i>								1		1								
? <i>Penardogromia sp</i>											1							
? <i>Hyperammina sp</i>												1						
<i>Quinqueloculina simplex</i>												1						
<i>Elphidium crispum</i>												3	3	37	1	9	16	29
<i>Triloculina inflata</i>													21			1	9	
<i>T. laevigata</i>													12			1	3	
<i>Quinqueloculina striata</i>													2					
<i>Q. lamarckiana</i>													3	4		2	13	7
<i>Q. subpolygona</i>													2	2				
<i>Spiroloculina angulata</i>													1					
<i>S. rotunda</i>													1					
<i>Miliolinella subrotunda</i>													5					
? <i>Hauerina bradyi</i>													1					
<i>Fissurina fasc. carinata</i>													1					
<i>Oolina striatopunctata</i>													1					
<i>Bolivina sp.1</i>													2	1				
<i>Buliminoides williamsonianus</i>													1					
<i>Reussella simplex</i>													1	2		3	3	7
<i>Rosalina vilardeboana</i>													3					
<i>Neoconorbina terquemi</i>													1					
<i>Pileolina australensis</i>													4			1	4	
<i>P. patelliformis</i>													2			1	9	1
<i>Mississippina concentrica</i>													1					
<i>Spirillina inequalis</i>													1					
<i>Elphidium advenum</i>													2	2		1		
<i>E. poeyanum</i>													8		22		9	
<i>Cibicides refulgens</i>													1	19	2	6	17	22
<i>G. pseudoungerianus</i>													2					

Figure 4.—Foraminiferal distribution chart, Part 1.

SPECIES	STATION																	
	9	10	8	7	6	5	4	3	11	12	2	1	17	13	15	14	16	18
Planorb. mediterraneensis													1					
Globigerina bulloides													1					
Turborotalia sp.													2					
Gaudryina convexa														3				1
Textularia pseudogramen														2		1	2	4
Marginopora vertebralis														4				1
Triloculina striatotrigonula														3				1
Discorbis australis														4		1	1	4
D. dimidiatus														40	1	16	15	67
Gen. et sp indet 2														1				
Elphidium jenseni														1		2	3	2
Valvulineria rugosa														1				
Acervulina inhaerens														11		4		7
Gypsina globulus														7				5
? Cassidulina sp														1				
Globigerina sp														1				
Rectobolivina raphanus															1			
Elphidium incertum															3			
E. simplex															1			1
Gypsina vesicularis															1			
Cymbaloporetta bradyi															1			
Q. seminulum																5		
Spiroloculina venusta																1	1	
Hyperammia ? cylindrica																1		
Oolina sp																	1	
Bolivinella australis																	2	
Buliminella gracilis																	1	
Bolivina striatula																	1	
Heronallenia lingulata																	1	
Planulinoides biconcavus																	3	2
Pileolina opercularis																	4	3
Spirillina decorata																	2	1
Calcarina calcar																	2	
Rotalia perlucida																	1	
Dyocibicides biserialis																	1	
Pyrgo lucernula																		1
Spiroloculina communis																		2
Triloculina trigonula																		1
Pavonina sp																		1
Rotalia trochidiformis																		1
Elphidium macellum																		1
Cellanthus craticulatus																		4
? Crespinella sp																		1
Amphistegina lessonii																		1

Figure 4.—Foraminiferal distribution chart, Part. 2.

A.—Swan Lakes

Station 15

Sediment: Pink, gelatinous, organic-calcium carbonate mud with superabundant ostracods. The sediment is almost an ostracod coquina. Study of this sample is hampered by difficulty in disaggregation due to high gelatinous organic content. Because of these difficulties the recorded relative abundance of various species may contain some error.

Salinity: Winter—low, less than 5‰. Summer—fully marine to a little hypersaline.

Station 14 (Location 05.5 of Imberger and Agnew)—channel leading from Swan Lakes to the Deadwater. Sea grass covers channel floor.

Sediment: Carbonate sand.

Salinity: Winter—low, less than 5‰. Summer—fully marine to a little hypersaline.

B.—Deadwater

Station 16 (Location 02 of Imberger and Agnew)—1.5-2 m—weed-covered lake floor.

Sediment: Poorly sorted carbonate sand showing much abrasion on the grains.

Salinity: Winter—(a) Low, less than 5‰ above 2 m. (b) Below 2 m, 10‰ or more. Summer—fully marine.

Station 18

Sediment: Approximately 90% carbonate sand. Well sorted.

Summer vs winter faunas

The sediment at Station 9 was resampled on 23 February 1975, to see if there is any detectable difference between summer and winter faunas. If any difference is to be expected in the Hardy Inlet, Stations 7 to 10 would be expected to show it as they are in positions where summer-winter contrasts are greatest because the freshwater phase lasts longer than farther downstream.

Minor differences may be present. *Ammonia beccarii* is dominant in both summer and winter but *A. tepida* is apparently absent from summer faunas. Winter faunas may contain a higher foraminiferal number but more detailed, more closely spaced samples would be necessary to check this.

Effects of substrate on foraminifera

The controlling feature on foraminiferal distribution in an estuarine system is mainly salinity but temperature and water depth also are important. Substrate influences generally are minor, but one species in Hardy Inlet is noteworthy for the relationship with substrate.

Psammosphaera sp. is common to dominant in some river and delta samples. Although it is not obvious in the figures (figures 6, 7) this species selectively isolates ilmenite for the construction of its agglutinated skeleton. The skeleton is not wholly of ilmenite but is very much enriched in it over the content in the sediment.

Summary

The main features are summarised on Figure 3 but are discussed in more detail below.

Tidal river biota: The faunas contain low numbers of foraminifera and diversity also is low. It is notable that the more upstream samples (8, 10) contain the more dominant *Ammonia beccarii* faunas and the more downstream ones the more dominant agglutinated foraminifera, especially *Ammobaculites*. These faunas are the only ones in the entire study with abundant or common *A. beccarii*, with the exception of that from Station 1.

The other noteworthy feature in this regime is the flora which contains considerable numbers of charophytes (oogonia of characean algae) in three of the four samples. This is the only part of the area to contain noteworthy numbers of these organisms. Congdon has identified *Lamprothamnion* from this area during the course of the study.

Delta biota: As with the tidal river samples, foraminiferal numbers and diversities are low. The minor exception is at Station 3 where both are higher due to influence of the adjacent lagoon proper and of possible tidal marshes (dominantly the rush *Juncus maritimus*), both common habitats of *Miliammina fusca* and *Trochammina inflata*.

Faunas are dominantly of agglutinated foraminifera similar to the lower reaches of the tidal river but significantly different from those in upstream tidal river samples.

Charophytes are absent and ostracods are rare. Diversity of the biota in the delta is lower than in the tidal river. This probably reflects the area being the buffer between fluvial and marine regimes. Few species are versatile enough to survive these rapidly changing conditions.

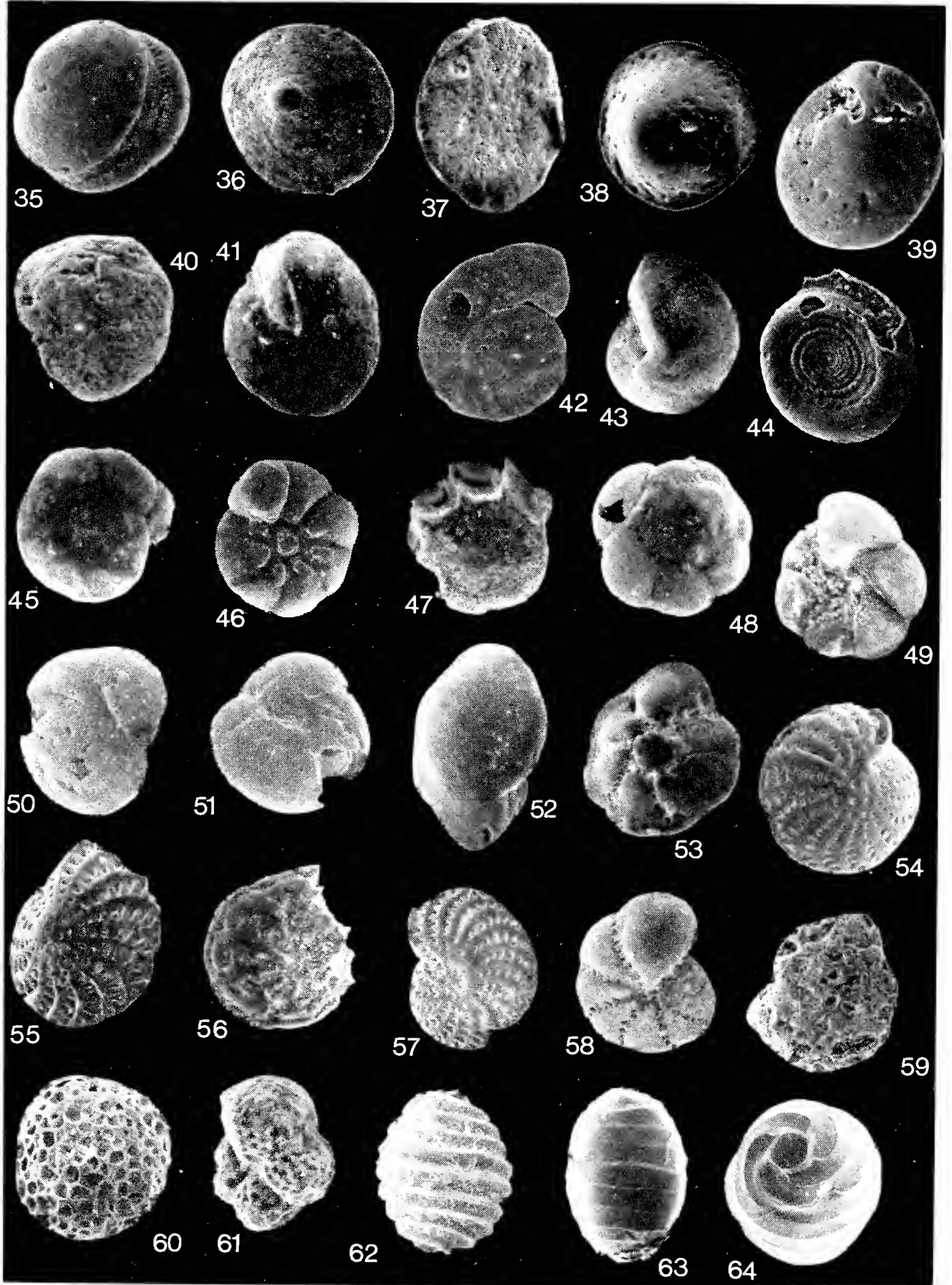
Lagoon proper: The faunas of the two samples are virtually identical and show a marked increase in both diversity and foraminiferal number over the delta or tidal river faunas.

While extremes of summer and winter salinities are much the same as for most other samples, the vicinity of these stations has 8-9 months per year in which the salinity is higher than extreme winter values, a value between the longer freshwater phase upstream and shorter freshwater phase downstream (1½-2 months).

Channel biota: The foraminifera at Station 1 are akin to those in the lagoon with the exception that miliolids are present, suggesting that salinity reaches 32‰ or more for a considerable part of the year on the sand flats flanking the channel.

Figures 5 to 34.—5.—? *Penardogromia* sp. Station 12, x 35. 6, 7.—*Psammosphaera* sp. 6; Station 3, x 60; 7. Station 5, x 45. 8.—*Protoschista findens* (Parker), Station 2, x 3. 9.—*Miliammina fusca* (Brady), Station 2, x 55. 10.—*Ammobaculites agglutinans* (d'Orbigny), Station 2, x 6. 11.—*A.* sp. 1, Station 2, x 45. 12.—*Trochammina inflata* (Montagu), Station 3, x 95. 13.—*Textularia pseudogramen* Chapman and Parr, Station 13, x 45. 14.—*Gaudryina convexa* (Karrer), Station 13, x 55. 15.—*Triloculina inflata* d'Orbigny, Station 17, x 30. 16.—*T. laevigata* d'Orbigny, Station 17, x 80. 17.—*T. striatotrigonula* Parker and Jones, Station 13, x 50. 18.—*Quinqueloculina lamarekiana* d'Orbigny, Station 17, x 70. 19.—*Q. seminulum* (Linné), Station 14, x 75. 20.—*Q. striata* d'Orbigny, Station 17, x 90. 21.—*Q. subpolygona* Parr var., Station 17, x 80. 22.—*Miliolinella subrotunda* (Montagu), Station 17, x 90. 23.—*Spiroloculina communis* Cushman and Todd, Station 18, x 45. 24.—*S. venusta* Cushman and Todd, Station 14, x 60. 25.—*Marginopora vertebralis* Blainville, Station 13, x 60. 26.—*Bolivina australis* Cushman, Station 16, x 65. 27.—*Bolivina* sp. 1, Station 13, x 65. 28.—*Reussella simplex* (Cushman), Station 13, x 45. 29, 30.—*Discorbis australis* Parr, Station 13, x 60; 29. dorsal; 30. ventral. 31, 32.—*D. dimidiatus* (Jones and Parker), Station 14, x 50.; 31. dorsal; 32. ventral. 33.—*Rosalina vilardeboana* d'Orbigny, Station 17, x 90. dorsal. 34.—*Planulinoides biconcavus* (Jones and Parker), Station 16, x 85.





The other two stations have typical marine faunas, that from station 17 probably approximately *in situ*, that from station 13 being virtually completely "*ex situ*". Both faunas contain a few planktonic specimens. The simple arenaceous forms so typical of the upstream faunas are absent, miliolids are common to dominant and euryhaline species are virtually absent. There is no evidence of anything other than normal marine conditions in these samples.

Saline lakes biota: Samples 14 and 16 have faunas with high diversity and low dominance by a single species. This suggests a stable salinity/temperature regime, in contrast to Station 15 in Swan Lakes where two species are dominant. This latter seems a more specialised fauna reflecting a less stable salinity/temperature regime, probably because of a longer period per year of reduced salinity.

Ocean beach fauna: Three very similar foraminiferal faunas are those from Stations 13 (channel), 16 (Deadwater) and 18 (oceanic beach). Those from Stations 13 and 18 could be expected to be very similar as both are marine beach faunas in effect, with virtually none of the contained fauna *in situ*. The fact that the fauna at Station 16 is so similar would suggest that Locality 16 has marine conditions operating all year.

List of species identified

(Figure numbers in brackets after the species names refer to the accompanying illustrations).
Superfamily LAGYNACEA.

?*Penardogromia* sp. (fig. 5).

Superfamily AMMODISCACEA.

Bathysiphon sp. 1.

Hyperammia ?*cylindrica* Parr, 1950. Rept. B.A.N.Z. Antarctic Research Expedn, 1929-31, Ser B, 5 (6): 254, pl. 3, fig. 5.

?*Hyperammia* sp.

Psammospiraera sp. (figs. 6, 7)—Like *P. fusca* but isolated from marine environment. *P. fusca* is deep water marine.

Superfamily LITUOLACEA.

Protoschista findens (Parker) (fig. 8)=*Lituola findens* Parker, 1870. *Canad. Nat.* 5: 176 text figure 1.

Miliammia fusca (Brady) (fig. 9)=*Quinqueloculina fusca* Brady, 1870. *Ann. Mag. Nat. Hist.* ser. 4, 6: 286, pl. 11 figs. 2, 3.

Ammobaculites agglutinans (d'Orbigny) (fig. 10) =*Spirolina agglutinans* d'Orbigny, 1846. "Foraminifères Fossils du Bassin Tertiaire de Vienne," 137, pl. 7, figs. 10-12.

Ammobaculites sp. 1 (fig. 11).

Textularia pseudogramen Chapman and Parr, 1937 (fig. 13). *Australas. Antarctic Expedn* 1911-14, *Sci. Rept.* Ser. C, 153.

Trochammia inflata (Montagu) (fig. 12)=*Nautilus inflata* Montagu, 1808. "Testacea Britannica . . .", Suppl. S. Woolmer, Exeter, 81, pl. 18, fig. 3.

Gaudryina convexa (Karrer) (fig. 14)=*Textularia convexa* Karrer, 1869. "Novara" *Expedn. Geol. Theil.* 1 (2): 78, pl. 16, figs. 8 a-c.

Superfamily MILIOLACEA.

Spiroloculina angulata Cushman, 1917. *Bull. U.S. natn. Mus.* 71: 36, pl. 7, fig. 5.

Spiroloculina communis Cushman and Todd, 1944 (fig. 23). *Spec. Publ. Cushman Lab. foramin. Res.* 11: 63 (figures, Brady, 1884. "Challenger" *Expedn. Scient. Results, Zool.* 9: pl. 9, figs. 5, 6).

Spiroloculina rotunda d'Orbigny, 1826. *Annls. Sci. nat. ser. 1*, 7: 299.

Spiroloculina venusta Cushman and Todd, 1944 (fig. 24). *Bull. U.S. natn. Mus.* 161: 39, pl. 9, figs. 11, 12.

Quinqueloculina lamarckiana d'Orbigny, 1839 (fig. 18). "Histoire physique et naturelle de l'Ile de Cuba". 189 (figures 8: pl. 11, figs. 14, 15).

Quinqueloculina seminulum (Linné) (fig. 19)=*Serpula seminulum* Linné. 1758. "Systema naturae" (10th edn) 1: 786.

Quinqueloculina simplex Terquem, 1882. *Mem. Soc. géol. France*, ser. 3, 2 (3): 172, pl. 18, figs. 5-13.

Quinqueloculina striata d'Orbigny, 1843 (fig. 20)=*Q. striata* d'Orbigny, 1826. *Annls. Sci. Nat. ser. 1*, 7: 301.

Quinqueloculina subpolygona Parr, 1945 (fig. 21). *Proc. R. Soc. Vict.* 56 (2): 196, pl. 12, figs. 2 a-c.

Triloculina inflata d'Orbigny, 1826 (fig. 15). *Annls. Sci. nat. ser. 1*, 7: 300.

Triloculina laevigata d'Orbigny, 1378 (fig. 16). *Annls. Sci. nat. ser. 1*, 7: 134.

Triloculina striatotrigonula Parker and Jones, 1865 (fig. 17). *Phil. Trans. R. Soc.* 155: 438.

Miliolinella subrotunda (Montagu) (fig. 22)=*Vermiculum subrotundum* Montagu, 1803. "Testacea Britannica . . .", 521.

Hauerina bradyi Cushman, 1917. *Bull. U.S. nat. Mus.* 71: 62, pl. 23, fig. 2.

Marginopora vertebralis Blainville, 1830 (fig. 25). "Dictionnaire des Sciences Naturelles". Levrault, Paris. v. 60, 377, (figures Blainville, 1834, "Manuel d'Actinologie", pl. 69, fig. 6).

Superfamily NODOSARIACEA

Bolvinella australis Cushman, 1929 (fig. 26). *Contr. Cushman Lab. foramin. Res.* 5 (2): 32, pl. 5, figs. 6, 7.

Oolina melo d'Orbigny, 1839. "Voyage dans l'Amerique Meridionale; Foraminifères". Levrault, Strasbourg. 5 (5) 20, pl. 5, fig. 9.

Fissurina fasciata carinata (Sidebottom), 1906. *Mem. Proi. Lit. Phil. Soc. Manchester*, 7, pl. 1, fig. 17.

Superfamily BULIMINACEA

Buliminoides williamsonianus (Brady)=*Bulimina williamsoniana* Brady, 1881. *Quart. Jour. microsc. Soc.* 21: 56.

Buliminella gracilis Collins, 1953. *Mem. Nat. Mus. Melbourne*, 18: 102, pl. 1, figs. 8 a, b.

Bolivina striatula Cushman, 1922. *Publ. Carnegie Instn. Washington*, 311, 27, pl. 3, fig. 10.

Bolivina sp. 1 (fig. 27).

Rectobolovina raphanus (Parker and Jones)=*Uvigerina* (Sagrina) *raphanus* Parker and Jones, 1865. *Phil. Trans. R. Soc.* 155: 364, pl. 18, figs. 16, 17.

Reussella simplex (Cushman), 1929 (fig. 28)=*Trimosina simplex* Cushman, 1929. *Jour. Washington Acad. Sci.* 19: 158.

Superfamily DISCORBACEA

Discorbis australis Parr, 1932 (figs. 29, 30). *Proc. R. Soc. Vict.*, 44 (2): 227, pl. 22, fig. 31.

Discorbis dimidiatus (Jones and Parker) (figs. 31, 32)=*Discorbina dimidiata* Jones and Parker, 1862, in Carpenter "Introduction to the study of the foraminifera", *Ray Soc. Publns. London*, 201, text fig. 32B.

Planulinoides biconcavus (Jones and Parker) (fig. 34)=*Discorbina biconcava* Jones and Parker, 1862. *Ray Soc. Publns* (1862): 201, tab. 32g.

Figures 35 to 64.—35.—*Pileolina australensis* (Heron-Allen and Earland), Station 16, x 100. Oblique view of plas-togamic pair. 36, 37.—*P. opercularis* (d'Orbigny), Station 16, x 100; 36. dorsal; 37. ventral. 38, 39.—*P. patelliformis* (Brady), Station 16, x 100; 38. dorsal; 39. ventral. 40, 41.—*Cibicides pseudoungerianus* (Cushman), Station 17, x 100; 40. dorsal; 41. ventral. 42, 43.—*C. refulgens* Montfort, Station 14, x 70; 42. dorsal; 43. ventral. 44.—*Spirillina decorata* Brady, Station 16, x 125. 45, 46.—*Ammonia beccarii* (Linné), Station 1, x 95; 45. dorsal; 46. ventral. 47.—*A. beccarii*, Station 7, x 70. Note effects of dissolution. 48, 49.—*A. tepida* (Cushman), Station 17, x 125; 48. dorsal; 49. ventral. 50, 51.—*Rotalia perlucida* Heron-Allen and Earland, Station 13, x 60; 50. dorsal; 51. ventral. 52, 53.—*Calcarina calcar* d'Orbigny, Station 16, x 120; 52. dorsal; 53. ventral. 54.—*Elphidium advenum* (Cushman), Station 13, x 50. 55.—*E. crispum* (Linné), Station 13, x c.70. 56.—*E. incertum* (Williamson), Station 15, x c.100. 57.—*E. jensenii* (Cushman), Station 13, x 50. 58.—*E. poeyanum* (d'Orbigny), Station 17, x 65. 59.—*Acervulina inhaerens* Schultze, Station 13, x 55. 60.—*Gypsina globulus* (Reuss), Station 13, x 65. 61.—*Globorotalia* sp., Station 17, x 125. 62-64.—Charophytes, Station 8; 62, x 50; 63, 64, different form, x 60.

- Rosalina (Neoconorbina) terquemi* (Rzehak)=
Discorbina terquemi Rzehak, 1888. *Verh. K.K. geol. Reichsanst. Wien* (1888): 228.
- Rosalina vilardeboana* d'Orbigny, 1839 (fig. 33). "Voyage dans l'Amerique Meridionale; Foraminiferes", Levrault, Strasbourg, 5 (5), 44, pl. 6, figs. 13-15.
- Heronallenia lingulata* (Burrows and Holland)=
Discorbina lingulata Burrows and Holland, 1895. *Monogr. Palaeontogr. Soc.* (1895), pl. 7, figs. 33 a-c.
- Pileolina australensis* (Heron-Allen and Earland) (fig. 35)—*Discorbina pileolus* (d'Orbigny) (See Brady, 1884, "Challenger" Expedn. *Scient. Results*, Zool. 9: 649, pl. 89, figs. 2-4).
- Pileolina opercularis* (d'Orbigny) (figs. 36, 37)=
Discorbina opercularis d'Orbigny (see Brady, 1884, "Challenger" Expedn. *Scient. Results*, Zool. 9: 650, pl. 89, figs. 8, 9).
- Pileolina patelliformis* (Brady), 1884 (figs. 38, 39)=
Discorbina patelliformis Brady, 1884. "Challenger" Expedn. *Sci. Results*, Zool., 9: 647, pl. 89, figs. 1 a-c.
- Pileolina tabernacularis* (Brady), 1881.—*Discorbina tabernacularis* Brady 1881. *Quart. Jour. microsc. Soc. n.s.* 21: 65 (Figures Brady, 1884—"Challenger" Expedn. *Scient. Results*, Zool. 9: pl. 89, figs. 5-7).
- Valvulineria rugosa* (d'Orbigny), 1839=
Rosalina rugosa d'Orbigny, 1839. "Voyage dans l'Amerique meridionale; Foraminiferes", Levrault, Strasbourg, 5 (5): 42, pl. 2, figs. 12-14.
- Mississippiina concentrica* (Parker and Jones)=
Pulvinulina concentrica Parker and Jones, 1864. *Trans. Linn. Soc.* 24: 470, pl. 48, fig. 14.
- Amphistegina lessonii* d'Orbigny, 1826. *Annls. Sci. Nat.*, ser. 1, 7: 304, pl. 17, figs. 1-4.
- Cibicides pseudoungerianus* (Cushman), 1922 (figs. 40, 41)=
Truncatulina pseudoungeriana Cushman, 1922. *Prof. Pap. U.S. geol. Surv.* 129E, 97, pl. 20, fig. 9.
- Cibicides refulgens* Montfort, 1808 (figs. 42, 43). *Conch. System.* 1: 122.
- Dyocibicides biserialis* Cushman and Valentine, 1930. *Contr. Dept. Geol. Stanford Univ.* 1 (1): 31, pl. 10, figs. 1, 2.
- Planorbulina mediterraneensis* d'Orbigny, 1826. *Annls. Sci. nat.* ser. 1, 7: 280, pl. 14, figs. 4-6.
- Acervulina inhaerens* Schultze, 1854 (fig. 59). Über der Organismus der Polythalamien (Foraminiferen) nebst Bemerkungen über die Rhizopoden im allgemeinen". Leipzig: Engelmann, 68, pl. 6, fig. 12.
- Superfamily SPIRILLINACEA
- Spirillina decorata* Brady, 1884 (fig. 44). "Challenger" Expedn. *Scient. Results*, Zool. 9: 633, pl. 85, figs. 22-25.
- Spirillina inequalis* Brady, 1879. *Quart. J. microsc. Soc.* 19: 278, pl. 8, fig. 25.
- Superfamily ROTALIACEA
- Ammonia beccarii* (Linné) (figs. 45, 46, 47)=
Nautilus beccarii, 1767. "Systema naturae" 12th edn., 1162.
- Ammonia tepida* (Cushman) (figs. 48, 49)=
Rotalia beccarii var. *tepida* Cushman, 1926. *Carnegie Inst. Washington Publ.* 344: 79, pl. 1.
- Rotalia perlucida* Heron-Allen and Earland, 1913 (figs. 50, 51). *Proc. R. Irish Acad.* 31 (64): 139, pl. 13, figs. 7-9.
- Calcarina calcar* d'Orbigny, 1826 (figs. 52, 53). *Annls. Sci. nat.* ser. 1, 7: 276, modeles No. 34.
- Elphidium advenum* (Cushman) (fig. 54)=
Polystomella advena Cushman, 1922. *Carnegie Inst. Washington, Publn.* 311, 56, pl. 9, figs. 11, 12.
- Elphidium crispum* (Linné) (fig. 55)=
Nautilus crispus Linné, 1758, "Systema naturae", 10th Edn. 709.
- Elphidium incertum* (Williamson), 1858 (fig. 56)=
Polystomella umbilicatulata var. *incerta* Williamson, 1858, "On the Recent foraminifera of Great Britain". *Ray Soc. London*, 44, pl. 3, fig. 82a.
- Elphidium jenseni* (Cushman) (fig. 57)=
Polystomella jenseni Cushman, 1924. *Carnegie Inst. Washington, Publn.* 342: 49, pl. 16, figs. 4, 6.
- Elphidium poeyanum* (d'Orbigny) (fig. 58)=
Polystomella poeyana d'Orbigny, 1839. "Histoire physique, politique et naturelle de l'île de Cuba". 55, pl. 14, fig. 26.
- Elphidium simplex* Cushman, 1933. *Bull. U.S. nat. Mus.* 161 (2): 52, pl. 12, figs. 8, 9.
- Gypsina globulus* (Reuss) (fig. 60)=
Ceriodora globulus Reuss, 1848. *Naturw. Abh., Berlin* 2 (2): 33.
- Gypsina vesicularis* (Parker and Jones), 1860=
Orbitolina vesicularis Parker and Jones 1862. *Ann. Mag. Nat. Hist.* ser. 3, 6: 31, no. 5.
- Cymbaloporetta bradyi* Cushman, 1915. *Bull. U.S. nat. Mus.* 71 (6): 25, pl. 10, figs. 2 a-c; pl. 14, figs. 2 a-c.
- Superfamily CASSIDULINACEA
? *Cassidulina* sp.
- Superfamily GLOBIGERINACEA
Globigerina bulloides d'Orbigny, 1826. *Annls. Sci. nat.* ser. 1, 7: 277, Modeles No. 17.
Globorotalia sp. (fig. 61).

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12.—The cadmium content of some river systems in Western Australia

by K. J. R. Rosman¹ and J. R. De Laeter¹

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Abstract

A stable isotope dilution technique has been used to measure the concentration of cadmium in aqueous solutions with a sensitivity of 0.003 ppb. The concentration of cadmium in the Swan and Peel Inlet river systems in Western Australia has been measured to establish an accurate baseline record against which future measurements can be compared.

The results demonstrate that the cadmium content in the river systems is about one hundredth of the limit set by the World Health Organisation. The data should therefore serve as a basis for comparison with cadmium concentrations in waterways in other parts of the world.

Introduction

Cadmium is a non-essential, potentially toxic metal that accumulates in human tissue with increasing age. Concern has been expressed at the inadvertent exposure of the general population to this toxic trace element. As is the case with mercury, widespread environmental exposure to cadmium is related to its increased technological use.

A survey of the concentration of cadmium in two river systems in Western Australia has been reported by Rosman and De Laeter (1976) who showed that the levels were about one hundredth of the limit set by the World Health Organisation. (W.H.O. 1963). The present work supplements the above paper and contains a complete description of the analytical results and the experimental procedure, and additional results relating to the reservoir systems and the sediment in the Peel Inlet.

Unfortunately there is still a paucity of accurate information on the content of cadmium in natural waterways, particularly in regions where there is an absence of industrial activity giving atmospheric contamination. Doolan and Smythe (1973) have recently measured the cadmium content in a number of waterways in eastern Australia. The present study complements this investigation for waterways in Western Australia. The stable isotope dilution technique used in this project is sufficiently sensitive to explore the variations in cadmium content along the waterways.

Experimental procedure

The loss of trace amounts of metallic ions on container walls during sample collection, handling and storage of aqueous solutions has been recognised for some time. Struempfer (1973) showed that polyethylene containers did not

adsorb cadmium from aqueous solutions, could be readily cleaned, and exhibited a very low cadmium blank. Consequently the 500 ml containers used in this project were made from high density polyethylene, and the chemical processing was carried out as soon as possible after the samples were collected.

The polyethylene bottles were cleaned with high purity 6M HCl for several weeks before sample collection. At the collection point each bottle was flushed several times with the river water before the sample was taken.

A 200 g aliquot of each water sample was acidified to a final concentration of 1M with HCl in a flask which had already been spiked with an isotopically enriched ¹¹¹Cd tracer. After ensuring that the spike and sample were well mixed, the solution was placed on a large silica column containing ~ 2 g of Dowex AG1 x 8 (100-200 mesh), anion exchange resin which had previously been equilibrated with 1M HCl. After washing the column with several column volumes of 1M HCl, the cadmium was eluted with 4 column volumes of 1M HNO₃ and collected in a teflon beaker. The eluate was taken to dryness, the residue was redissolved in a minimum of 0.1M HCl and transferred to a small ion exchange column containing ~ 1 g of Dowex AG50 x 8 (100-200 mesh) cation exchange resin, equilibrated at 0.1M HCl. The Cd was eluted with 6 column volumes of 0.5M HCl and after taking to dryness, was ready for mass spectrometric analysis.

The stable isotope dilution technique has a number of advantages when compared with many other analytical techniques. Because of its excellent sensitivity, high accuracy and precision, it is ideally suited to the analysis of cadmium in the environment. Doolan and Smythe (1973) have drawn attention to the necessity of developing more sensitive and accurate methods of analysing cadmium in the range 2×10^{-2} to 10 ppb (gram metal per 10^9 gram water). The isotope dilution technique enables this to be achieved provided the blank is small and accurately known.

A blank was included with each batch of samples undergoing chemical processing. The blank was observed to vary over the period the analyses were made, but was found to be about 1.8 ng. The 6M HCl which was used to acidify the samples and prepare other solutions needed for the extraction was the main source of this cadmium.

The samples were analysed in a 30.5 cm radius, 90° magnetic sector field solid source mass spectrometer equipped with an electron

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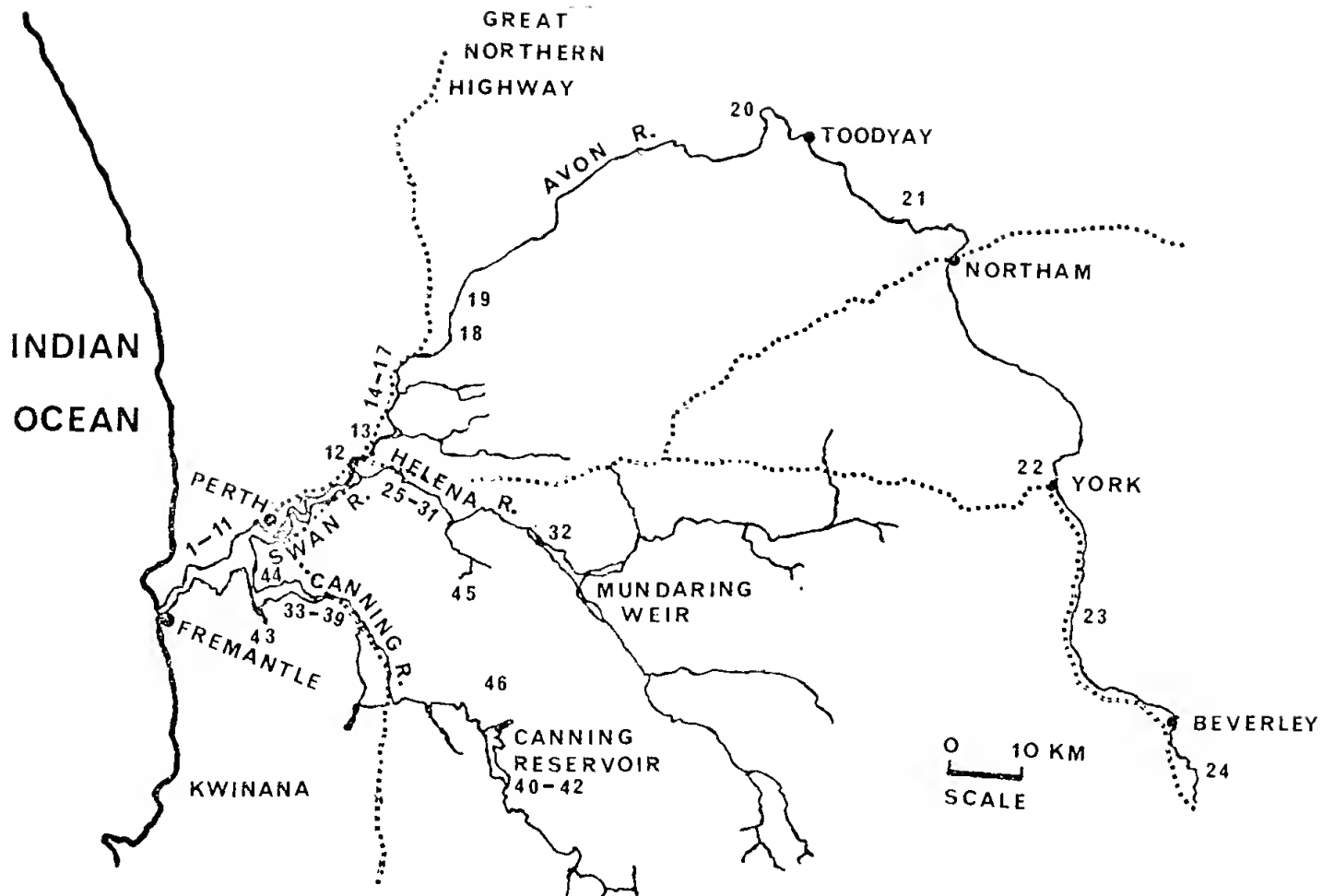


Figure 1.—Sample locations for the Swan River system.

multiplier. The samples were mounted on a single rhenium filament using the silica gel loading technique (Cameron *et al.* 1969). Full details of the mass spectrometric procedures used in the project are given by Rosman and De Laeter (1975).

Results and discussion

Two river systems were selected for study. The Swan River and its tributaries is the major river system for Perth and the surrounding metropolitan area (Figure 1). The second system studied is south of Perth near the Peel Inlet (Figure 2).

The first set of samples was collected during the period 26 April to 24 May 1975. There was little rain in the 6 months preceding sample collection or during the sample collection period itself. The second set of samples was collected from 26 February to 11 April 1976 when conditions similar to those in the 1975 collection period prevailed. Wherever possible the samples were collected from the centre of the smaller streams or away from the bank at places where the river was wide.

Swan River system

The information on the Swan River system is given in Table 1 and includes sample number, collection date, locality and cadmium concentra-



Figure 2.—Sample locations for the Peel Inlet river system.

tion. The corresponding sample numbers and localities are shown in Figure 1. The cadmium concentration listed with each location is the mean of duplicate analyses, and the error for each sample is listed in the table. The greater part of the error is due to the uncertainty in correcting for the chemistry blank.

Table 1

Cadmium content of the Swan River System

Sample no.	Collection date	Locality	Concentration (ppb)
<i>Lower Swan</i>			
1	26 April 1975	Fremantle Bridge	0.064 ± 0.003
2	26 April 1975	Crawley	0.14 ± 0.01
3	26 April 1975	Kings Park Foreshore	0.070 ± 0.003
4	26 April 1975	Narrows Bridge	0.10 ± 0.05
5	26 April 1975	Causeway (South)	0.12 ± 0.01
6	17 May 1975	Causeway (North)	0.21 ± 0.02
7	17 May 1975	Rivervale	0.44 ± 0.01
8	17 May 1975	Garratt Road Bridge	0.14 ± 0.01
9	17 May 1975	Ashfield	0.068 ± 0.006
10	17 May 1975	Guildford	0.10 ± 0.06
11	26 April 1975	Bassendean Bridge	0.04 ± 0.01
<i>Middle Swan</i>			
12	26 April 1975	Caversham Bridge	0.17 ± 0.007
13	11 May 1975	Midland Junction	0.082 ± 0.003
14	11 May 1975	Junction of Jane Brook	0.061 ± 0.003
15	10 May 1975	Off Swan, on Suzzana Brook Tributary	0.02 ± 0.01
16	11 May 1975	Gnangara Road (near Church)	0.14 ± 0.01
17	10 May 1975	Baskerville	0.13 ± 0.01
<i>Upper Swan—Avon River</i>			
18	10 May 1975	Walyunga National Park	0.14 ± 0.01
19	10 May 1975	Walyunga National Park (up stream)	0.010 ± 0.006
20	24 May 1975	West Toodyay	0.063 ± 0.003
21	24 May 1975	Toodyay—Northam	0.013 ± 0.003
22	24 May 1975	York	0.010 ± 0.003
23	24 May 1975	Gilgering	0.04 ± 0.01
24	24 May 1975	East Kokeby Bridge	0.06 ± 0.02
<i>Helena River</i>			
25	26 April 1975	Near Junction with the Swan River	0.04 ± 0.01
26	26 April 1975	Guildford	0.04 ± 0.01
27	26 April 1975	Guildford	0.02 ± 0.01
28	26 April 1975	Bellevue	0.03 ± 0.01
29	26 April 1975	Bellevue	0.014 ± 0.005
30	26 April 1975	Boya	0.010 ± 0.003
31	26 April 1975	Darlington	0.006 ± 0.003
32	7 March 1976	Mundaring Weir	0.04 ± 0.01
<i>Canning River</i>			
33	20 May 1975	Canning Bridge	0.07 ± 0.03
34	20 May 1975	Mt. Pleasant	0.06 ± 0.01
35	20 May 1975	Rossmoyne	0.032 ± 0.006
36	20 May 1975	Riverton	0.071 ± 0.006
37	20 May 1975	Riverton Bridge	0.06 ± 0.03
38	20 May 1975	Nicholson Road Bridge (Cannington)	0.024 ± 0.003
39	20 May 1975	Thornlie	0.035 ± 0.003
40	8 March 1976	Canning Reservoir (Nr Dam Wall)	2.2 ± 0.1
41	25 March 1976	Canning Reservoir (Nr Dam wall)	1.4 ± 0.1
42	25 March 1976	Canning Reservoir (upstream)	0.30 ± 0.01
43	8 March 1976	Tap water, Rossmoyne	0.020 ± 0.003
44	26 February 1976	Tap water, Bentley	0.030 ± 0.003
45	24 March 1976	Tap water, Kalamunda	0.020 ± 0.003
46	10 April 1976	Tap water, Roleystone	0.070 ± 0.004
47	16 March 1976	Bore water, Perth area	0.005 ± 0.003

As can be seen in Table 1 the data on the Swan River system has been subdivided into regions. In the Lower Swan the cadmium concentrations are about 0.1 ppb except upstream from the Causeway where a value of 0.44 ppb was obtained. This is presumably related to the higher than average level of industrial activity in the area. It is apparent however that the quantity of cadmium is sufficiently small to be quickly diluted, so that a few km downstream it had decreased to 0.21 ppb and then to 0.12ppb. Bowen (1966) states that the cadmium concentration in normal sea water is 0.11 ppb, and our measurements at sample collection points 1-4 are in good agreement with this value. The Middle Swan portion of the river is situated amongst vineyards in a semi-rural area. The cadmium concentration is again of the order of 0.1 ppb in this region.

The course of the Swan River now changes as it traverses the Darling Scarp. To the east of the Darling Scarp for some 60 km, are State Forests and farmlands. The Swan River traverses the Walyunga National Park, which is just to the east of the Darling Scarp. It is interesting to note that the cadmium content of the water collected near the picnic area in the park (Sample 18) was 0.14 ppb, whereas a few km upstream the cadmium content decreased by a factor of 10. This could be the result of contamination at the picnic site, or alternatively be associated with the rocks underlying this region of the river. A large basic intrusion cuts across the river in the vicinity of the sample collection site, whereas most of the surrounding area consists of granite rocks. Rosman and De Laeter (1974) have shown that granitic rocks have substantially smaller cadmium concentrations than basic rocks, and it is therefore possible that the high cadmium content in sample 18 is an indicator of the underlying rock type. It is unlikely that the effect would have been measurable at periods of the year when the river is flowing rapidly. The lower concentration level is maintained in the Avon River as it flows through Toodyay and Northam, and does not increase to any great extent in the upper reaches of the Avon River at York and Beverley, even though the river at the time of sample collection consisted of a series of stagnant pools south of Northam.

The cadmium concentrations are extremely low throughout the length of the Helena River region despite the fact that the river is situated along the Darling Scarp in a semi-residential area. Sample 31 came from a forested catchment area. The water was clear and fast moving and gave the lowest cadmium value of all the samples of 0.006 ppb. A sample of water from Mundaring Weir gave a higher value of 0.04 ppb.

The Canning River is tidal for most of the localities where samples were collected. The average of the cadmium concentrations over this region is 0.06 ppb, but further up-stream where it is no longer tidal, the mean concentration is half this value.

Three water samples were collected from the Canning Reservoir in March 1976. Two of the samples were collected near the retaining wall

of the reservoir, one from the east bank and the other from the west bank. Both gave surprisingly high Cd concentrations of 1.4 and 2.2 ppb respectively. Another sample, collected approximately 2 km upstream near the west bank, gave a value of 0.3 ppb. Water samples from taps in the metropolitan area gave values between 0.02 to 0.07 ppb, and typical river water values as measured in this study are of the order of 0.05 ppb. Thus one would have expected the Cd concentration of water in the Canning Reservoir to be approximately 0.05 ppb, yet the measured values are significantly higher.

The Canning Reservoir samples were collected in March 1976, at the end of a long dry summer, during which little influx of water took place from the catchment area. The water in the reservoir was quite low, and the samples were collected from close to the surface. It appears that during the hot summer period the water in the Canning Reservoir collects into stratified layers, between which little mixing takes place. The topmost layer loses water through evaporation, and hence the concentration of dissolved elements in this surface layer would increase as the summer progresses. It is possible that fallout of atmospheric particulates also contributes to the cadmium content of this upper water layer. It is also possible that the catchment water into the Canning Reservoir has a higher cadmium content than the Mundaring Reservoir where most of the water percolates through adjacent sediments. The first influx of fresh, catchment-area water into the Canning Reservoir in winter would cause the stratified layers to mix, and a much lower cadmium concentration would be expected throughout the reservoir. The metropolitan area receives water from a number of sources, the Canning Reservoir being one of them. In some areas this water is supplemented by water from artesian and subartesian bores. This bore water has an extremely low cadmium concentration (<0.01 ppb), and this will have the effect of lowering the cadmium concentration in tap water. In addition water is drawn off the Canning Reservoir from a series of outlet pipes situated at different levels below the surface, and the resultant mixture is then reticulated to the metropolitan area.

Peel Inlet system

Peel Inlet is situated some 50 km south of Perth and is a large body of salt water connected to the sea by a narrow channel. The surrounding area is mainly rural, although in the close vicinity of the Peel Inlet there is a residential area. The Murray River and its tributaries flow into the Peel Inlet. The data for this system are given in Table 2, and the sample locations shown in Figure 2.

The cadmium concentrations in the Peel Inlet are remarkably uniform, and the average value for the inlet as a whole is about 0.04 ppb. It is possible that over the summer months when there is little interchange of water with the ocean, the cadmium content of the water is

Table 2
Cadmium content of the Peel Inlet river system

Sample no.	Collection date	Locality	Concentration (ppb)
1	9 May 1975	} Peel Inlet	0.051 ± 0.003
2	9 May 1975		0.046 ± 0.006
3	9 May 1975		0.050 ± 0.006
4	9 May 1975		0.040 ± 0.003
5	9 May 1975		0.041 ± 0.003
6	9 May 1975		0.020 ± 0.005
7	9 May 1975		0.051 ± 0.008
<i>South Western Highway river crossings</i>			
8	15 May 1975	Mundijong (Medulla Brook)	0.010 ± 0.006
9	15 May 1975	Serpentine (Serpentine River)	0.031 ± 0.006
10	15 May 1975	North Dandalup (Nth Dandalup River)	0.142 ± 0.007
11	15 May 1975	South Dandalup (Sth Dandalup River)	0.101 ± 0.005
12	15 May 1975	Pinjarra (Murray River)	0.022 ± 0.004
13	15 May 1975	Waroona Dam	0.023 ± 0.004
14	15 May 1975	Hamel (Irrigation Channel)	0.151 ± 0.005
<i>Peel and Harvey Inlets</i>			
15 (a)	12 April 1976	Robert Bay, Peel Inlet	0.060 ± 0.005
15 (b)	12 April 1976	Core Sample (Top)	253 ± 12
15 (c)	12 April 1976	Core Sample (Bottom)	74 ± 4
16 (a)	12 April 1976	Near Channel, Peel Inlet	0.110 ± 0.007
16 (b)	12 April 1976	Core Sample (Top)	8 ± 1
16 (c)	12 April 1976	Core Sample (Bottom)	35 ± 3
17 (a)	12 April 1976	Harvey Inlet, West Bank	0.070 ± 0.005
17 (b)	12 April 1976	Core Sample (Top)	49 ± 3
17 (c)	12 April 1976	Core Sample (Bottom)	222 ± 11

reduced by adsorption into the underlying sediments of the Peel Inlet. Gardiner (1974) has shown that cadmium is adsorbed on river muds, and that adsorption and desorption processes are likely to be major factors in controlling the concentration of cadmium in natural waters. It is likely that in the future, pollution will increase in the Peel River system. It would therefore be desirable to monitor the cadmium content of the inlet and compare it with the 1975 base values. In April 1976 another three water samples were collected from the Peel and Harvey Inlets. These additional samples gave cadmium concentrations of 0.06, 0.07 and 0.11 ppb. The first two samples are only slightly higher than the average value of 0.04 ppb measured in the previous year.

To test the hypothesis that much of the cadmium is adsorbed on underlying sediments, core samples from the three additional locations were also collected. The core samples were approximately 10 cm long, and 0.5 g portions from the top and bottom of the cores were digested by a HF-HClO_4 mixture, and then subjected to an extraction procedure described by Rosman and De Laeter (1974). The results are listed in Table 2. At first sight the data may appear confusing, but the type of material sampled is significant. The Robert Bay core sample was very rich in humic constituents at the surface, whereas the bottom portion contained a higher portion of clay and other silicates. The Harvey Inlet sample was almost the reverse of the Robert Bay sample, the bottom part of the core being richer in humic material, whereas the upper portion contained some small shells. The core sample from the channel comprised white

sandy material throughout its length, and the low cadmium concentration reflected this preponderance of silicate material.

Thus the underlying river mud acts as a sink for the dissolved cadmium, most of the cadmium being adsorbed in regions where humic material predominates. This conclusion is in agreement with the work of Gardiner (1974), who found that the humic constituents of mud are principally responsible for its adsorptive properties. Gardiner has shown that in any fresh water system which has attained equilibrium, the concentration of cadmium on finely divided solids may be 5 000-50 000 times higher than in solution. In the present case the factor is at the lower level of this range, but it must be remembered that the water is salty and the inlet is open to the sea for much of the year.

Florence and Batley (1976) have shown that a proportion of the cadmium in sea water is present either as organic chelates or adsorbed on organic or inorganic particles. Colloidal particles are not retained by most ion-exchange resins because the resin pore size is too small to allow the colloids to enter the resin network (Samuelson 1963). It was therefore decided to check if the chemical extraction used in this project was effective in measuring the total cadmium content in the water samples. A sample of water was taken from the upper reaches of the Helena River for this purpose and four 100 ml aliquots from the same polyethylene bottle were analysed.

The first was spiked with ^{111}Cd and evaporated to dryness with distilled HNO_3 . 6M HCl was added to the residue and then taken to dryness. The residue was treated with 1M HCl and subjected to the normal ion exchange procedure. A Cd concentration of 0.01 ± 0.01 ppb was obtained. The second and third samples were spiked and allowed to equilibrate for 3 and 7 days respectively, before processing. The last sample taken was observed to contain some particulate matter. This sample was spiked and allowed the normal mixing time. The second, third and fourth determinations yielded concentrations of 0.01 ± 0.01 , 0.01 ± 0.01 and 0.02 ± 0.01 ppb respectively. The first three samples gave identical concentrations whereas the higher value obtained for the fourth sample is attributed to the presence of particulate matter.

The remaining 7 samples were collected at river crossings between Mundijong and Waroona along the South West Highway. This highway skirts the base of the Darling Scarp and is crossed by some 14 streams and rivers within the 60 km sector sampled. The water samples were collected upstream from the highway and as near to the centre of the stream as possible. After leaving the Darling Scarp the waterways traverse the coastal plain, and many finally feed into Peel Inlet. The waterways originate in the ranges behind the Darling Scarp in a region of virgin bush. The Serpentine and Waroona reservoirs are situated on two of the major streams. The cadmium concentrations are very low, for the most part being less than 0.1 ppb.

Conclusions

The World Health Organisation has declared that the maximum advisable concentration limit for cadmium in drinking water is 10 ppb (W.H.O. 1963). The recommended maximum level for irrigation purposes is 5 ppb for continuous use (Committee on Water Quality Criteria 1968). The results of this study demonstrate that the cadmium content in the two major river systems in south Western Australia are of the order of 100 times lower than the W.H.O. limits. The data indicate that the cadmium content tends to decrease upstream from the mouth of the rivers studied, and that in the reservoir catchment areas the cadmium content is as low as 0.01 ppb in many places.

These values compare very favourably with waterways in other parts of the world. Abdullah and Royle (1972) give a value of 0.41 ppb for "clean" stream water in Wales, whilst in some of the rivers in England the average cadmium content is approximately 25 ppb (Valdez 1975). In North America many streams contain more than 1 ppb cadmium (U.S.G.S. 1970).

Dale *et al.* (1974) have measured the cadmium content of a number of rivers in Victoria, Australia. Unfortunately their detection limit was 30 ppb and the cadmium content of many of the samples was below their detection limit. However the cadmium content of a number of samples was in excess of 30 ppb. Doolan and Smythe (1973) also found a range of cadmium concentrations (from < 0.02 to 7.7 ppb) in some rivers in New South Wales, Australia. The sensitivity of their technique was 0.02 ppb which compares favourably with ours.

It is likely that much of the published work on the cadmium content in water has been based on analytical techniques which were incapable of measuring accurately below the ppb level. The present study has succeeded in adapting the stable isotope dilution technique using solid source mass spectrometry to the measurement of cadmium in river waters, and we believe the measured concentrations establish a definitive set of low level base line determinations for cadmium in the environment.

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13.—Middle Holocene marine molluscs from near Guildford, Western Australia, and evidence for climatic change

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Abstract

Thirty one species of fossil molluscs are reported from a subsurface Middle Holocene deposit near Guildford, Western Australia, 26 km upstream from the mouth of the Swan Estuary. A radiocarbon age of 6660 ± 120 yr BP (shell carbonate) indicates that the fauna lived near the end of the Flandrian transgression. In the light of their modern distributions, the fossils indicate that in Middle Holocene time, the Swan Estuary was a hydrologically stable arm of the sea, which experienced considerably less winter flooding than at present. A period of regional aridity is indicated, continuing on to some time after 4500 yr BP.

Introduction

During 1969-70, the Western Australian Public Works Department was engaged in channel clearing and deepening along a part of the estuary of the Swan River below Guildford (lat. $31^{\circ} 54' S$, long. $115^{\circ} 58' E$) and about 26 km upstream from the mouth at Fremantle. The area dredged was about 1 000 m long by 45 m wide, on either side of but mainly below the Helena River confluence (Fig. 1). Spoil was pumped ashore and discharged from a steel pipe line about 0.7 km away on the flood-plain of the Helena River adjacent to Great Eastern Highway and the Guildford State Primary School to provide for an extension of the school grounds.

As discharged from the pipe, the spoil comprised a coarse, greyish-brown, poorly sorted quartz sand with a high proportion of angular grains, together with fragments of granitic rock and feldspar, mica flakes and occasional small ferruginous nodules. These components suggest a recent origin from the Precambrian rocks and associated laterite of the Darling Range. In addition, scattered sparsely within the spoil, were occasional mollusc shells and small pieces of soft, grey, calcareous, sandy siltstone, mostly shell-bearing. Many shells however were free of sediment (referred to below as "clean") and a large proportion were also freshly broken or abraded; likewise the pieces of siltstone showed evidence of heavy abrasion as a result of their passage along the discharge pipe.

The stratigraphic relationship of the elements of the spoil-pile has not been observed directly but according to the Public Works Department the modern channel bed is composed of "coarse sand". Dredging removed from 0.3 to 2.1 m of the substrate, and the resulting channel bed had a reduced level ranging from 4.4 to 5.6 m below Australian Height Datum (equivalent to mean sea level). It seems probable that the shell-bearing siltstone came from low in the cut beneath the channel sand and, from its relative

scarcity in the spoil, was either of no great thickness or was only slightly or intermittently penetrated by the dredge.

Collections of shells from the spoil-pile were made firstly by Mrs. H. E. Merrifield in December 1969, and subsequently by the writer in January and February 1970 and again in February 1971. The specimens have been accessed into the collection of the Western Australian Museum and provide the basis of this report. Most are in fresh, unweathered condition and, apart from some recent breakage, are well preserved.

The fossil species

Altogether, 35 species of molluscs, as well as crustaceans, polychaete tubes and a bryozoan were represented in the material collected. Identifications are available only for the molluscs, of which 18 species were represented by specimens directly associated with the grey siltstone. The remaining 17 species are considered to comprise two groups, the larger, of 13 species, being mostly fragmentary shells which evidently had been washed and tumbled free of sediment in passage along the pipe. The lesser group of 4 species comprised the bivalves *Westralunio carteri* Iredale, *Xenostrobus securis* (Lamarck) and *Anticorbula amara* (Laseron) and the gastropod *Plotiopsis australis* (I. and H. C. Lea). With the exception of the first-mentioned, these are permanent inhabitants of the Swan near Guildford (Chalmer *et al.* 1976); *W. carteri* inhabits freshwater tributaries such as the Helena River and Bennett Brook. The shells of these 4 species are believed to be associated with the sand of the channel substrate rather than the calcareous siltstone and to represent the modern fauna at Guildford and upstream. Likewise, specimens of the flat-backed crab *Halicarcinus australis* (Haswell) (WAM 70.138), collected from the spoil-pile, are considered to be modern.

With this adjustment, the fossil molluscs are found to comprise 31 species, of which 16 are bivalves and 15 gastropods. In the following discussion, subdivisions (Lower, Middle and Upper) of the Swan Estuary and modern distributions within the estuary are from Chalmer *et al.* (1976). Other non-estuarine records are from the collection of modern molluscs of the Western Australian Museum.

Bivalves

Mytilidae

Musculus sp. cf. *M. nanulus* Thiele. Material: numerous specimens of mature size, mostly disarticulated valves embedded in grey siltstone;

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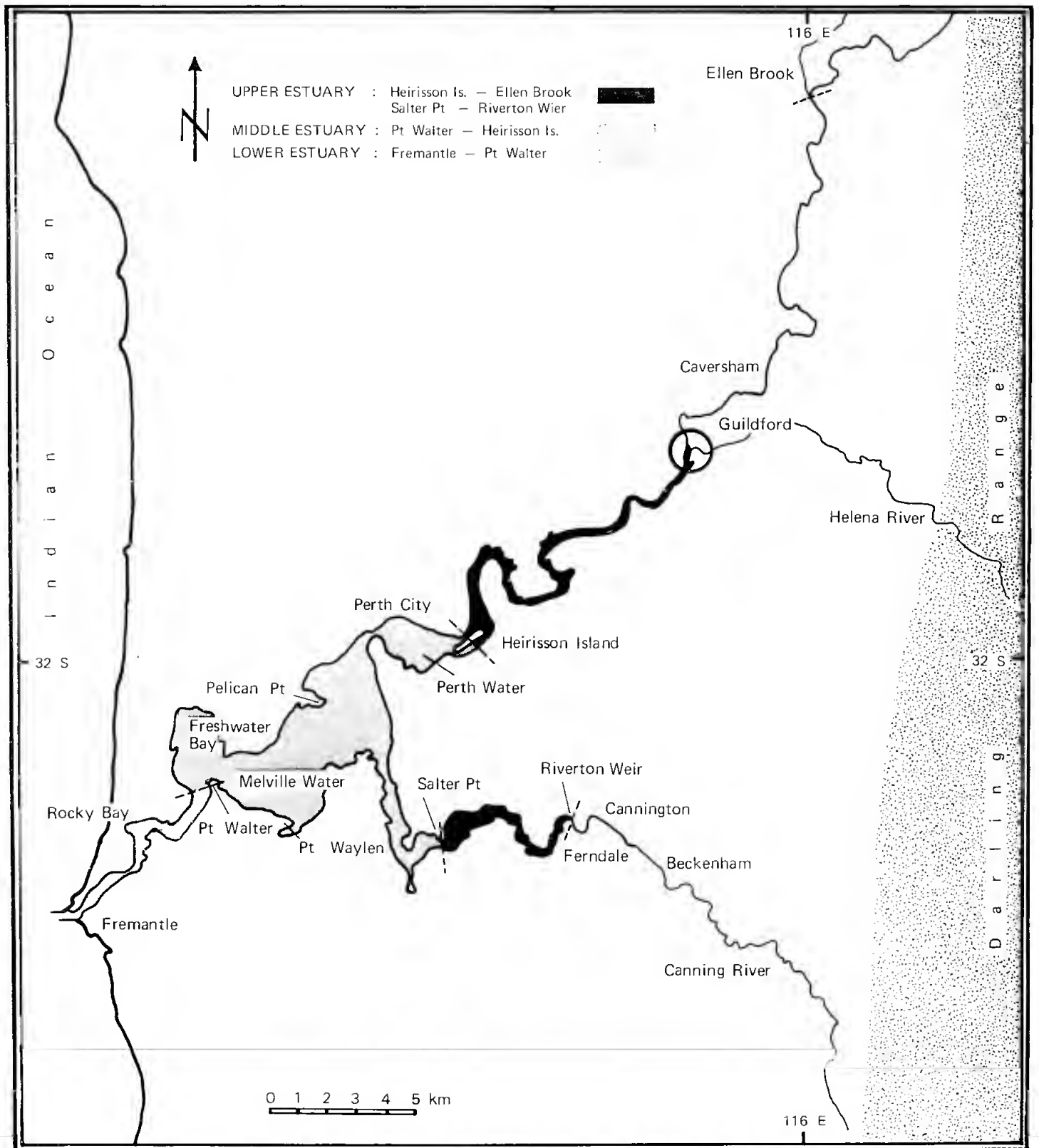


Figure 1.—Swan River estuary. Localities mentioned in text. Fossil site circled.

two "clean" singles. WAM 70.66, 70.73, 70.110, 70.111, 70.143. The relationship of this to Thiele's species, described from Shark Bay (Thiele 1930) is not clear. Guildford specimens have 35-40 ribs on the posterior slope and are up to 8 mm long. Habitat unknown but probably byssally attached to seagrasses, etc. This species now lives periodically within the Lower Estuary.

Pectinidae

Pecten modestus Reeve. Material: a substantially complete left valve and a fragment of a

right, both "clean". WAM 70.69, 70.112. The latter measures 55 x 61 mm and is about $\frac{3}{4}$ mature size. Modern geographic range: southern Australia north to Shark Bay. Not recorded living from the Swan Estuary. An epifaunal species with some swimming ability.

Ostreidae

Ostrea angasi Sowerby. Material: an articulated pair of mature size, filled with grey siltstone; two small singles embedded in siltstone; eight "clean" singles, mostly mature, four

attached in a cluster and with adherent *Chama* valves; the largest 11 x 9 cm (slightly damaged). WAM 70.67, 70.68, 70.70, 70.113, 71.483. Modern geographic range: southern Australia, principally in estuaries (Macpherson and Gabriel 1962) but apparently not now living north of Cape Leeuwin. An epifaunal species, attached to stones, other shells, etc. below low water mark.

Chamidae

Chama ruderalis Lamarck. Material: three articulated pairs and five lefts embedded in grey siltstone; 13 left valves attached to oyster and other shells; five right and three left singles, all "clean". Most specimens are comparable in size with local modern marine specimens. WAM 70.70, 70.113, 70.115, 71.483. Modern geographic range: South Australia, southern Western Australia (Cotton 1961), north to about Fremantle. Now lives probably permanently in the Lower Estuary. A sessile, epifaunal species, attached to firm substrates at or below low water mark.

Cardiidae

Laevicardium (Fulvia) apertum (Bruguère). Material: two articulated pairs and three single valves embedded in grey siltstone; one fragment with adherent *Chama* valves; two "clean" fragments. Specimens are comparable in size with local marine shells. WAM 70.70, 70.71, 70.72, 70.73, 70.111. Modern geographic range: Indo-SW Pacific; in Western Australia south to Cockburn Sound (common) and Geographe Bay (rare). Now lives periodically in the Lower Estuary and part of the Middle Estuary (in the vicinity of Pt Walter). An infaunal burrower in sandy to muddy substrates.

Laevicardium (Fulvia) tenuicostatum (Lamarck). Material: one small left valve and two fragments from larger valves, all "clean". WAM 70.74. Modern geographic range: southern Australia, north to about Fremantle; not recorded living from the Swan Estuary. An infaunal burrower in sandy to silty substrates.

Tellinidae

Tellina (Tellinangulus) sp. Material: two single valves, one with a little adherent grey calcareous sediment; the larger 5 mm long. WAM 70.83, 70.146. Modern geographic range: not known. Now common in the deeper parts of Cockburn Sound; lives periodically within the Lower Estuary. Probably an infaunal burrower.

Tellina (Pinguittellina) sp. Material: a "clean" left valve of mature size (14 x 10 x 3 mm). WAM 70.121. Modern geographic range: Cockburn Sound to Shark Bay; now lives probably permanently within the Lower Estuary. Probably an infaunal burrower.

Tellina sp. Material: 21 "clean" valves, the largest 24 x 15 x 3 mm and comparable in size to local modern marine specimens. WAM 70.81, 70.120, 70.145. Modern geographic range: not known. Now common in the sea near Fremantle, particularly Cockburn Sound, and lives periodically within the Lower Estuary. Of uncertain subgenus, this is an infaunal burrower in fine substrates.

Psammodiidae

Sanguinolaria (Psammodiellina) biradiata (Wood). Material: a fragmentary left valve of medium size. WAM 70.119. Modern geographic range: southern Australia north to about Fremantle; lives permanently within the Lower Estuary. A deep burrower in sandy to muddy substrates.

Veneridae

Dosinia (Pectunculus) sculpta (Hanley). Material: one juvenile, articulated pair embedded in grey siltstone; three left and three right valves, all "clean", the largest 37 x 40 x 9 mm. WAM 70.75, 71.483. Modern geographic range: northern and Western Australia, south to about Cockburn Sound; living periodically within the Lower Estuary. A burrowing species in fine substrates.

Circe sulcata Gray. Material: two articulated pairs containing grey siltstone and a single embedded in the same; one left valve with

adherent siltstone; seventeen "clean" singles, the largest 29 x 31 x 7 mm. WAM 70.76, 70.77, 70.116, 70.144, 70.2719. Modern geographic range: Indo-SW Pacific; in Western Australia, south to Albany; living periodically within the Lower and Middle Estuaries. A burrowing species in fine substrates; living specimens sometimes found on the surface of the substrate.

Paphia (Callistotapes) crassisulca (Lamarck). Material: one broken left valve with adherent grey siltstone; a complete juvenile right and part of an adult left valve, both "clean"; a shell of *Ostrea angasi* with the external impression of a mature *P. (C.) crassisulca* on the lower valve. WAM 70.68, 70.78, 70.79. Shells of this species were common in the original collections and most were used for radiocarbon dating. Modern geographic range: Indian Ocean, northern Australia (Fischer-Piette and Métivier 1971); in Western Australia south to Cockburn Sound (common) and Cape Naturaliste (rare); probably living permanently in the channel of the Lower Estuary. A burrowing species in fine substrates.

Irus irus (Linnaeus). Material: two "clean" single valves and a fragmentary single extracted from a cavity of a piece of teredine-bored wood. WAM 70.117, 70.118. Modern geographic range: E. Atlantic, Mediterranean, Indo-W. Pacific (Fischer-Piette and Métivier 1971), Western Australia south to Cockburn Sound; not recorded living from the modern Swan Estuary. Inhabits crevices of rocks, shells, wood, etc.

Hiattellidae

Hiattella australis Lamarck. Material: four articulated pairs and three singles embedded in siltstone; eleven "clean" singles, the largest 13 x 5 mm, which is small compared with marine specimens. WAM 70.66, 70.68, 70.71, 70.84, 70.111, 70.123, 70.144, 71.483. Modern geographic range: Australia generally (Macpherson and Gabriel 1962); living periodically within the Lower Estuary. A sessile species inhabiting crevices of rocks, shells, etc.

Pholadidae

Pholas sp. cf. *P. australasiae* Sowerby. Material: a posterior fragment of a "clean" medium-sized right valve, probably of this species. WAM 70.82. Modern geographic range: Australia generally (Macpherson and Gabriel 1962); not recorded living from the modern Swan Estuary. A sedentary species confined to burrows near low water mark; often collected near the mouths of estuaries.

Gastropods

Trochidae

Monilea callifera (Lamarck). Material: two shells, one filled with siltstone, the other "clean". The larger shell measures 12 x 9 mm, about half mature size. WAM 70.124, 70.139. Modern geographic range: Indo-SW Pacific; in Western Australia, south to Safety Bay; living periodically in the Lower Estuary. A herbivore associated with seagrasses in marine bays.

Cyclostrematidae

Elachorbis tatei (Angas). Material: four shells, one embedded in siltstone and three "clean", the largest 3 mm in diameter. WAM 70.86, 70.111. Modern geographic range: South and Western Australia north to Shark Bay; living periodically within the Lower Estuary. A herbivore associated with seagrass and algal growth in sheltered waters.

Diastomatidae

Obtortio (Alabina) sp. Material: five shells embedded in siltstone and 25 "clean" shells, generally of mature size. WAM 70.71, 70.87, 70.111, 70.126, 70.143. Modern geographic range: southwestern Australia, Albany to Shark Bay; living periodically within the Lower Estuary. Associated with fine substrates in sheltered waters. This may be the species listed by Thiele (1930) as *Finella pupoides* A. Adams, from Shark Bay and Warnbro Sound.

Cerithiidae

Alaba fragilis (Thiele). Material: three shells embedded in siltstone; two "clean" shells, the largest 6 mm high. WAM 70.88, 70.111, 70.127. Modern geographic range: not known. Lives in Cockburn Sound and permanently in the Lower Swan Estuary, being described originally from Freshwater Bay (Thiele 1930). A herbivore associated with algal and seagrass beds in sheltered waters.

Epitonidae

Epitonium sp. cf. *E. imperiale* (Sowerby). Material: two "clean" shells, the larger 9 mm high, which may be either juveniles of *E. imperiale* or another, closely related species. WAM 70.140. Modern geographic range: *E. imperiale* occurs in the Indo-SW Pacific and in Western Australia, south to Cape Naturaliste (Wilson and Gillett 1971). In Cockburn Sound it is believed to be associated commensally with the anemone *Radianthus concinnata* Lager (S. Slack-Smith, pers. comm., April 1975). Modern shells apparently conspecific with the Guildford specimens, are occasionally collected in the Lower Estuary of the Swan, where they may be living periodically.

Naticidae

Polinices (Conuber) conicus (Lamarck). Material: five "clean" shells, the largest damaged but originally about 4 cm high. WAM 70.89, 70.128. Modern geographic range: Australia generally; not recorded living from the Swan Estuary. An active, infaunal predator on bivalves, etc. A gastropod drill-hole of the bevelled type attributed to the Naticidae by Bromley (in Crimes and Harper 1970) was observed on a specimen of *Dosinia sculpta* (WAM 70.75c).

Nassariidae

Nassarius rufulus (Kiener). Material: one "clean" fragment from a shell probably about 17 mm high. WAM 70.131. Modern geographic range: south-western Australia, Albany to Geraldton (Wilson and Gillett 1971); not recorded living from the Swan Estuary. An infaunal scavenger/predator in shallow marine habitats.

Nassarius pauperatus (Lamarck). Material: 32 shells, one filled with grey sandy siltstone; several incomplete. The largest shell measures 14 x 8 mm. WAM 70.129, 70.130, 70.141. Modern geographic range: southern Australia; in Western Australia north to Geraldton (Wilson and Gillett 1971); permanently living in the Lower and Middle Estuaries. An infaunal scavenger/predator, common in estuaries and marine bays.

Nassarius pyrrhus (Menke). Material: a fragmentary shell, lacking the spire, when intact about 10 mm high. WAM 74.895. Modern geographic range: southern Australia, Victoria to Fremantle (Hodgkin *et al.* 1966); living periodically within the Lower Estuary. A scavenger/predator common in estuaries and marine bays.

Pyramidellidae

Turbonilla (Chemnitzia) mariae Tenison Woods. Material: four "clean" shells. WAM 70.92. Modern geographic range: southern Australia (Cotton 1959); not recorded living from the Swan Estuary. An ectoparasite.

Turbonilla (Chemnitzia) sp. Material: one shell embedded in and another extracted from siltstone; one "clean" shell. WAM 70.134, 71.484, 75.821. Distinguished from the preceding by having more ribs per whorl and a larger protoconch perched atop poorly ribbed apical whorls; akin to *T. (C.) macleayana* Tenison Woods (R. Burn, pers. comm., Jan. 1975). Modern geographic range: unknown; not recorded living from the Swan Estuary. An ectoparasite.

Agatha simplex (Angas). Material: one shell extracted from a piece of grey siltstone and one "clean" shell. WAM 70.91, 74.1123. Modern geographic range: Queensland—southern Australia—north western Australia (Cotton 1959); not recorded living from the Swan Estuary. An ectoparasite.

Atysidae

Liloa brevis (Quoy and Gaimard). Material: six "clean" shells, the largest 6.5 mm high. WAM 70.90, 70.132, 70.142. Modern geographic range: southern Australia, New South Wales to Fremantle (Hodgkin *et al.* 1966); living periodically within the Lower Estuary. A herbivore associated with seagrasses in sheltered waters.

Retusidae

Retusa sp. A. Material: one shell embedded in grey siltstone. WAM 70.111. A thin-shelled species, differing in shape from *Retusa* sp. B. Modern geographic range: not known, but living at least periodically in the Lower Estuary (R. Burn, pers. comm., Jan. 1975). An infaunal carnivore on foraminifers and/or small molluscs.

Retusa sp. B. Material: one juvenile shell, extracted from a piece of grey siltstone. WAM 70.133. Modern geographic range: not known. Close to *R. pygmaea* (A. Adams), a southern Australian species (R. Burn, pers. comm., Jan. 1975). An infaunal carnivore on foraminifers and/or small molluscs.

Age and correlation

One of the more common species in the fossil material was the bivalve *Paphia crassisulca*, a robust, medium-sized clam, mature specimens of which measure from 2 to 3 mm through each valve. A comparative X-ray diffraction examination of a Guildford fossil (WAM 70.79b) of *P. crassisulca* and a modern specimen of the same species from Cockburn Sound near Fremantle showed that each was composed of aragonite; no calcite was detected in either specimen and no significant compositional or crystallographic differences were noted between the two (M. Price and D. Burns, Government Chemical Laboratories, pers. comm., Dec. 1975). Thus the material has not been involved in any detectable carbonate exchange and is suitable for carbon-14 dating.

A 200 g sample of these shells from Guildford was submitted for radiocarbon dating and a C^{14} age of 6660 ± 120 yr BP (GaK 2874) was determined (Kigoshi *et al.* 1973). From this it is concluded that the deposit of siltstone presumed to underlie the modern channel sand at the dredged site was formed during Middle Holocene time and near the end of the Flandrian or last major glacio-eustatic transgression of the sea (Mörner 1976). There is a general agreement between the age and estimated position of the Guildford deposit (about 5 m below datum) and data presented by Thom and Chappell (1975) from Australian sources. However no precise sea level can be deduced from the evidence available at Guildford.

Shell beds of similar composition and age occur in the Swan Estuary at Heirisson Island, Perth and Melville Waters, etc., and have been discussed by Maitland (1919, p. 53), Reath (1925), Serventy (1955, p. 71) and Clarke *et al.* (1967, p. 136). The Guildford occurrence is more distant from the sea than any of these. Other shell beds from excavations at Cannington, Beckenham and Ferndale, on the Canning River well upstream from the modern broadwaters of the estuary, are under study by the writer. These contain mollusc faunas similar to that from Guildford and are considered to be of approximately similar age.

The Guildford Mid-Holocene molluscs differ markedly in species and preservation from those of the Caversham clay pits of Brisbane and Wunderlich Pty, located some 3 km to the north (Fairbridge 1954). Lying several metres above Datum, the Caversham deposit contains the bivalves *Anadara trapezia* (Deshayes), *Mactra* (*Diaphoromactra*) *versicolor* Tate and other species unknown in the Guildford fauna. The Caversham deposit is noticeably weathered and evidently is of Pleistocene age (Noakes *et al.* 1967), probably deriving from the high sea levels of the Last Interglacial, approximately 100 000 yr ago (Broecker and van Donk 1970).

Comparison of fossil and modern faunas

The present Swan Estuary experiences a well defined, two phase, annual hydrologic cycle, which derives from the Mediterranean type climate of the region (Spencer 1956; Wilson 1968, 1969). Reliable, intense winter rainfall results in strong river discharge into the estuary, leading to a sharp drop in salinity and temperature, stratification and deoxygenation of the water body; during each summer drought, this is replaced by marine circulation induced by a weak tidal oscillation. This marked seasonal contrast in the estuarine environment is reflected in the distribution of the permanent benthic fauna, the species diversity of which declines sharply with distance from the sea. Thus Chalmer *et al.* (1976) report 23 mollusc species living permanently in the Lower Estuary, 10 in the Middle Estuary and only 6 in the Upper Estuary; only 4 species are known to live permanently in the Upper Estuary near Guildford.

An analysis of the Guildford molluscs is presented in Table 1. They are grouped into three categories of "permanently resident", "periodically resident" and "not recorded" in the present day Swan Estuary. Of the 31 species represented, only 7 are believed to still inhabit the estuary permanently and 6 of these appear to be confined to the Lower Estuary; the seventh ranges further upstream into parts of the

Middle Estuary. A second group of 13 species lives from time to time in the Lower Estuary, when conditions are temporarily favourable (i.e., during periods of low river discharge), but appears to be unable to live permanently in any part of the modern estuary, dying out in times of high winter discharge. The remaining 11 species have not been recorded from the modern estuary as either periodic or permanent inhabitants; all are of marine affinity and are either known or presumed to occur in marine environments in south-western Australia. Chalmer *et al.* (1976) recorded 6 mollusc species, all permanent residents of the Middle Estuary of the Swan, which appeared to be more abundant in estuarine rather than normal marine environments. Of these 6, only 1, *Nassarius pauperatus*, is represented among the Guildford fossils. The modern upstream limit of this species is at about Pelican Point (Fig. 1). The same workers further recognized a group of 5 exclusively estuarine mollusc species characteristic of the Middle and Upper Estuaries, none of which is represented among the Guildford fossils.

The differences in range and composition noted between the Guildford fossil assemblage and the modern estuary fauna show that there has been a general contraction seaward by all of the former (grouping of species) since the Middle Holocene, indicating that a substantial environmental change has affected the estuary since that time. The fossils include filter-feeding infaunal and epifaunal bivalves and herbivorous, scavenging, carnivorous and ectoparasitic gastropods. Other groups probably also present by inference were seagrasses, one or more actinarians and other host-species, such as sabellid worms, for a suite of pyramidellid snails. Most species are represented by specimens of average-mature size and the fauna has a balanced diversity consistent with relatively stable, near-normal marine salinity in a marginal, sheltered, gulf environment. The Guildford fossils probably represent a life assemblage or biocoenosis (Schafer 1972). If so, the evidence obtained is not compatible with modern levels of river dis-

Table 1

Mollusc species from Guildford grouped according to their modern occurrences in the Swan Estuary; comparative data from Chalmer *et al.* (1976) and R. Burn (pers. comm., April 1975).

- | | |
|---|---|
| (i) Probable permanent inhabitants of the Lower Estuary (7 species). Asterisk denotes species probably also living permanently in part of the Middle Estuary. | |
| <i>Chama ruderalis</i> | <i>Paphia</i> (<i>Callistotapes</i>) <i>crassisulca</i> |
| <i>Tellina</i> (<i>Pinguitellina</i>) sp. | <i>Alaba fragilis</i> |
| <i>Tellina</i> sp. | <i>Nassarius pauperatus</i> * |
| <i>Sanguinolitaria</i> (<i>Psammotellina</i>) <i>biradiata</i> | |
| (ii) Periodic inhabitants of the Lower Estuary (13 species). Asterisk denotes species which may range periodically into the lower part of the Middle Estuary. | |
| <i>Musculus</i> sp. cf. <i>M. nanulus</i> | <i>Elachorbis tatei</i> |
| <i>Laevicardium</i> (<i>Fulvia</i>) <i>apertum</i> * | <i>Obtortio</i> (<i>Alabina</i>) sp. |
| <i>Tellina</i> (<i>Tellinangulus</i>) sp. | <i>Epitonium</i> sp. cf. <i>E. imperiale</i> |
| <i>Dosinia</i> (<i>Pectunculus</i>) <i>sculpta</i> | <i>Nassarius pyrrhus</i> |
| <i>Circe sulcata</i> * | <i>Liloa brevis</i> |
| <i>Hiatella australis</i> | <i>Retusa</i> sp. A (advice from R. Burn) |
| <i>Monilea callijera</i> | |
| (iii) Not recorded in the modern estuary fauna (11 species). | |
| <i>Pecten modestus</i> | <i>Nassarius rufulus</i> |
| <i>Ostrea angasi</i> | <i>Turbonilla</i> (<i>Chemnitzia</i>) <i>mariae</i> |
| <i>Laevicardium</i> (<i>Fulvia</i>) <i>tenuicostatum</i> | <i>Turbonilla</i> (<i>Chemnitzia</i>) sp. |
| <i>Irus irus</i> | <i>Agatha simplex</i> |
| <i>Pholas australasiae</i> | <i>Retusa</i> sp. B (advice from R. Burn) |
| <i>Polinices</i> (<i>Conuber</i>) <i>conicus</i> | |

charge and indicates that a qualitatively different hydrologic regime prevailed in the estuary during the Middle Holocene.

Hydrologic regime

From Fremantle Harbour to Rocky Bay, the Swan Estuary in its lowermost, inlet section is partly obstructed by an extensive sand-sill, which acts as a barrier to the free circulation of sea water into the Middle Estuary and beyond (Chalmer *et al.* 1976). Dredge spoil from this sill has been found to contain a high proportion of fresh mollusc shell and other biogenic carbonate and appears to be of marine origin (G.W.K., unpublished data). The Guildford fossil deposit was formed near the culmination of the transgressive phase of the Holocene depositional cycle, at which time the estuary was rather deeper than is now the case. This was particularly so of the lower reaches, as a consequence of extensive downcutting by the Swan during the low sea levels of the late Pleistocene (Churchill 1959). The presence of a deep oceanic connection extending through the Lower Estuary and most if not all of the Middle Estuary would have greatly enhanced marine influence throughout the entire estuary but, in conjunction with modern levels of stream discharge, could not, of itself, account for the presence of marine molluscs at Guildford.

The marine component of the estuarine Swan environment was clearly stronger than at present during the Middle Holocene but the character of the complementary fluvial element needs to be considered also. Of the various parameters of river discharge, the two most relevant appear to be volume and concentration (i.e. seasonality). A volume of discharge equal to or greater than present levels is ruled out by the fossil and lithologic evidence. The site is located around the Swan-Helena confluence, the latter now being a major freshwater tributary. Geological maps of the district (Low and Lake 1971) suggest that there have been no more than minor changes in the position of the confluence during the Holocene. The presence at Guildford of marine species, such as *Pecten modestus*, *Laevicardium tenuicostatum*, *Polinices conicus* and *Nassarius rufulus* is highly significant. These species are now living in the sea around Fremantle but apparently are unable to live anywhere within the Swan Estuary under prevailing conditions. Their presence as fossils in the Swan near the Helena confluence is incompatible with active discharge from that tributary, whether this was seasonal (as now) or continuous. The same reasoning applies with almost equal force to other species in the fossil assemblage, for example, *Chama ruderalis*, *Laevicardium apertum*, *Sanguinolaria biradiata*, *Circe sulcata*, *Paphia crassisulca* and *Epitonium* sp. cf. *E. imperiale*. These are now able to live either permanently or temporarily in the estuary within a few km of the sea, but nowhere within 20 km of Guildford.

The most likely reconstruction of the hydrologic situation in the Middle Holocene Swan would seem to require a substantially reduced volume of river discharge throughout the entire

drainage basin. Under such conditions, the importance of seasonality of discharge would tend to diminish, even to the point of becoming difficult to recognize and assess. The indications are, however, that both discharge volume and seasonality were much lower than at present and, hence, that the climate was relatively dry.

Climatic change in the Middle Holocene

The time of onset of this postulated dry episode pre-dates 6700 yr BP but is otherwise unknown. Radiocarbon dates from an undisturbed, partly emergent shell bed at Point Waylen, Melville Water, may help to clarify an upper, terminal date. Mollusc shell carbonate from 10-20 cm above and 60-80 cm below Datum have produced ages of 4500 ± 100 yr BP (SUA 339) and 5940 ± 110 yr BP (SUA 341) respectively (Gillespie and Temple 1976). Faunal studies in progress on the Point Waylen deposit indicate that the mollusc assemblage, with over 60 species, is highly diverse and, like the Guildford material, lived under hydrologically stable, marine-gulf conditions. The fossil assemblages from Guildford and Point Waylen are similar and lead to the tentative conclusion that the modern hydrologic seasonality of the Swan Estuary did not develop until some time after 4500 radiocarbon yr BP.

Late Quaternary climates in south-western Australia have received little detailed study and interpretations of evidence obtained by Lundelius (1960) and Churchill (1968) have not supported the concept of a relatively dry Mid-Holocene in the region. Churchill (1960) envisaged a Mid-Holocene extinction of a "Eucalyptus-Casuarina woodland, *Xanthorrhoea*, *Macrozamia* and possibly *Banksia* and *Agonis* scrubs" on Rottnest Island, seeing this as a consequence of "a marine transgression to at least 9 feet above present sea level in 2000 B.C.", corresponding to the Older Peron strandline of Fairbridge (1950). Such a post-Pleistocene stand of the sea has not won general acceptance (Mörner 1976; Thom and Chappell 1975) and is not supported by the writer's observations of the Holocene shell beds of the Swan Estuary, located within 50 km of Point Peron. These suggest that the maximum Mid-Holocene transgression in this region stood little, perhaps 0.5 m, above Datum. A transgression of that magnitude or less would tend to favour the alternative suggestion of Grant-Taylor and Rafter (1963) that extinction of *Xanthorrhoea* on Rottnest may have resulted from "desiccation during the Hypsithermal Maximum", corresponding to the warm Atlantic climatic phase of the northern hemisphere, which Wendland and Bryson (1974) locate between 8490 and 5060 yr ago.

Substantial quantities of rain-derived salt have accumulated in ground waters of lateritic profiles in the Darling Range and the adjacent wheat belt of south-western Australia. Studies by Dimmock *et al.* (1974) have shown that the concentration of this salt tends to increase sharply with lower rainfall and raised evaporation; the lowest salt concentrations occur in the more humid western areas, characterized by higher and more constant levels of stream discharge. Under the present climate on un-

cleared land in the Darling Range, salt discharge slightly exceeds input, according to Peck and Hurle (1973).

Clearly the net rate of salt accession has been greater in the past, and this build-up could be expected to occur in periods of lower rainfall and stream discharge associated with increased evaporation and concentration of ground water salt. If so, this phenomenon may be viewed as an index of past regional climate. It has been pointed out by Dimmock *et al.* (1974) that only a relatively brief period of time would be required to account for the large quantity of salt stored in ground water at Bakers Hill in the eastern Darling Range. The fossil evidence at Guildford suggests that the regional climate was much drier than present during the Middle Holocene, at least from 6700 yr BP until some time after 4500 yr BP. This dry period, beginning at some unknown time, may therefore have been the most recent episode of net salt accumulation in the ground waters of the Darling Range.

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Postscript.—An extension of the present fossil fauna has recently been discovered in core samples from the flood plain of the Swan near Guildford Grammar School, some 4.2 km upstream from the Helena confluence. It is associated with a black clay lying between 3 and 6 m below the ground surface. Molluscs are similar to the present assemblage; also present are echinoderm ossicles which represent an asteroid of the genus *Astropecten* (L. M. Marsh pers. comm.). The core samples, which are uncontaminated by the modern channel substrate of the Swan, do not contain the molluscs *Westralunio carteri*, *Xenostrobus securis*, *Anticorbula amara* and *Plotiopsis australis*, species excluded from the present study because of their association with the modern channel substrate at Guildford. The new material justifies this exclusion and supports the palaeoenvironmental deductions of this paper. Presentation of this new material by Messrs. H. Grant and J. Backhouse is gratefully acknowledged.

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14.—Potassium-argon ages of hornblendes from Precambrian gneisses from the south coast of Western Australia

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Abstract

Potassium-argon ages obtained from hornblendes from seven samples of amphibolite and basic granulite from three localities in the gneiss-granite complex of the south coast of Western Australia range from 1060 to 1160 m.y., with no detectable differences between localities. These results show good agreement with the Rb-Sr isochron age of 1100 ± 50 m.y. previously obtained from the Albany Adamellite. This could suggest that the K-Ar hornblende ages reflect the period of late-kinematic emplacement of anatectic granitic plutons (represented by the Albany Adamellite) which is believed to have occurred during waning metamorphism. Alternatively, they could be regarded as indicating the age of late-orogenic regional uplift and cooling. These are not necessarily conflicting interpretations because it is possible that late-kinematic emplacement of granitic magmas and regional uplift were roughly synchronous events. About 1150 m.y. can be regarded at present as only a minimum estimate of the age of high-grade regional metamorphism in the south coast area.

Introduction

Precambrian gneisses and granitic plutons outcrop along the south coast of Western Australia between Point D'Entrecasteaux and Israelite Bay, a distance of roughly 750 km. This area forms part of the Albany-Fraser Province, a narrow arcuate belt wrapped around the southern and southeastern margins of the Archaean Yilgarn Block. This belt appears to represent the site of a younger Precambrian orogenic belt that cut across the Archaean shield (Wilson 1969).

A general account of the geology of the region has been given by Clarke *et al.* (1954). The gneisses are predominantly granitic in character, with intercalated metasedimentary and metabasite bands; migmatitic types are common. The metamorphic grade varies from upper amphibolite to lower granulite facies, with the higher-grade rocks occurring as large enclaves scattered through the amphibolite facies terrain. The gneisses have been intruded by numerous porphyritic coarse-grained granitic plutons, cut in turn by fine-grained granitic dykes and, later, by occasional dolerite dykes. Stephenson (1973*a*, *b*, 1974) believes that the granitic plutons and dykes have been derived from the gneissic country rocks by anatexis during orogeny and high-grade regional metamorphism, and that emplacement and crystallisation occurred during waning metamorphism under syn- to late-kinematic conditions.

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The geochronology of the south coast area has not been adequately investigated. Turek and Stephenson (1966) reported a microcline-total-rock Rb-Sr isochron age of 1100 ± 50 m.y. for one of the granitic plutons (the Albany Adamellite) but there may, of course, have been more than one episode of granitic magma emplacement. The main phase of high-grade regional metamorphism responsible for the gneisses is thought to have preceded the emplacement of granitic plutons, but it has not been reliably dated. The only published radiometric data on these gneisses are a chemical U-Pb age (uncorrected for Pb isotopes) of 1390 ± 50 m.y. given by allanite from pegmatitic schlieren in charnockitic gneiss from Doubtful Island Bay (Prider 1954), and a Rb-Sr age of 970 m.y. given by biotite from gneiss from the same locality (Wilson *et al.* 1960). The significance of these dates is not yet fully understood, but the latter is clearly only a minimum estimate of the age of the main metamorphism.

The geochronology of the northeastern part of the Albany-Fraser Province (i.e. in the vicinity of the Fraser Range) is better known and possibly of some significance to the south coast region. Compston and Arriens (1968) and Arriens and Lambert (1969) reported a total-rock Rb-Sr isochron of 1330 ± 15 m.y., which is interpreted as a reliable estimate of the age of an episode of granulite facies metamorphism in this area. Preliminary data presented by Arriens and Lambert (1969) and Bunting *et al.* (1976) suggest that gneisses and granites flanking the 1330 m.y.-old granulites were formed during an earlier metamorphism around 1600-1900 m.y. ago. A period of retrogression and pegmatite emplacement during uplift and waning metamorphism about 1280-1290 m.y. ago is suggested by a Rb-Sr age of 1280 m.y. obtained by Aldrich *et al.* (1959) on muscovite from one of the numerous small pegmatites in the 1300 m.y.-old granulites, and by a Rb-Sr total-rock isochron age of 1289 ± 21 m.y. given by muscovite-bearing gneisses and pegmatites associated with gneisses possibly 1900 m.y. old (Bunting *et al.*, 1976). In view of the structural continuity between the south coast and Fraser Range areas (Doepel 1969) it is likely that they experienced regional metamorphism at least broadly contemporaneously. Furthermore, it seems reasonable to suppose that the history of metamorphism of the south coast gneisses was possibly as long and complex as it appears to have been in the Fraser Range area.

The purpose of this paper is to report and interpret K-Ar ages obtained from hornblendes

separated from seven samples of amphibolite and basic granulite from three localities in the gneissic complex along the south coast. Two of these samples are from Albany near the Albany Adamellite, two from Forsyth Bluff near the Torbay Adamellite, and three from Cape Riche where there are no known granitic plutons. These localities are shown in Figure 1, and short petrographic descriptions of the samples are given in the Appendix. It was hoped that a comparison of the ages of the Albany and Forsyth Bluff samples, which are expected to reflect the period of granitic magma emplacement, with those obtained from the Cape Riche samples would clarify the temporal relations between high-grade metamorphism and granitic magma emplacement in the south coast area. It is realised that the scope of this investigation is far too limited to provide a detailed geochronological analysis of the possibly complex metamorphic history of the region.

Methods

Hornblende was separated from the washed -120 to +200 mesh fractions of the crushed rock samples using a Frantz isodynamic separ-

ator followed by repeated centrifuging in heavy liquids. The purity of the final separates was better than 99%.

The methods used in the K-Ar age determinations have been described by McDougall (1966). Potassium was determined by flame photometry. Argon measurements were carried out in the Isotope Geology Laboratory at the University of Queensland using the isotope dilution technique, following fusion of the sample and extraction of argon in a high vacuum line. After purification of the gas the isotopic composition was determined on an A.E.I.G.E.C.—MS20 mass spectrometer. The constants used in the calculations were: $\lambda_e = 0.585 \times 10^{-10} \text{ yr}^{-1}$; $\lambda\beta = 4.72 \times 10^{-10} \text{ yr}^{-1}$; $^{40}\text{K}/\text{K} = 0.000119$. Errors were calculated using the method of Kirsten (1966). The results are listed in Table 1.

Discussion of results

Table 1 shows that the measured ages range from 1060 to 1160 m.y., with no detectable differences between the three sample localities.

Samples R36265 and R36266 were collected from basic granulite bands in the gneiss within the granitised zone around the Albany Adamel-

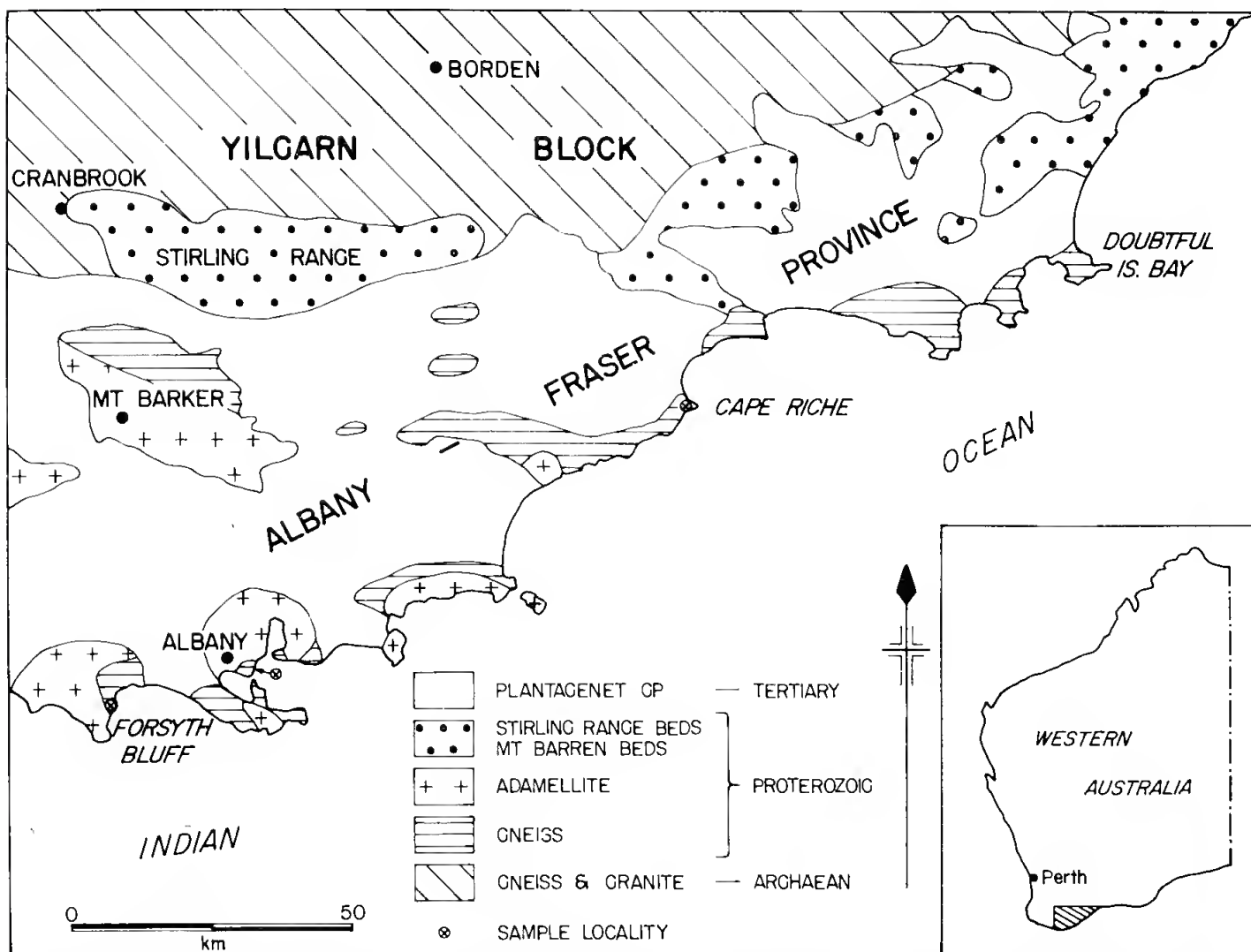


Figure 1.—Geological map of part of the south coast of Western Australia showing the sample localities at Forsyth Bluff, Albany, and Cape Riche. (Based on the Geological Map of Western Australia compiled by the Geological Survey of Western Australia, 1973. Modifications by N. C. N. Stephenson.)

Table 1

K-Ar ages on hornblendes from amphibolites and basic granulites from the south coast of Western Australia

Sample No.*	QA No.†	Rock Type	K %	Rad. ⁴⁰ Ar %	Age (m.y.)	Error‡ (m.y.)	Latitude (south)	Longitude (east)	Locality
54563	267	Amphibolite	0.71	29.71 §	1059	±51	35°05.1'	117°38.6'	Forsyth Bluff
65581	273	Amphibolite	1.04	99.75	1151	±15	35°05.1'	117°38.7'	Forsyth Bluff
R36265	268	Granulite	1.13	97.57	1156	±24	35°01.8'	117°55.1'	King Point, Albany
R36266	269	Granulite	1.04	34.86 §	1103	±31	35°01.5'	117°55.1'	Ellen Cove, Albany
R36269	270	Granulite	1.38	98.64	1133	±24	34°36.5'	118°46.3'	Cape Riche
R36270	271	Granulite	1.45	99.49	1153	±24	34°36.5'	118°46.3'	Cape Riche
R36271	272	Granulite	1.41	97.86	1066	±18	34°36.2'	118°46.2'	Cape Riche

$$\lambda_{\epsilon} = 0.585 \times 10^{-10} \text{ yr}^{-1} \quad \lambda_{\beta} = 4.72 \times 10^{-10} \text{ yr}^{-1} \quad {}^{40}\text{K}/\text{K} = 0.000119$$

* Numbers prefixed by R refer to the collection of the Geology Department, University of New England. The remainder refer to the collection of the Geology Department, University of Western Australia.

† University of Queensland, Isotope Laboratory catalogue number.

‡ Errors calculated using the method described by Kirsten (1966).

§ The low values of radiogenic argon percentages are due to a malfunction in the pumping system and they are reflected in the rather large error. For a discussion of the effect of atmospheric contamination see Cox & Dalrymple (1967).

lite. The rocks within this zone show extensive metasomatic enrichment in Si and K, and partial retrogression to amphibolite facies assemblages, presumably due to the introduction of hydrous fluids from the adamellite magma (Stephenson 1974). Both samples contain a little orthoclase and quartz of probable metasomatic origin (see Appendix), and there seems little possibility that they escaped the thermal influence of the pluton. The ages obtained from these samples (1156 ± 24 and 1103 ± 31 m.y.) show good agreement with the Rb-Sr isochron age of 1100 ± 50 m.y. obtained by Turek and Stephenson (1966) for the Albany Adamellite, and they therefore seem to reflect the episode of magma emplacement.

Samples 54563 and 65581 are from amphibolite bands outcropping 800 m and 1400 m respectively from the southeastern margin of the Torbay Adamellite. Neither sample shows obvious thermal or metasomatic effects attributable to the pluton, but 54563 lies within the zone of appreciable Si and K metasomatism, and 65581 is from the perimeter of this zone. Hence the age obtained for 54563 (1059 ± 51 m.y.) is likely to reflect the emplacement of the Torbay Adamellite. This pluton has not been dated but it shows late-kinematic characteristics similar (though less obvious) to those of the Albany Adamellite (Stephenson 1974), so it is tentatively believed to be of comparable age; i.e. roughly 1100 m.y. The age given by 65581 (1151 ± 15 m.y.), though older, may also have been influenced by emplacement of the Torbay Adamellite, and hence it provides only a minimum estimate of the age of high-grade regional metamorphism.

The significance of the results obtained from the Cape Riche samples is not entirely clear. Although there are no known granitic plutons in the area, the dates obtained from these samples—namely 1133, 1155, and 1066 m.y.—are not detectably older than the inferred age of granitic magma emplacement. Hence the data have failed to demonstrate that the phase of high-grade regional metamorphism in the south coast area occurred significantly earlier than the emplacement of granitic magmas represented by the Albany Adamellite. However this

is a possibility that still cannot be ruled out because the dates obtained from the Cape Riche samples could reflect any of several events in the orogenic cycle following the most intense phase of metamorphism. For example, the emplacement of large masses of granitic magma about 1100 m.y. ago may have been caused by, or given rise to, a period of regional reheating detectable by K-Ar dating even in areas remote from these plutons. The minor retrograde effects which appear to be ubiquitous in granulite facies areas of the south coast should also be considered. The Cape Riche samples from which the hornblendes were separated for dating were chosen for their relative freedom from these effects, but incipient alteration is nevertheless evident in their orthopyroxenes and plagioclases (see Appendix). Although the hornblendes show no visible signs of alteration the dates obtained from them could reflect this minor retrogression. Another possible interpretation of the predominance of Rb-Sr and K-Ar dates around 1100-1150 m.y. obtained from the intrusive and gneissic rocks is that they represent the phase of regional uplift and cooling during the final stages of the orogenic cycle in the south coast area. Even in hornblende, a relatively retentive mineral (e.g. Dalrymple and Lanphere 1969, p. 174), diffusion loss of radiogenic argon does not cease until cooling has reached a temperature a few hundred degrees below the temperature of upper amphibolite to lower granulite facies metamorphism to which these rocks have been subjected. Therefore it is unlikely that K-Ar dating will record the age of the most intense phase of metamorphism unless cooling was particularly rapid.

The K-Ar ages reported above show an interesting correlation with the total-rock Rb-Sr isochron age of 1150 ± 40 m.y. obtained by Turek and Stephenson (1966) from slates and phyllites from the nearby Stirling Range Beds, and this merits brief discussion. The Stirling Range Beds, together with the Mt Barren Beds to the east, form an east-west-trending strip of Precambrian low-grade metasediments outcropping discontinuously along the junction between the Albany-Fraser Province and the Yilgarn Block in the south coast area (Fig. 1).

Contact relations are not well exposed but the low-grade metasediments appear to overlie the gneiss-granite complexes of the Albany-Fraser Province and the Yilgarn Block with a faulted unconformity (Sofoulis 1958a, b). The Stirling Range and Mt Barren Beds exhibit structures interpreted by several observers as indicating thrusting from the south; either thrusting of the metasediments themselves towards and over the adjacent Yilgarn Block, or overthrusting of the metasediments by the gneiss-granite complex of the Albany-Fraser Province, or a combination of both (Wilson 1952; Clarke *et al.* 1954; Sofoulis 1958a, b). It seems likely that these thrusting movements may have been associated with uplift of the Albany-Fraser Province in the south coast area. Clarke *et al.* (1954) indicated that the low-grade metamorphism of the Stirling Range Beds was associated with the thrusting described above, and Turek and Stephenson (1966) interpreted the 1150 m.y. Rb-Sr isochron obtained by them from slates and phyllites from the Stirling Range Beds as the age of this metamorphism and thrusting. If this low-grade metamorphism and thrusting was associated with uplift of the Albany-Fraser Province as suggested above, then this uplift occurred roughly 1150 m.y. ago. This is consistent with the suggestion that the 1060-1160 m.y. K-Ar ages reported in this paper reflect mainly the post-metamorphic regional uplift and cooling of the gneiss-granite complex of the south coast area. This conclusion does not necessarily conflict with the alternative suggestions that late-kinematic emplacement of granitic magmas or widespread incipient retrogression, or both, have influenced the recorded ages because it is not improbable that these events were roughly synchronous with regional uplift. In any case, about 1150 m.y. can probably be regarded at present as only a minimum estimate of the age of regional metamorphism in the south coast area. Because it seems likely that this region has had a long and complex history of deformation, metamorphism, and granitic magma emplacement yet to be unravelled, further structural, petrological, and geochronological studies should prove rewarding.

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Appendix—Petrography

Samples 54563 and 65581: Amphibolites

These are fine- to medium-grained equigranular rocks composed of hornblende (roughly 50%) with X = pale yellowish brown, Y = yellowish green, Z = green, andesine (40%) showing patchy saussuritisation, and biotite (10%). Quartz, magnetite, sphene, apatite, and zircon are minor accessories. The texture is predominantly granoblastic-polygonal, modified by a vague preferred orientation of biotite and hornblende producing a weak foliation.

*Samples R36265 and R36266:
Basic granulites*

These are fine- to medium-grained granoblastic-textured rocks containing andesine (roughly 40%), hornblende (30%) (X = light brown, Y = brown, Z = dark green), orthopyroxene (10%), biotite (5%), perthitic orthoclase (5%), quartz (5%), and (in R36266 only) clinopyroxene (5%). Opaque oxide, apatite, and zircon are minor constituents. Orthoclase and quartz occur as irregularly distributed poikiloblasts up to 4 mm in diameter which corrode and enclose the other minerals suggesting metasomatic introduction. In R36265 some of the hornblende and biotite also occurs as poikiloblasts enclosing pyroxene, plagioclase, and opaque oxide. In both samples plagioclase forms occasional porphyroblasts relatively free of inclusions. Orthopyroxene shows incipient alter-

ation to fibrous green amphibole and minor chlorite along fractures and grain boundaries.

*Samples R36269, R36270, and R36271:
Basic granulites*

These are medium-grained equigranular rocks composed of andesine (roughly 50%), hornblende (25%) (X = light brown, Y = brown, Z = brownish green), orthopyroxene (15%), clinopyroxene (5%), and biotite (5%). Quartz and orthoclase are additional minor constituents of R36269. Opaque oxide, apatite, and zircon are minor accessories. Orthopyroxene shows slight alteration to green amphibole and rare chlorite along fractures and grain boundaries. Plagioclase in R36270 and R36271 shows incipient alteration to chlorite, calcite, and sericite. The texture is granoblastic-polygonal. A faint mineralogical banding is evident in R36269.

15.—In search of the Dibbler, *Antechinus apicalis* (Marsupialia: Dasyuridae)

by P. Woolley¹

Communicated by B. K. Bowen

Manuscript received 25 May, 1976; accepted 16 November, 1976

Abstract

The Dibbler, *Antechinus apicalis*, was considered to be extremely rare, if not extinct, prior to 1967 when two specimens were collected at Cheyne Beach, Western Australia. Since then several attempts have been made to collect more specimens, both in the locality in which they were rediscovered and in other localities in the vicinity. Altogether, only 7 Dibblers have been trapped and the only known habitat is one small area of scrub situated close to the fishing settlement and camping area at Cheyne Beach.

Recently, another Dibbler was brought in by a cat on a farm near Jerdacuttup, Western Australia. Despite an intensive trapping effort on all uncleared areas, of land on or immediately adjacent to the farm, and in some nearby areas of bushland, no further specimens were obtained and the habitat of the Dibbler in this region remains unknown.

Introduction

The Dibbler, *Antechinus apicalis*, had not been collected for 83 years when Morcombe (1967) captured two specimens at Cheyne Beach (also known as Hassell Beach), Western Australia. Since then several workers have attempted to collect further specimens of this apparently rare species, with little success. This paper records the results of all attempts to trap the Dibbler, both at Cheyne Beach and at other localities, that are known to the author, from the date of rediscovery.

Trapping at Cheyne Beach

January 1967.—Using 10 traps specially constructed to fit over the flowers of banksias, Morcombe (1967) captured 2 Dibblers in area A (Figure 1) at Cheyne Beach (locality 1, Figure 2). The traps were set for 4 consecutive nights commencing on 25th January. One female *A. apicalis* was found in a trap on the morning of the 27th and one male on the 29th. This represents a trapping success of 5%. In addition to the Dibblers, 2 bush rats, *Rattus fuscipes*, were trapped. Morcombe kept the Dibblers in captivity for several weeks to photograph them and observe their habits.

April 1967.—Ride (1970) captured a female Dibbler in area A (Figure 1) on 8th April. It was caught in a Sherman trap (23 x 8 x 9 cm) baited with 'universal' bait (Ride, pers. comm.). This animal, together with the two collected by Morcombe in January, were sent to the author in May 1967 for study of their reproductive biology (Woolley 1971).

August 1967.—On 1st August, Baynes and Kirsch (Baynes, pers. comm.) trapped a female *A. apicalis* in area A (Figure 1.) Twenty Sherman traps (23 x 8 x 9 cm) were set for 4 nights and the animal was caught on the third night. This represents a trapping success of approximately 1%. The bait used was either 'universal' or beef mince or both. There were no young on the nipples but judging by the appearance of the pouch this female was suckling young; seven of the 8 nipples were elongated, the mammary glands were enlarged and the pouch fur was a reddish-brown colour. The weight of the animal was 78 g and the pes length 24 mm. It was released at the site of capture immediately after inspection.

January/February 1970.—Between 29th January and 4th February Butler (unpublished report, Western Australian Department of Fisheries and Wildlife) trapped in three areas designated Major Area (area A, Figure 1), Coastal Strip (area B, Figure 1) and Hillside Area, the precise location of which cannot be determined from the report. Elliott (32 x 8 x 10 cm), Sherman (23 x 8 x 9 cm), cat (60 x 25 x 30 cm), breakback and pit traps (60 cm deep and 35 cm in diameter) were used. The bait used and the number and types of trap set in each area are not given but in a total of 400 trap-nights 5 *Sminthopsis murina*, 5 *Tarsipes spencerae*, 12 *Rattus fuscipes*, 15 *Mus musculus* and 19 reptiles were captured. No Dibblers were trapped.

March 1970.—Burbidge (pers. comm.) trapped for 4 nights from the 12th in areas C and D (Figure 1). Twenty Elliott traps (32 x 8 x 10 cm), were set in each area. A bait containing peanut paste, sultanas, rolled oats and bacon was used. The only mammals caught were *Mus musculus* and *Rattus fuscipes*.

November 1975.—With the objectives of obtaining a pair of *A. apicalis* for further laboratory studies of the reproductive biology of the species and of determining the distribution of the animals at Cheyne Beach the author trapped in 4 areas over a five-day period commencing on 25th November. Both small (16 x 5 x 6 cm) and large (23 x 8 x 9 cm) Sherman traps baited with bacon and peanut butter were used.

Twenty large Sherman traps were set on 3 consecutive nights and thirty on the fourth night (a total of 90 trap-nights) in the known

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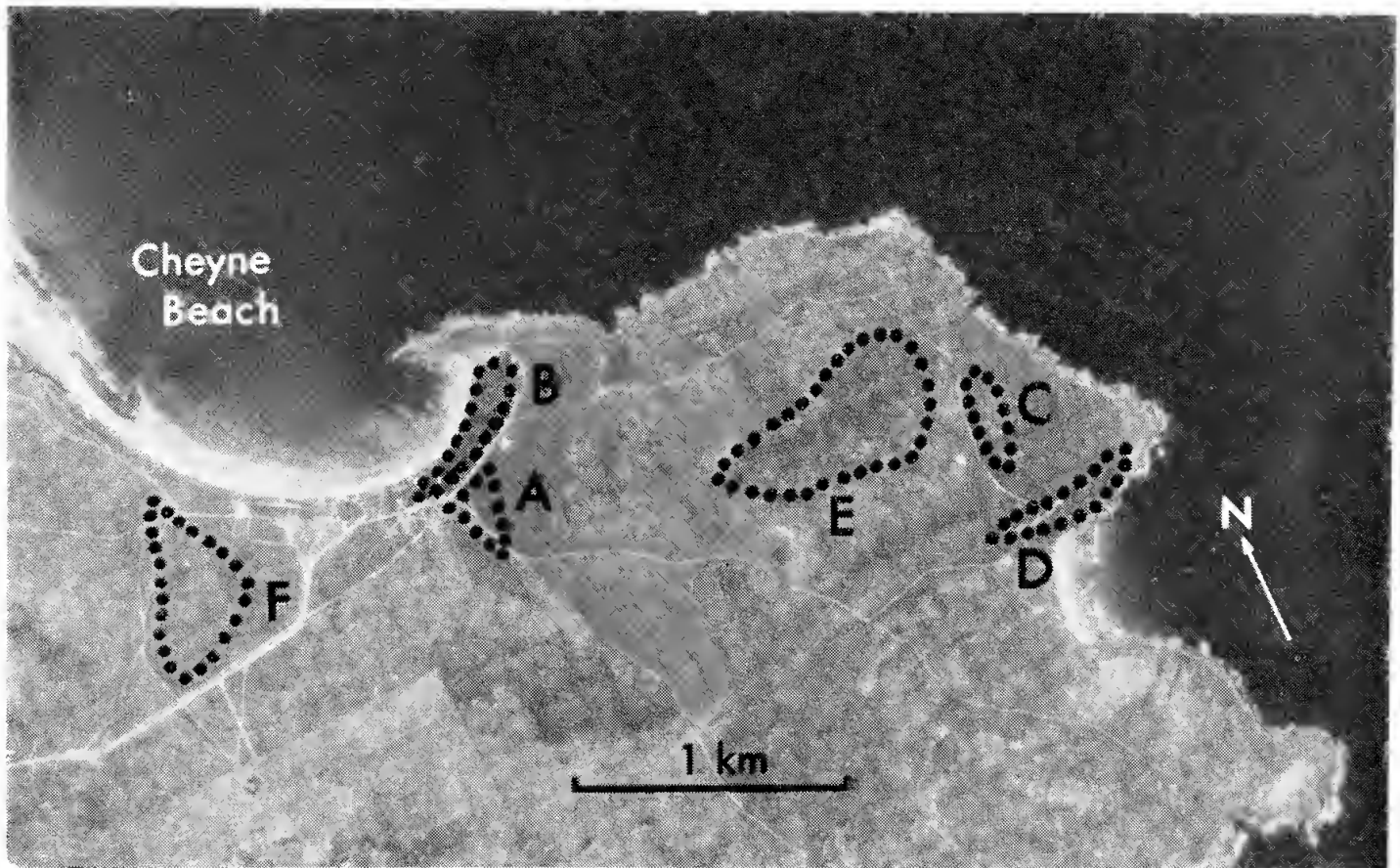


Figure 1.—Aerial photograph of locality 1 (Cheyne Beach) showing the six trapping areas (A, B, C, D, E and F). Commonwealth of Australia Air Photograph, 1971.

Dibbler locality (area A, Figure 1). Three *A. apicalis*, 8 *Rattus fuscipes* (minimum of 3 individuals) and 1 lizard were trapped. Trapping success for *A. apicalis* was approximately 3%. Two *A. apicalis*, one male (number 11) and one female (number 12) were captured on the first night of trapping at trap sites approximately 200 m apart. A second female (number 13) was trapped on the second night at the same trap site as female 12. The animals were not in breeding condition when captured; the male was not showing spermatorrhea and there were no young in the pouches of the two females. The body weight and pes length of each of the animals was as follows:— male 11, 60 g, 25 mm; female 12, 48 g, 24.5 mm; female 13, 73 g, 24.5 mm. Examination of the pouches of the females suggested that female 12 had not previously reared a litter (pouch fur pale, nipples minute) and was therefore probably less than one year old, while female 13 had reared a litter (pouch fur reddish-brown, nipples slightly elongated) and was more than one year old. Male 11 was estimated, by comparison of the body weight with that of laboratory maintained males of known age (Woolley 1971), to be less than one year old.

No Dibblers were captured in the 3 other areas in which trapping was carried out. In area D (Figure 1) no animals were captured in a total of 55 trap-nights over 2 consecutive nights using small Sherman traps. In area E (Figure 1) 1 *Rattus fuscipes*, 1 *Isoodon obesulus* and 3 lizards were captured in a total of 60

trap nights over 2 consecutive nights using large Sherman traps. The bandicoot, *I. obesulus*, which was found dead in the trap on 26th November, was a female with 2 young in the pouch. The three were lodged in the Western Australian Museum (numbers M14364-66). In area F (Figure 1) 50 small Sherman traps were set for 1 night only. One *Mus musculus* and 1 lizard were trapped.

Trapping at other localities

Trapping was carried out by the author at 5 other localities in the vicinity of Cheyne Beach in November and December, 1975 and, following the report of a specimen of *A. apicalis* brought in by a cat on a farm near Jerdacuttup, at another 4 localities in February, 1976.

The owners of the cat, Mr. and Mrs. Goldfinch, who were presented with the dead Dibbler at their house on 24th January, 1976, lodged the specimen in the Western Australian Museum (number M13997). The specimen, which has been examined by the author, is an adult male with a body weight (in spirit) of 95 g and a pes length of 27 mm. Histological sections of one testis and epididymis have been prepared and, although the animal had been frozen before preservation in alcohol, spermatozoa could be recognised and were present in both the testis and epididymis.

Large and small Sherman and Elliott traps (see above for dimensions) were used in the 1975 trapping period; in 1976 only large Sherman

and Elliott traps were used. The traps were baited with bacon and peanut butter.

Location and reserve numbers of the localities in which trapping was carried out are from Western Australian Government Department of Lands maps.

“Bulla Park” (Plantagenet Location 5310)—Locality 2, Figure 2.—Twenty large Sherman traps were set each night on 26th and 27th November on the road reserve adjacent to the property “Bulla Park” on Manypeaks Road. One *Rattus fuscipes* was trapped.

Off Bluff Creek Road (Reserve No. 30033—Mining)—Locality 3, Figure 2.—Trapping was carried out for 3 nights on 29th, 30th November and 1st December at this locality. In a total of 278 trap nights (131 using small and 147 using large Sherman traps) 3 *Rattus fuscipes* were trapped.

“Bluff Creek” (Plantagenet Location 6502)—Locality 4, Figure 2.—Twenty small and 20 large Sherman traps were set on the night of 2nd December. No animals were trapped.

“Umagalee” (Plantagenet Location 6481)—Locality 5, Figure 2.—No animals were trapped in a total of 96 trap-nights, using large Sherman traps, on the nights of 2nd and 3rd December.

Off Cheyne Road (Vacant Crown Land between Plantagenet Location 6501 and coast)—Locality 6, Figure 2.—Using 40 small and 40 large Sherman traps, a total of 160 trap nights in this area on the nights of 2nd and 3rd December yielded 2 *Rattus fuscipes* and 1 male *Isoodon obesulus*.

Tamarine Road—Locality 7, Figure 3.—Forty Sherman traps were set along 1.6 km of the road reserve, and 50 Elliott traps in the adjoining property (Oldfield Location 829). In a total of 260 trap-nights over four consecutive days from 18th February, 25 *Rattus fuscipes* (minimum of 12 individuals), 2 lizards and 1 frog were captured.

Flora and Fauna Reserve No. 31128, Jerdaccuttup North Road—Locality 8, Figure 3.—Fifty Elliott traps were set for 3 nights from 20th February. Three *Mus musculus* and 2 lizards were trapped.

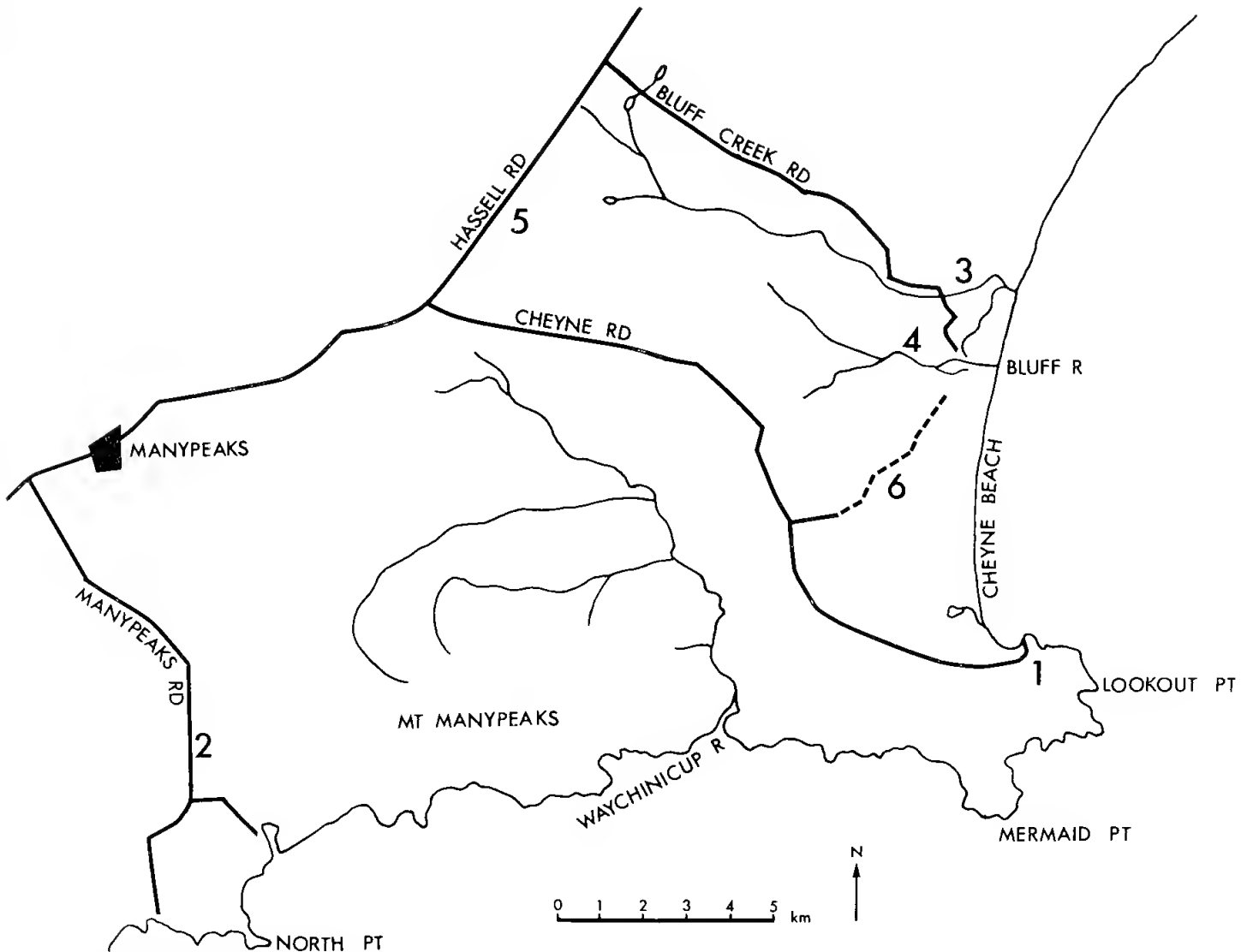


Figure 2.—Map showing the 6 localities in which trapping was carried out in the Cheyne Beach region in the south of Western Australia. Drawn from W.A. Department of Lands 1 inch to 1 mile maps.

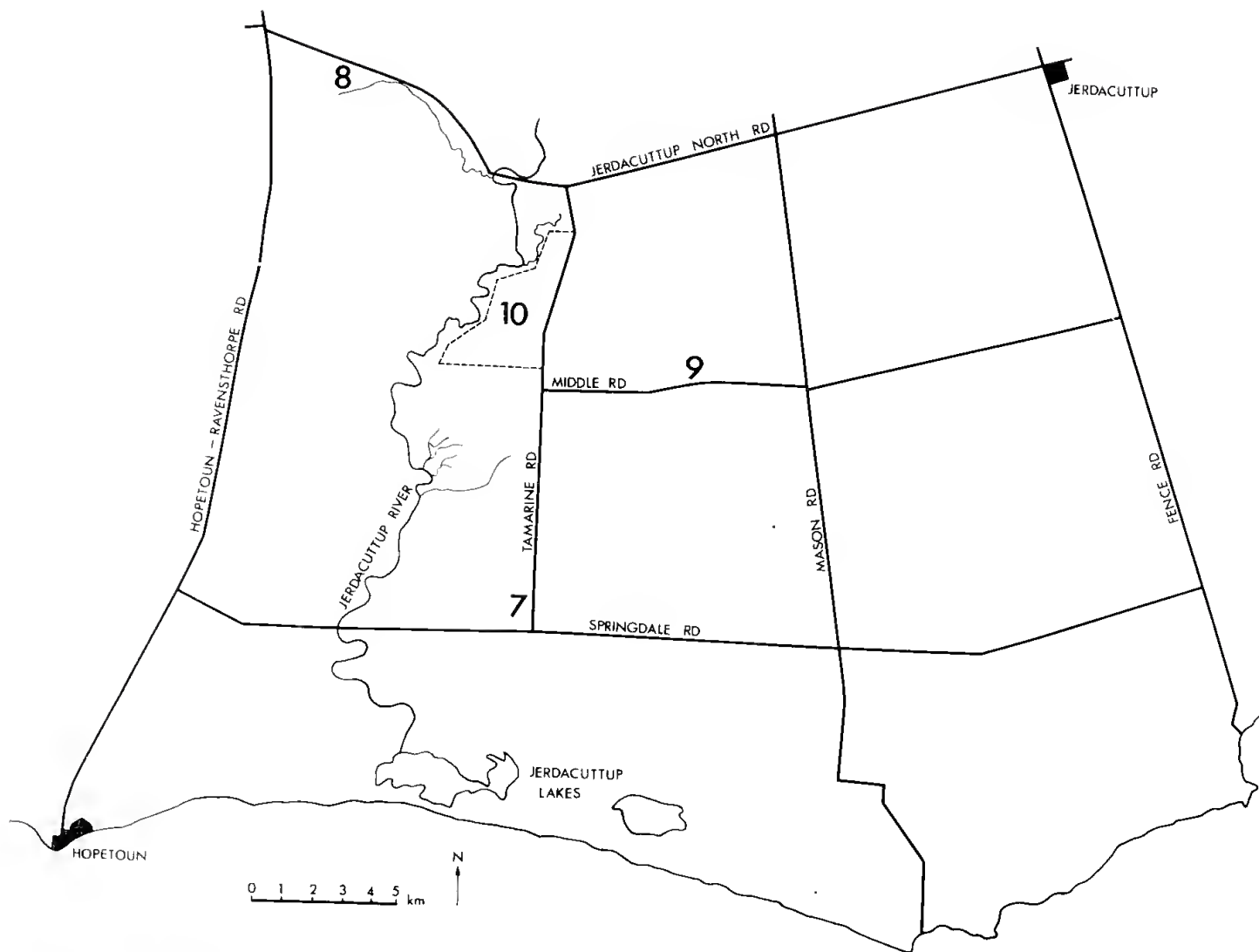


Figure 3.—Maps showing the 4 localities in which trapping was carried out near Jerdacuttup, in the south of Western Australia. Drawn from W.A. Department of Lands 1 inch to 1 mile maps.

Government Requirement Reserve No. 28110, Middle Road—Locality 9, Figure 3.—Forty Sherman traps were set on the nights of 21st and 22nd February along part of the western and southern boundaries of this block. One *Mus musculus* was trapped.

“Slieve Donard” (Oldfield Location 826) and adjacent land—Locality 10, Figure 3.—In this locality trapping was carried out in the five areas shown in Figure 4. Areas A and B are parts of the only two remaining areas of uncleared land on “Slieve Donard”. Area C is part of the Jerdacuttup River Reserve; area D, Crown Land at the northern boundary of “Slieve Donard” and area E, the road reserve at the entrance to “Slieve Donard” on Tamarine Road. Sherman traps were used in all areas, and in area C Elliott traps also were used.

No animals were caught in areas A (95 trap-nights over 5 consecutive nights from 18th February, B (120 trap-nights on the 18th, 19th, 23rd and 24th February), D (70 trap-nights on 23rd, 24th February) or E (20 trap-nights on 21st, 22nd February). In area C, 1 *Rattus fus-*

cipes, 2 *Mus musculus* and 2 lizards were caught in 203 trap-nights over 5 consecutive nights from 18th February.

Choice of the trapping localities

A botanical survey of area A at Cheyne Beach where Morcombe (1967) rediscovered the Dibbler was carried out in 1970 by Butler (unpublished report, Western Australian Department of Fisheries and Wildlife). The species listed for the area are *Banksia attenuata*, *B. baxteri* and *B. coccinea*, to a height of 2.5 m; *Agonis hypericifolia*, *A. linearifolia*, *Adenanthos cuneata*, *Beaufortia micrantha*, *Cassytha* sp, *Jacksonia spinosa* and *Phyllota barbata* to a height of 1.2 m and, in the undergrowth, *Anarthria gracilis*, *Andersonia caerulea*, *Burchardia umbellata*, *Calothamnus gracilis*, *Casuarina humilis*, *Dasypogon bromeliaefolius*, *Daviesia juncea*, *D. polyphylla*, *Haemodorum spicatum*, *Hakea ruscifolia*, *Hibbertia triandra*, *Hypocalymma strictum*, *Isopogon longifolius*, *Johnsonia lupulina*, *Lepidosperma* sp, *Leptocarpus* sp, *Leucopogon* (4 species), *Lobelia tenuiflora*, *Lysinema ciliatum*, *Melaleuca striata*,

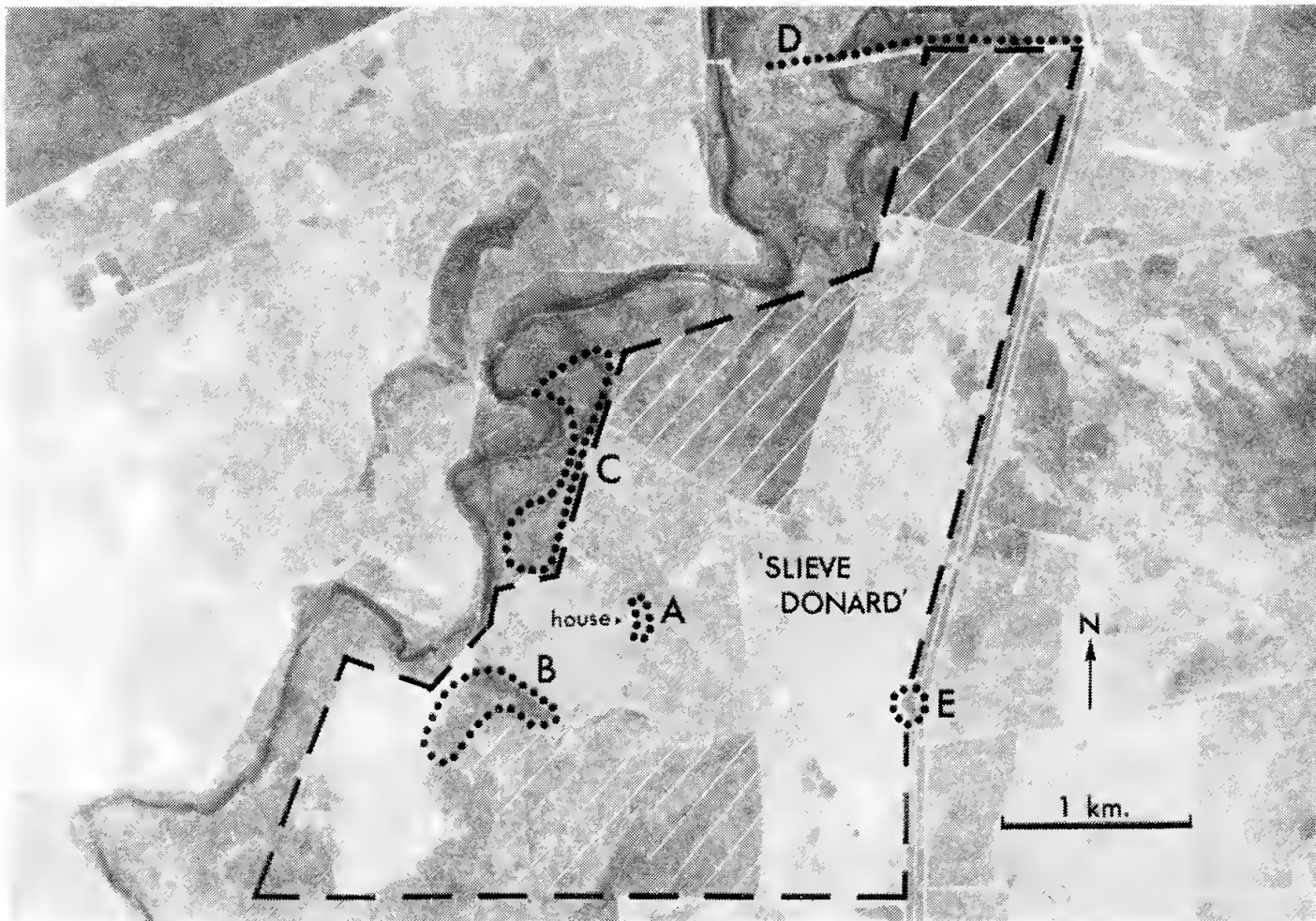


Figure 4.—Aerial photograph of locality 10 ("Slieve Donard" and adjacent land) showing the 5 trapping areas (A, B, C, D and E). Commonwealth of Australia Air Photograph, 1971. More land (indicated by diagonal white lines) has been cleared since this photograph was taken.

Petrophile longifolia, *P. rigida*, *Pimelea longiflora*, *P. rosea* and *Stylidium scandens*. The vegetation is very dense and the ground litter thick, the area not having been burnt for many years. Figure 5 shows the appearance of area A at the site of capture of male 11 in November 1975.

Much of the surrounding countryside was burnt in 1966 (Morcombe 1967) and is now largely covered by lower and less dense vegetation than is present in area A. An exception is the "Coastal Strip" (area B) in which the species listed by Butler are *Acacia decipiens*, *Agonis flexuosa*, *Banksia occidentalis*, *Hardenbergia comptoniana*, *Lepidosperma gladiatum*, *Oxylobium lanceolatum*, *Rhagodia baccata*, *Sollya fusiformis* and *Spyridium globulosus* to a height of 2.5 m; *Agonis linearifolia*, *Beaufortia micrantha*, *Muehlenbeckia adpressa*, *Melaleuca striata* and *Scirpus nodosus* to a height of 1.2 m. Areas C, D, E and F are patches of slightly taller and denser vegetation amid the generally low vegetation surrounding areas A and B. The composition of the flora in these areas has not been analysed.

Because Dibblers have only been trapped in the one area at Cheyne Beach which has very dense vegetation dominated by species of *Bank-*

sia a search was made in the vicinity of Cheyne Beach during November and December 1975 for other localities with similar vegetation. Three localities (3, 5 and 6) were selected and, superficially, one of these, locality 3, appeared to be similar to the known Dabbler habitat. Here the banksias extended southwards for about 1 km from the point of access on Bluff Creek Road in a narrow zone along the foot of a ridge. At "Umagalee" (locality 5) trapping was carried out in an approximately 200 ha block of uncleared land adjacent to Flora and Fauna Reserve No. 27157 and Waychinicup River Catchment Area Reserve No. 29883. Locality 6 on Crown Land north of Cheyne Road, was a small area on a hillside between cleared farm land and a swamp.

In addition to these 3 localities some trapping was carried out in 2 others in the vicinity of Cheyne Beach. Morcombe suggested locality 2 ("Bulla Park"), a small area of sandplain on which banksias were growing. Access to the area could not be arranged so trapping was only carried out on the fringe area road reserve. Locality 4 was a small area on "Bluff Creek" where the owner, when clearing the land some years previously, had caught an animal which he thought might be a Dabbler. When shown a

Dibbler he was sure that the animal he had found was not the same, so trapping was discontinued after one night.

Choice of the trapping areas near Jerdacuttup was largely determined by the presence of uncleared land. Trapping was carried out in all areas of uncleared land on or immediately adjacent to the farm "Slieve Donard", on which a Dibbler was brought in by a cat, regardless of the type of vegetation. In addition to these areas three other localities in the vicinity were selected. Two (localities 8 and 9) were selected because they were sizeable areas of Crown Land with vegetation representative of the patches remaining in much of the largely cleared surrounding countryside. The third (locality 7) was selected because the vegetation had the same characteristics as that in the known Dibbler habitat, the tall dominant *Banksia* species here being *B. baxteri* and *B. speciosa*.

Discussion

Only 7 *A. apicalis* have been trapped since the species was rediscovered in 1967, and the only known habitat is one small area of scrub situated very close to a fishing settlement and camping area. On four of the five occasions when traps were set in this area (A) Dibblers were caught; specimens being obtained in January,

April and August 1967 and again in November 1975. The animals were caught in two types of traps, one of special design by Morcombe, and the larger sized Sherman trap. Although Butler was not using Sherman traps his failure to trap Dibblers in the area in late January and early February 1970 cannot be readily explained. Elliott traps, which are of only slightly greater dimensions than the large Sherman traps, would appear to be equally suitable for trapping the animals. Trapping success, which could only be calculated for 3 of the successful trapping periods, was low, the maximum being achieved by Morcombe (5%). It is possible that the small Sherman traps are not large enough for the animals to enter readily and this may have been a contributing factor to the lack of success in catching Dibblers in areas D and E, locality 1 in November 1975, when only small Sherman traps were used.

At Cheyne Beach *A. apicalis* appears to be restricted to one small area (A). None have been caught in any of the other 5 trapping areas in the locality. The vegetation of area A is different from that in the other areas. Here the *Banksias* are taller and denser than elsewhere, and the ground litter thicker. Morcombe (1967) has commented on the ability of the Dibbler in captivity to climb, and to feed upon the nectar and possibly the insects attracted by the nectar



Figure 5.—Dibbler habitat (area A at Cheyne Beach). The photograph shows the part of the area in which male 11 was captured.

of *Banksia* flowers. He has also noted their habit of rapidly burrowing beneath loose leaf litter when disturbed. These observations, together with those on the vegetation of the various trapping areas in the Cheyne Beach locality, suggest that *A. apicalis* may be dependent on the type of habitat found only in area A. If this is so then there is no obvious explanation for the lack of success in trapping Dibblers in locality 3, near Cheyne Beach, where the vegetation showed a remarkable similarity to that in area A, assuming that the species was widespread prior to the clearing of large areas of land.

The habitat of the Dibbler in the Jerdacuttup region remains unknown. Despite an intensive trapping effort (over 1 000 trap-nights) covering all areas of uncleared land on or adjacent to the farm on which a specimen was brought in by a cat, and in other nearby localities, no Dibblers were captured. One possible explanation for the lack of success may be found in the timing of the trapping in relation to the breeding season. In the related species, *A. stuartii*, changes in trapping success throughout the year have been correlated with breeding activity (Woolley 1966). For this species trapping success was highest (about 15%) in the 2 to 3 months before the breeding season, and it declined to about 5% as the mating period approached. *A. apicalis* is known to mate in the laboratory in March and April and the little available evidence suggests that mating also occurs during this time in the field (Woolley 1971). Trapping in late February might therefore be expected to be less successful than in

earlier months in relation to the breeding season. Further attempts to trap the Dibbler in the Jerdacuttup region should therefore be made at another time of the year. Further, although few comparative data are available, *A. apicalis* appears to be more difficult to trap than *A. stuartii* and it may be necessary to devise new trapping methods for greater success.

Acknowledgements.—The author is grateful to the Department of Fisheries and Wildlife, Western Australia for permission to trap and collect *A. apicalis*, and for making available a vehicle in February, 1976. I wish to thank Dr. Marilyn Renfree and Mr. R. Young of Murdoch University for assistance with the trapping at localities 5 and 6 in December, 1975 and Dr. A. A. Burbidge and Mr. W. K. Youngson of the Department of Fisheries and Wildlife for assistance in February, 1976. I also wish to thank Mr. W. Dunlop, Mr. G. White, Mrs. Boothey and Mr. and Mrs. I. Goldfinch for permission to trap on their properties. Special thanks are due to Mr. and Mrs. Goldfinch for the hospitality extended to Dr. Burbidge, Mr. Youngson and the author at their farm in February. Dr. Burbidge kindly commented on the manuscript. Financial support for the work was provided by the Australian Research Grants Committee.

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16.—Distribution and function of resins and glandular hairs in Western Australian plants

by B. Dell¹

Manuscript received 22 June 1976; accepted 19 October 1976

Abstract

The taxonomic distribution of glandular hairs and resins is documented. Resinous plants are prevalent in some genera within the Mimosaceae, Euphorbiaceae, Sapindaceae, Boraginaceae, Dicrastylidaceae, Lamiaceae, Myoporaceae, Solanaceae, and Goodeniaceae. With few exceptions there is a correlation between surface resin and glandular hair distribution. The genus *Eremophila* is discussed as representative of a resinous, arid genus. Some properties of the leaf resins of *Beyeria viscosa* and *Eremophila fraseri* are discussed in detail. Resins may have a function in reducing water loss by increasing resistance to cuticular transpiration and by reducing leaf temperature by increasing radiation reflectance from the leaf.

Introduction

A systematic treatment of glandular hairs and leaf resins in Western Australian plants has not been attempted previously. Interest in resin formation in some species (Dell and McComb 1975) and the possibility that plant resins may be of use in difficult taxonomic groups (Dell 1975) led to an investigation of the relationship between glandular hairs and surface leaf resins.

The significance of resins in plants has remained an enigma, proposed functions having little experimental proof. In *Beyeria viscosa* the distribution of the resin on the leaf surface varies according to leaf maturity and is closely tied to the early stages of glandular hair formation (Dell and McComb 1974). Incidental observations that this pattern of resin distribution could be altered by temperatures not lethal to some plants, led the author to evaluate the possible importance of the resin in increasing reflectance of light from the leaves. Pearman (1966) has indicated the importance of surface features such as hairs and scales in increasing reflectance. Slatyer (1964) and Waggoner (1966) have noted that the possession of shiny leaf surfaces could probably reduce the heat load by 10-15% under stress conditions. This factor together with the high heat resistance of some Western Australian plants (e.g. up to 59°C., Grieve and Hellmuth 1968) could be of importance to plants subject to irregular and often prolonged droughts.

Distribution of glandular hairs and resins

Collections of plants bearing resins and/or glandular hairs were made in the field. Voucher specimens are housed in the University of Western Australia (UWA) (see Appendix I). Sections

of fresh, preserved and in some cases, dried herbarium material, were examined and types of trichomes and their distribution recorded. The results are summarized in Table 1 and a few of the trichome types are illustrated in Fig. 1.

It is apparent that the majority of resinous genera are either woody or herbaceous dicotyledons. Nearly all plants with external resinous exudations bear glandular hairs beneath the exudate. It can be assumed that the glandular hairs in these species are implemented at least in resin secretion and perhaps also in resin synthesis. Exceptions include some taxa of the Myrtaceae, Celastraceae, Fabaceae, Poaceae and Haemodoraceae. The secretion sites of sticky exudates in some species of *Calytrix*, *Pileanthus*, *Psammomoya* and *Burtonia* need to be investigated further. There is a possibility that epidermal cells have a glandular function in these genera.

Not all plants with glandular hairs secrete resins (Table 1): some glandular hairs are pigmented (e.g. *Diplopeltis*), others produce volatile oils (e.g. *Anthocercis*), mucilages etc. In some plants glandular hairs are confined to the inflorescences (e.g. members of the Proteaceae); in others the trichomes are confined to the leaves, phyllodes and stems (e.g. *Acacia*) or may occur on both the leaves and the flowers (e.g. *Eremophila*, *Stylidium*).

Western Australian plants with resinous sheets are prevalent in some genera within the Mimosaceae, Euphorbiaceae, Sapindaceae, Boraginaceae, Dicrastylidaceae, Lamiaceae, Myoporaceae, Solanaceae and Goodeniaceae.

The genus *Eremophila* is an example that illustrates the prevalence of resinous species in dry habitats. Approximately 70% of the species occur in Western Australia where they are most abundant in the north and interior regions of the State. About 43% of these have resinous leaves and stems. The resin may exist as a continuous varnish over the leaves (e.g. *E. fraseri*, *E. serrulata*), be confined to one surface (e.g. *E. latrobei*), or exist as isolated patches (e.g. *E. angustifolia*, *E. duttonii*). This variation is reflected in the amount of resin expressed as a percentage of leaf dry weight in Table 2. Species with high resin yields usually have continuous sheets of resin, at least on the young leaves.

Surface resins in all *Eremophila* species are produced by glandular hairs. The nearly universal glandular hair has a short stalk with up to eight cells in the head. Many of the species

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Table 1

Occurrence and taxonomic distribution of glandular hairs and resinous plants in Western Australia. Voucher specimens are cited in Appendix I.

Family	Examples	Distribution of glandular hairs	Surface features*
Poaceae	<i>Triodia</i>	?	resinous
Orchidaceae	<i>Elythranthera</i>	leaves and stems	—
	<i>Caladenia</i>	inflorescences	—
Liliaceae	<i>Agrostocrinum</i>	inflorescences	—
Haemodoraceae	<i>Conostylis</i>	?	resinous leaf edges
Proteaceae	<i>Adenanthos</i>	inflorescences	viscid
	<i>Grevillea</i>	inflorescences	viscid
Chenopodiaceae	<i>Chenopodium</i>	leaves and stems	—
Nyctaginaceae	<i>Boerhavia</i>	leaves and stems	—
Gyrostemonaceae	<i>Didymotheca</i>	leaves and stems	resinous
Capparidaceae	<i>Cleome</i>	leaves, stems, and inflorescences	viscid
Droseraceae	<i>Drosera</i>	leaves and stems	specialized for insect-ivory
Byblidaceae	<i>Byblis</i>	leaves and stems	specialized for insect-ivory
Mimosaceae	<i>Acacia</i>	young leaves	viscid, resinous
Caesalpinaceae	<i>Cassia</i>	rare on leaves	—
Fabaceae	? Genus	leaves, stems and inflorescences	resinous
Tremandraceae	<i>Burtonia</i>	?	resinous
	<i>Tetratheca</i>	rare on young stems	—
Euphorbiaceae	<i>Bertya</i>	leaves and stems	resinous
	<i>Beyeria</i>	leaves and stems	resinous
	<i>Ricinocarpos</i>	leaves and stems	viscid
Celastraceae	<i>Psammomoya</i>	?	resinous stems
			—
Sapindaceae	<i>Diplopeltis</i>	mainly inflorescences	—
Malvaceae	<i>Dodonaea</i>	leaves and stems	resinous
	<i>Abutilon</i>	leaves and stems	—
	<i>Hibiscus</i>	leaves and stems	rarely viscid
Myrtaceae	<i>Encalyptus</i>	rare on leaves	?
	<i>Calytrix</i>	?	viscid
	<i>Pileanthus</i>	?	viscid
Plumbaginaceae	<i>Plumbago</i>	inflorescences, fruits	± viscid
Boraginaceae	<i>Halgania</i>	leaves and stems	resinous
Dicrastylidaceae	<i>Chloanthes</i>	leaves and stems	—
	<i>Cyanostegia</i>	leaves and stems	resinous
	<i>Dicrastylis</i>	leaves and stems	—
	<i>Lachnostachys</i>	leaves and stems	—
	<i>Newcastelia</i>	leaves and stems	viscid, resinous
Avicenniaceae	<i>Pityrodia</i>	leaves and stems	—
	<i>Avicennia</i>	leaves and stems	specialized for salt secretion
Lamiaceae	<i>Hemigenia</i>	leaves and stems	—
Solanaceae	<i>Prostanthera</i>	leaves and stems	resinous
	<i>Anthocercis</i>	leaves and stems	resinous
	<i>Nicotiana</i>	leaves, stems and inflorescences	viscid
Scrophulariaceae	<i>Gratiola</i>	leaves and stems	viscid
	<i>Stemodia</i>	leaves and stems	viscid
	<i>Verbascum</i>	leaves, stems and inflorescences	—
Orobanchaceae	<i>Veronica</i>	rare on leaves	—
	<i>Orobanche</i>	stems	viscid
Lentibulariaceae	<i>Utricularia</i>	rare on traps	specialized for insect-ivory
Myoporaceae	<i>Eremophila</i>	leaves, stems and inflorescences	resinous
Goodeniaceae	<i>Myoporum</i>	leaves and stems	resinous
	<i>Calogyne</i>	leaves and stems	—
	<i>Coopernookia</i>	leaves and stems	resinous
	<i>Goodenia</i>	leaves and stems	viscid, resinous
Stylidiaceae	<i>Scaevola</i>	leaves and stems	—
	<i>Stylidium</i>	inflorescences, rare on leaves	viscid
Asteraceae	<i>Brachycome</i>	leaves and stems	—
	<i>Helichrysum</i>	leaves and stems	—
	<i>Helipterum</i>	leaves and stems	—
	<i>Ixiolaena</i>	leaves and stems	—
	<i>Olearia</i>	leaves and stems	resinous
	<i>Pluchea</i>	leaves and stems	—

* resinous—leaf has a continuous or broken layer of resin. viscid—sticky; resin, when present, confined to glandular hairs, where the glandular hairs do not produce viscid or resinous material this is indicated as —.

which do not appear resinous, for example species with a dense tomentum of stellate or branched hairs, also have an understorey of stalked glandular hairs (Fig. 1). Large branched hairs with some glandular tips are scattered through the tomentum of similar but non-glandular trichomes of *E. leucophylla* and *E. turtonii*.

Distribution of resin on the leaf surface

Whilst observing *Beyeria* leaves under bright lights it was noticed that the surface of the leaf changed from matt-like to mirror-like in appearance (Fig. 2). It was possible to see reflection of images from the mirror surface. Leaves continued to grow after this transformation and presumably were not affected internally by the additional radiant heat. When heated in an oven it was found that at 55°C. the abaxial sheet of resin coalesces within two minutes. At 51°C. the youngest leaves form a sheet in about the same time but the half-expanded leaves take up to five minutes to achieve the same resin flow. Twelve minutes exposure at 44°C. causes the resin to run on young and mature leaves as at the higher temperatures. Resin, removed from the leaf surface, melts at about 48°C. to form a thick, viscous liquid.

The effect of radiant heat on the leaf surface causes the resin to become mobile and, on the younger leaves, the resin flows together on the abaxial surface and forms a continuous sheet with a smooth surface. On mature leaves the resin droplets are widely spaced and the effect of heat causes the resin to coalesce into 'rivers'.

The composition of the resin on the leaf surface is probably determined by genetic factors whereas the amount of resin on the leaf surface is a combination of genetic and environmental factors and is closely related to the distribution and abundance of glandular hairs. The distribution of the resin on the leaf surface is dependent on such factors as resin composition, amount of resin/unit area and surface topography.

If the resin is of adaptive value to the plant, it might be expected that plants growing under some stress conditions would produce more glandular hairs and hence more resin than plants growing under mesophytic conditions. New shoots of plants transferred from the field to glasshouses were always softer and had fewer glandular hairs than those at the time of removal.

Reflectance of light from leaves

The technique of Pearman (1966) was used. A Bausch and Lomb Spectronic 20 colorimeter with an integrating sphere-reflectance attachment was used for measuring the total reflected visible radiation from leaves. The colorimeter produces wavelengths from 340 to 620 nm in bands of 20 nm width, and these were directed onto the leaf with an angle of incidence of 0°. The reflectance spectrum from *Beyeria* leaves produced a maximum at 560 nm for both surfaces. Heated leaves showed a small increase in total reflectance especially towards 540 nm. However, for any one wavelength the difference was less than 5%. Removal of resin from the

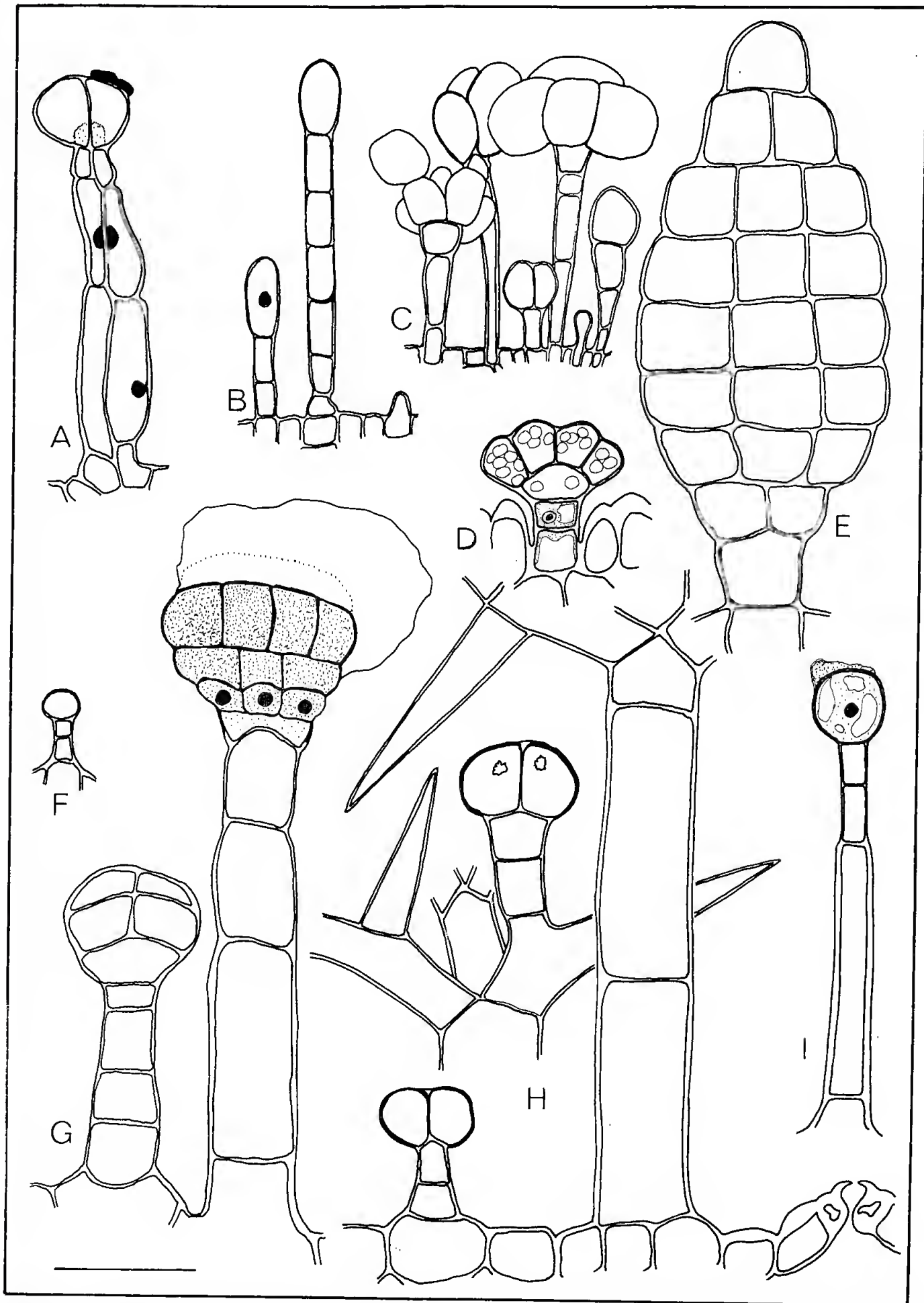


Figure 1.—Glandular hairs of some of the genera referred to in Table 1. A.—*Helichrysum rosea*. B.—*Grevillea eriostachya*. C.—*Acacia aneura*. D.—*Acacia glutinosissima*. E.—*Anthocercis littorea*. F.—*Scaevola canescens*. G.—*Scaevola glandulifera*. H.—*Eremophila leucophylla*, stellate and shortly stipitate glandular hairs are shown. I.—*Pityrodia bartlingii*. Length of bar 50μ .

leaf surface of *Eremophila fraseri* caused a considerable reduction in total reflectance from the leaf (Fig. 3). An increase in reflection of light by the resin layer decreases the amount entering the leaf and subsequently being absorbed.

It was originally thought that the mirror-like surface would reflect more light than the unheated surface. Reflectance from a surface, as opposed to reflectance from within a surface, is dependent on surface features alone. When

measuring total reflected light from a surface with an integrating sphere (see above) the specular (or mirror) reflectance could be close to diffused reflectance depending on the angle of incidence. The control *Beyeria* leaves have irregular-shaped resin deposits and for low angles of incidence, on leaves naturally held towards the vertical, a considerable amount of diffused reflectance could be directed into the leaf. The distribution and optical properties of the resin can be compared with glaucous and non-glaucous eucalypt leaves where the orientation and type of wax deposits affect the amount



Figure 2.—Effect of heating on the appearance of *Beyeria* leaves. Control is on the left.

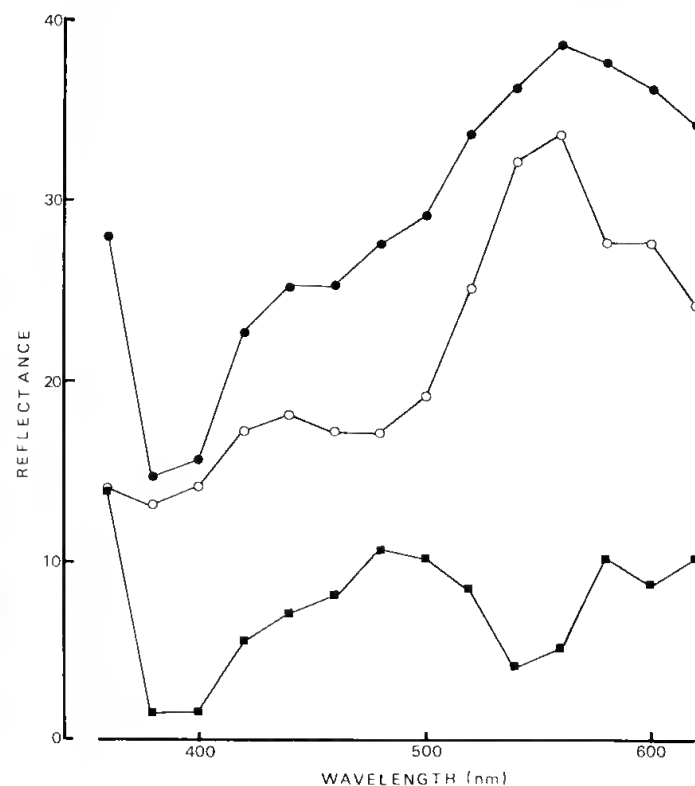


Figure 3.—Effect of resin on the reflectance of light from *Eremophila* leaves. (●—abaxial surface, ○—abaxial surface after resin wash, ■—difference between reflectance spectra of control and washed leaf. The graphs are for one leaf. Reflected radiation is expressed as a percentage of the reflectance from magnesium carbonate.)

Table 2
Resin yields of some *Eremophila* species

Species	Locality	Collection No.	Resin (% leaf dry wt.)	Distribution of resin on leaf surface
<i>alterifolia</i>	Sandstone	1015	4.5	isolated patches
<i>decepius</i>	Boulder	1060	18	sheet
<i>deupsteri</i>	Norseman	1066	10	broken sheet
<i>drummondii</i>	Boulder	1058	17	sheet
<i>duttonii</i>	Wiluna	1036	8	isolated patches
<i>fraseri</i>	Yalgoo	56	17	sheet
<i>foliosissima</i>	Agnew	1025	22	sheet
<i>georgei</i>	Agnew, Leonora	1022, 1051	17.5	sheet
<i>granitica</i>	Sandstone, Leonora	1013, 1048	29.5	sheet
<i>interstans</i>	Boulder	1057	22	sheet
<i>latifolia</i>	Agnew	1024	18	sheet
<i>metallicorum</i>	Leonora	1046	18	broken sheet
<i>miniata</i>	Menzies	1052	7	isolated patches
<i>platycalyx</i>	Barwidgee Station	1038	21	sheet
<i>saligna</i>	Norseman	1065	3	scarce over glandular hairs
<i>serrulata</i>	Leonora	1078	15	sheet
<i>scoparia</i>	Payne's Find, Boulder	1008, 1055	1.5	not resinous
<i>willsii</i>	Agnew	1027	12	broken sheet

of light reflected from the leaf (e.g. Cameron 1970). The surface construction of leaves can be important in the reflection of wavelengths other than those measured above. Gates and Tantraporn (1952) indicate that 80% or more of the infrared radiation is effectively reflected from the outer epidermal surfaces. Wong and Blevin (1967) showed that surface hairs and dry vesicular tissues were responsible for slightly higher infrared reflectances in several species. Surface features were shown by Pearman (1968) to reflect an appreciable proportion of the visible spectrum.

The distribution of the resin over the leaf surface is important if it is to be considered that the resin has a function in reducing water loss. Reduction in water loss by resins could be achieved in two ways. Firstly, the presence of a sheet of resin over the leaf surface must increase resistance to cuticular transpiration. Gardner (1968) considered that resinous leaf coverings in species of *Eremophila* protect the leaves from the drying influence of wind. Secondly, the presence of resin does not qualitatively alter the wavelengths of light available to photosynthesis though it may reduce the amount of light entering the leaf, e.g. in *Eremophila*. In this way transpiration could be reduced by a slight lowering of leaf temperature.

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Appendix 1

Voucher specimens

Except where stated otherwise all specimens are housed in the University of Western Australia and specimens are cited by accession numbers.

Triodia pungens 2203; *Elythranthera brunonis* 2202; *Caladenia discoidea* 2201; *Agrostocrinum scabrum* 2197; *Conostylis aurea* 2196; *Adenanthos meissneri* 2199, *A. venosa* 2200; *Grevillea criostachya* 2062, *G. excelsior* 2198, *G. petrophiloides* 2052; *Chenopodium plantaginellum* 2195; *Boerhavia repandra* 2194; *Didymotheca thesioides* 2193; *Cleome viscosa* 2192; *Acacia denticulosa* MURD 27, *A. glutinosissima* MURD 26, *A. kempeana* 2190, *A. ramulosa* 2189, *A. rossei* 2053, *A. tetragonophylla* 2188; *Cassia phyllodinea* 2180, 2181, 2182, 2183; *Burtonia scabra* 2179; *Beyeria drummondii* 2177, *B. leschenaultii* 2176; *Ricinocarpos velutinus* 2178; *Psammomoya choretroides* 2048; *Diplopeltis huegelii* 2175; *Dodonaea attenuata* 2206, *D. boroniaefolia* 2205, *D. bursartifolia* 2208, *D. caespitosa* 2207, *D. concinna* 2215, *D. filifolia* 2212, *D. inaequifolia* 2209, *D. larraeoides* 2210, *D. piniifolia* 2214, *D. parmiciifolia* 2213, *D. stenozuga* 2063, *D. viscosa* 2211; *Eucalyptus citriodora* MURD 28; *Calytrix glutinosa* 2173; *Pileanthus filifolius* 2172; *Plumbago zeylanica* 2171; *Halgania cyanea* DELL 127 (PERTH), *H. lavendulacea* DELL 167 (PERTH), *H. viscosa* DELL 84 (PERTH), *Halgania* sp. DELL 113 (PERTH); *Chloanthes coccinea* 2168; *Cyanostegia angustifolia* 2054, *C. lanceolata* 2055, *C. microphylla* 2056; *Dicrastylis micrantha* 987; *Lachnostachys bracteosa* 2170, *L. cliffonii* 2169; *Newcastelia viscida* 2057; *Pityrodia bartlingii* 2167; *Hemigenia divaricata* 2166; *Prostanthera eckersleyana* 2164, *P. grylloana* 2165; *Anthocercis aromatica* 2159, *A. littorea* 2217, *A. viscosa* 2610, DELL 1002; *Nicotiana occidentalis* 2161, *N. rosulata* 2162; *Verbascum virgatum* 2163; *Eremophila alternifolia* 2086, 2087, *E. angustifolia* 2088, 2090, *E. clarkei* 2091, 2098, *E. compacta* 2073, *E. decipiens* 2103, 2105, 2109, *E. delisseri* 2070, *E. drummondii* 2100, *E. duttonii* 2069, 2102, *E. eriocalyx* 2072, 2110, *E. exilifolia* 2111, *E. foliosissima* 2112, 2113, 2114, *E. fraseri* 2058, 2060, 2061, *E. freelingii* 2068, *E. georgii* 2115, 2119, 2125, *E. glabra* var. *viridiflora* 2050, *E. granitica* 2126, 2127, *E. hughesii* 2128, *E. interstans* 2075, *E. latifolia* 2131, *E. latrobei* 2065, 2130, *E. leucophylla* 2134, *E. longifolia* 2132, 2133, *E. macmilliana* 2066, 2135, 2136, *E. margarethae* 2071, *E. miniata* 2059, *E. oppositifolia* 2138, 2139, *E. platycalyx* 2140, 2141, *E. platythamnos* 2142, *E. punicea* 2074, *E. pustulata* 2143, 2144, *E. ramosissima* 2146, *E. saligna* 2147, *E. scoparia* 2051, *E. serrulata* 2148, 2149, *E. spathulata* 2150, *E. subfloccosa* 2151, *E. virens* 2049, *E. woollsiana* 2152, 2153, *E. youngii* 2067; *Myoporum deserti* 2158; *Calogyne berardiana* 2156; *Coopernookia polygalacea* 2085; *C. strophiolata* 2080; *Goodenia glandulosa* 2084, *G. pinatifida* 2079, *G. viscida* 2081; *Scaevola glandulifera* 2077, *S. restiaca* 2076; *Stylidium spathulatum* var. *glandulosum* 2204; *Brachycome* sp. 2155; *Olearia muelleri* 2047.

17.—Australites from northern Western Australia

by R. C. Horwitz¹ and D. R. Hudson¹

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Abstract

Recent discoveries of tektites in the Patterson Ranges and western Pilbara regions indicate that australites are more abundant in northern Western Australia than was previously believed. They include the compositional varieties of normal australites and philippinites, indochinites, and high-Mg tektites, which supports the existence of a NNW-SSE trending primary distribution pattern extending from the Philippines through northern Western Australia to southern Australia. The present distribution of tektites in Western Australia has been influenced by geomorphological features. This has resulted in numerous tektite occurrences in areas such as the Eastern Goldfields, where concentration has occurred in playas, and relative scarcity of tektites in areas of fast drainage and dissection, such as the Ashburton River valley. Areas of sand cover or areas of recent sediment deposition also contributed to the apparent absence of tektites in northern Western Australia.

Introduction

Tektites are natural objects of silica-rich glass found in thousands on the surface of certain parts of the Earth. Baker (1959, p. 13) lists eight recognised true tektite provinces; those from Australia are designated australites and are believed to result from a single fall. Radiometric age data for australites are reviewed by Lovering *et al* (1972, p. 409) and the fall has been dated as about 700 000 years B.P. These authors also review (p. 408) and present new evidence concerning the relative age of the fall to geological and morphological features in the Quaternary.

The genesis of shapes and inner structures of australites is described and classified by Baker (1959). Their mode of preservation in present-day fields varies according to occurrences; i.e. well preserved in some scattered occurrences, to abraded pebbles in placer deposits and to dreikantered pebbles in desert areas of central Australia, such as the occurrences described by Johnson (1965) at Lake Wilson near the junction of the three states (W.A., S.A., N.T.). Australites have a strong mythological association for the Australian Aborigines of parts of Western Australia (R. C. Gould, pers. comm. 1965) and are found at aboriginal camp-sites and water holes, sometimes chipped and worked.

They occur most abundantly in the banks and on the floors of playas and internal drainage flats, where they are concentrated by drainage, in association with quartz pebbles and rocks of similar density.

Baker (1959, p. 31) estimates that 30 000 to 35 000 australites have been found. Cleverley and Dortch (1975, p. 243) refer to a "continental line of known occurrence" which they draw through about south of Geraldton to Lake MacKay and to south of Brisbane; this general northern boundary to the province (Figure 1) had been accepted following Baker (1959, p. 18). Cleverley and Dortch (1975) record that 23

occurrences of single australites exist north of this line in Western Australia; their paper discusses six australites found at archaeological sites of the eastern part of the Kimberley region.

Chapman *et al* (1964) studied specific gravities for tektites from Australia, Indonesia and Indo-China, grouping several tektite provinces under the heading Australasian tektites. Chapman and Scheiber (1969) established zones with varying chemical characteristics in Australasian tektites attributed by Chapman (1971) to a single fall erupted from Tycho (a Lunar Crater), with a spread on earth containing "streaks" of compositionally distinct tektites. This general spread differs from the distribution pattern accepted by Cleverley and Dortch (1975) in that it includes northern Australia, and in particular crosses northern Western Australia between about Exmouth and Derby.

This note is published to record that—(a) australite occurrences are more abundant in northern Western Australia than was previously believed; (b) in agreement with Chapman (1971) their distribution is best explained as primary in origin and related to NNW-SSE depositional streaks rather than to transport by man, as was believed by Cleverley and Dortch (1975); (c) to account for their relative absence from large areas of northern Western Australia; (d) to record some chemical compositions for northern Western Australian tektites and compare them to Chapman's model.

Australites in northern Western Australia

A minimum of nine australites, some intact, others worked, were found recently during exploration in the Patterson Ranges (Figure 1). A tektite was collected in 1974 near the mouth of the Sherlock River and some were found in the Teichmans-Pilbara townsite area (125 km ESE of Roebourne) during exploration in 1975 (M. J. Fitton, pers. comm. 1975). According to aboriginal stockmen, they occur in the Pilbara "north of Tom Price but are essentially absent from the Ashburton River valley". This river is conspicuous by its relative fast erosion compared to the areas of classical australite fields in the Eastern Goldfields.

The general dissection and fast drainage could have removed tektites and the surfaces on which they were deposited in most areas of the Pilbara and the Kimberley region of Western Australia and could contribute to their relative scarcity in these areas.

Our observations in central Australia suggest that tektites get concentrated, as in the Eastern Goldfields and Lake Nabberu-Lake Carnegie regions, in small playas, resulting from natural damming on areas of bedrock (the Lake Wilson occurrence, described by Johnson 1965, is a typical occurrence. Here one of us (RCH) in 1965, found 53 small australites in 25 minutes over 77 m² marginal to the salt pan, in optimum conditions, with the back to the sun, as recom-

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mended by Baker 1959, p. 29). They are, however, not found in such concentrated patches in playas in interdunal hollows where the catchment area is smaller. A combination of sand cover or erosion with removal to the ocean (or burial in coastal deposits) could be sufficient to produce the apparent absence of tektites in northern Western Australia.

Distribution of compositional groups of tektites

Chapman (1971) has described the geographic distribution of tektite compositional groups for the southeast Asia-Indonesia-Australia region.

He recognised a serious of compositional "streaks" with a general NNW-SSE trend. The most prominent of these in Australia are the high-Ca streak which extends from Alice Springs to the west coast of Tasmania, and the high-Mg streak which curves its way from the northern Philippines through Borneo and Java to cross the Australian coast between Exmouth and Derby and then extends SE towards Adelaide. These high-Mg tektites together with a ubiquitous population of normal australite-philippinites (some of which approach the high-Ca group) comprise the described tektite population of Western Australia. With the exception

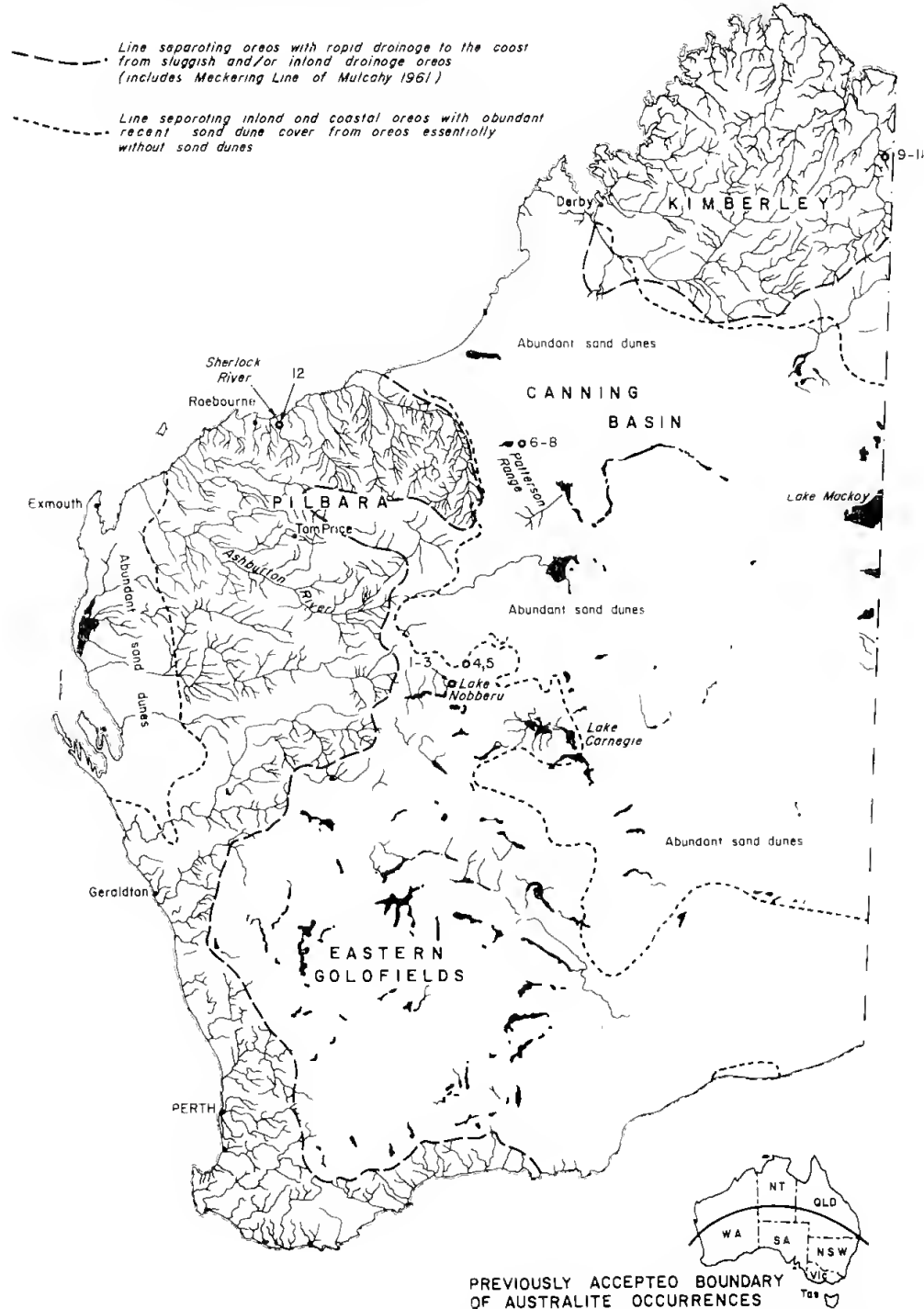


Figure 1.—Map of Western Australia showing geomorphological divisions that have influenced the present distribution of australites. The areas without fast erosion and without sand-dune cover equate broadly with Salinaland and Euclonia of Jutson (1950, p. 22). Nos. 1-12 indicate the location of the analysed tektites referred to in the text.

of one high-Mg tektite from the Pilbara, all previously analysed Australian tektites reported by Chapman (1971) come from below the line described by Cleverley and Dortch (1975).

Compositions of tektites

Twelve tektites from localities in central and northern Western Australia have been analysed using the electron microprobe. The analyses were made in order to compare the compositions of the new tektite occurrences with those predicted from Chapman's (1971) distribution model. All analyses were made on polished chips of tektites mounted in epoxy resin. Refractive indices were determined on the chips using a Raynor gem refractometer, and specific gravity determinations were made by hydrostatic weighing. Operating conditions for the electron microprobe are given in Table 1.

With the exception of analyses 7 and 8 the totals are generally low, and this combined with a low and variable sodium determination (probably due to the sodium loss under the focussed electron beam) renders the analyses semiquantitative. Nevertheless, the element ratios are believed to be significant, and enable a classification of the tektites to be made (Figure 2) into the compositional groups of Chapman and Scheiber (1969).

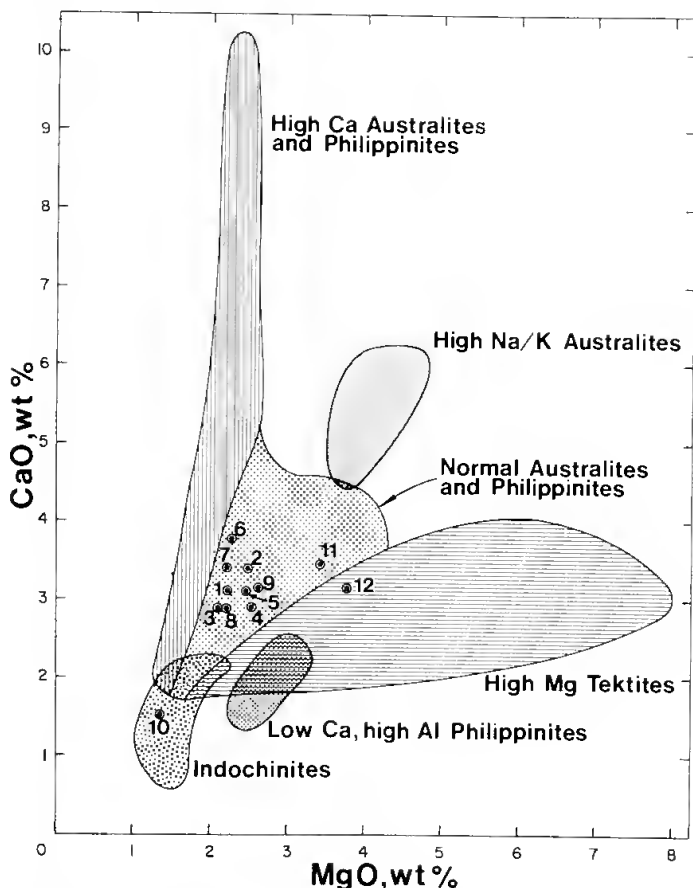


Figure 2.—Compositional grouping of tektites, based on the classification of Chapman and Scheiber (1969).

Analyses 1 to 9 are typical of the composition of "normal australites and philippinites" with MgO contents ranging from 2.13 to 2.57 weight percent. All three of the analysed tektites from

the Lake Naberu general area (including two tektites from the Canning Stock Route), three tektites from the Patterson Range and a tektite from the Kimberley district are thus of normal australite composition. Analysis 10 is of a tektite from the Kimberleys that falls within the "indochinite" compositional group, with low MgO and CaO contents of 1.27% and 1.50% respectively. Both analyses 11 (from Kimberleys) and 12 (from the Pilbara) are "high-Mg" tektites with MgO values of 3.38 and 3.73%.

The new analyses thus confirm the continuity of the high-Mg streak through the Pilbara-Canning Basin-Kimberley districts of Western Australia, and increase the known distribution of normal australite-philippinites to northern Western Australia.

The occurrence of an indochinite (analysis 10, from Miriwun) in the Kimberley district is puzzling. In Chapman's study this compositional group was found to be restricted to a small tear-shaped streak over southeast Asia. It is not inconsistent with Chapman's overall thesis that the indochinite distribution could extend to Australia, but the fact that the Miriwun tektite is a glass chip from an aboriginal site means that in this instance we cannot rule out the possibility of transport by man.

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Table 1

Chemical Analyses of Tektites

CSIRO No.	Western Australian Tektites*											Average Tektites†			
	1	2	3	4	5	6	7	8	9	10	11	12	High-Mg	Australite	Indochinite
SiO ₂	68.78	67.67	67.79	68.53	69.39	70.03	71.68	71.26	69.13	75.58	69.71	67.35	70.18	71.32	75.50
TiO ₂	1.04	0.84	0.94	0.93	0.94	0.71	0.68	0.73	0.83	0.69	0.80	0.74	0.71	0.81	0.70
Al ₂ O ₃	13.31	12.62	12.03	12.20	12.24	11.58	12.80	13.00	12.55	10.27	11.30	11.65	12.08	13.36	11.86
FeO	4.54	4.60	4.61	4.73	4.61	4.33	4.83	4.99	4.41	3.75	5.09	5.36	6.38	4.81	4.24
MnO	0.04	0.06	0.08	0.09	0.05	0.05	0.11	0.10	0.12	0.05	0.09	0.06	0.13	0.10	...
MgO	2.21	2.46	2.13	2.57	2.41	2.20	2.18	2.13	2.56	1.27	3.38	3.73	4.59	2.27	1.68
CaO	3.05	3.39	2.85	2.82	3.05	3.80	3.38	2.80	3.13	1.50	3.41	3.11	2.76	3.22	1.63
Na ₂ O	1.31	0.56	0.17	0.94	0.39	0.79	1.30	1.04	0.13	0.18	0.60	0.80	1.00	1.44	1.42
K ₂ O	2.68	2.29	2.32	2.39	2.34	2.08	2.31	2.46	2.32	1.94	1.91	2.00	1.91	2.46	2.55
Total	96.96	94.49	92.92	95.20	95.42	95.57	99.27	98.51	95.18	95.23	96.29	94.80	99.74	99.79	99.58
SG	...	2.44	2.44	2.46	2.46	2.46	...	...	2.45	2.40	2.46	2.45	2.49	2.45	2.36
RI	...	1.514	1.522	1.520	1.518	1.520	...	...	1.512	1.500	1.515	1.516	1.524	1.513	1.501

* Microprobe analyses—MAC probe; MAGIC IV correction program; Standards—Ti/Ti (LJF), Mn/Mn (LJF), Fe/Fe (LJF), Si/Si (PET), K/Nepheline (PET), Ca/Apatite (PET), Na/Nepheline (RAP), Mg/MgO (RAP), Al/Al₂O₃ (RAP). † Data from Chapman and Scheiber (1969).

Description of analysed tektites.

CSIRO No.	Location	Approx. Latitude South	Approx. Longitude East	Description
1	Nabberu	25° 33'	120° 33'	Abraded, elongate fragment of normal australite; 0.6 g.
2	Nabberu	25° 33'	120° 33'	Abraded, rounded fragment; normal australite; 0.5 g.
3	Nabberu	25° 33'	120° 33'	Abraded fragment; minor 20µm bubbles; normal australite; 1.2 g.
4	Canning	25° 34'	120° 48'	Fragment from elliptical normal australite; 18 x 12 mm; rare 20µm bubbles; 1.6 g.
5	Canning	25° 34'	120° 48'	Weathered hemispherical normal australite; some 40µm bubbles; 6.0 g.
6	Patterson	21° 46'	122° 17'	Abraded, complete "button" normal australite; 18 x 18 x 7 mm; 2.8 g.
7	Patterson	21° 46'	122° 17'	Abraded hemispherical normal australite.
8	Patterson	21° 46'	122° 17'	Ellipsoidal normal australite with aboriginal shaping chips, near Bwana R.H.; 38 x 35 x 20 mm; 28 g.
9	Gundarin Hill	16° 10'	128° 45'	Elliptical disc, normal australite; 28 x 21 x 9 mm; small aboriginal shaping chips; 6.0 g.
10	Miriwan	16° 18'	128° 42'	Small greenish glass chip of an indochinite from an aboriginal site; 11 x 8 x 3 mm; 0.2 g.
11	Monsmont	16° 18'	128° 43'	Chip of high-Mg tektite; 17 x 10 x 4 mm; 0.8 g.
12	Sherlock	20° 45'	117° 37'	Vesicular, rounded to acorn shaped high-Mg tektite; 20 x 18 x 18 mm; vesicles up to 1.5 mm diameter; 8.0 g.

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