

AUSGEO *news*



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**9-PAGE SPECIAL
ESTUARIES**

**BIGHT'S
ancient deltas**
ideal setting for oil & gas

*Oil
production*
IN DECLINE

PP 255003/00048

Also: Findings in southern Fairway, offshore basement defined, new acreage for petroleum exploration...

Editor Julie Wissmann

Graphic Designer Karin Weiss

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Geoscience Australia

GPO Box 378
Canberra ACT 2601 Australia

cnr Jerrabomberra Ave & Hindmarsh Dr
Symonston ACT 2609 Australia

Internet: www.ga.gov.au

Chief Executive Officer

Dr Neil Williams

Subscriptions

Dave Harris

Phone +61 2 6249 9333

Fax +61 2 6249 9982

E-mail dave.harris@ga.gov.au

Sales Centre

Chris Thompson

Phone +61 2 6249 9519

Fax +61 2 6249 9982

E-mail sales@ga.gov.au

GPO Box 378

Canberra ACT 2601 Australia

Editorial enquiries

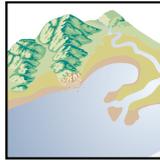
Julie Wissmann

Phone +61 2 6249 9249

Fax +61 2 6249 9977

E-mail julie.wissmann@ga.gov.au

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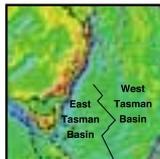


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Australia has enjoyed a high level of oil self-sufficiency, but total crude oil reserves are now at levels not encountered since the 1980s.

If current trends of discovery are maintained, production is expected to decline by 40 to 50 per cent in the medium term and then to steadily decline even further. See the article on page 17.

Photo: Arthur Mostead



GA an authority for *estuary & coastal waterway* management

Sediments and nutrients from catchments threaten Australia's coastal and marine ecosystems and their biodiversity. Suggestions on how to 'fix' the problem can affect residents of towns bordering waterways. Local councils and environmental managers therefore want to make informed decisions.

Geoscience Australia set up the Urban and Coastal Impacts program to provide reliable scientific data that helps in management decisions. For about five years industry and government groups have called on Geoscience Australia to advise on nutrient, sediment and toxicant concerns in waterways around Australia. Dr David Heggie, who leads the UCI program, describes the research being carried out.

Most of the sediments and nutrients that come from the catchment remain within the estuary, trapped in the underlying sediments. They are microbially recycled within the sediments and returned to the overlying waters. Nutrients seem to get trapped in the estuary in periods of low rainfall and tend to be flushed to the sea when the river is in flood.

Our work has identified that nutrients stored in sediments can drive algal blooms. Some algal blooms can be toxic, and result in poor ecosystem health and at times present threats to human health.

Our data are being used to develop estuarine management plans at regional and state levels. The findings are being used to reduce nutrient loadings from all sources into the estuaries—whether the nutrients come from the catchments or sources such as sewage treatment plants or industrial overflows.

Several industry clients and state and regional governments have been funding the work. These include Melbourne Water on Port Phillip Bay, and in Moreton Bay a consortium of Brisbane and shire councils, through funding from the Land and Water Resources Development Corporation. In Western Australia, research has been carried out in Wilsons Inlet and the Swan River estuary for the Waters and Rivers Commission. Work in Myall Lakes and Wallace Lake and other small estuaries in New South Wales was for the Department of Land and Water Conservation.

Important finding

In the course of our research we found that estuaries have an important safety valve, a naturally occurring process that allows an estuary to rid itself of anthropogenically (human) introduced nitrogen. Microbes or bacteria provide the safety valve.

If the microbial process (called denitrification) functions effectively in the sediments, it can manage the nitrogen. But if the microbial process is overloaded and its efficiency is reduced, the water and sediment quality will deteriorate in the estuary.

The microbes are called denitrifying bacteria. They are present in all estuaries, in fresh and salt water. They exist in environments where there is little to no oxygen, and most commonly at the sediment-water interface in estuaries. The bacteria have been around for millions of years.

Unique tracers

Our research began in the early 90s when we were identifying unique tracers or indicators of anthropogenic discharges of nutrients, sediments and toxicants into the sea. One client was Sydney Water who hired us to trace the dispersion of sewage in deep-water ocean outfalls.

Sydney's deep-water ocean outfalls vary from 40- to 80-metres water depth and discharge sewage through a series of rises in the pipeline at distances between two and four kilometres offshore. Sewage rises vertically in the water column because it is fresh and more buoyant than seawater. We found that methane in particular (which was produced by bacteria) was a unique tracer of sewage discharge. We could identify sewage as far south as Wollongong that appeared to be dispersed parallel to the coastline about four kilometres offshore.



We used the same equipment to trace the dispersion of produced formation water (PFW) from petroleum platforms in Bass Strait and on the North West Shelf. The former Australian Petroleum Exploration Association supported this research.

Field analysis

For sediment–nutrient surveys, field laboratories are set up on site and one or two small run-about boats place equipment on the sediments of the estuary. Generally the equipment is in place for up to 24 hours. It records data on in-situ loggers and collects samples for subsequent analysis in laboratories. Some data are interpreted on the spot to choose subsequent sites for investigation.

The surveys take up to three weeks, depending on the scope of the research. Three people run the sediment sampling, while two others continuously run lab analyses. Geoscience Australia laboratories and contractors analyse the data. The information is then summarised into a report and visuals (maps, 3-D models) for the client that commissioned the work.

Community interaction

We gather the data, and tell the clients what we found, provide an explanation for it and offer some management options. They integrate the geoscience information with their social and economic considerations and decide what they are going to do.

We often talk to the community, even though our client is likely to be an industry group or the local council rather than the community. We've also had open days at our field sites and made presentations to stakeholder meetings. Our reception is generally very positive and often 50 people come.

At one meeting a resident said, 'We don't want to see any more scientists running up and down our estuary. We'll solve the problem.'

'We've got a drag line and a tractor out there and we're going to open the entrance to the estuary and let all this stuff just run out to sea.'

Sometimes an issue divides the community. Often there are positive and negative benefits associated with a range of remedial options. We provide the scientific data and information about what is likely to happen with management options such as, 'If you open the estuary on the western side, the whole water circulation will change'. But we don't make the decision. Our role is to inform the decision-making.

Estuary audit

In 2000–2001, we were involved in taking an inventory of Australian estuarine conditions for the National Land and Water Resources Audit. Our component focused on mapping the distributions of different sedimentary environments in roughly 1000 Australian estuaries. This was laborious work, mapping from many thousands of aerial photographs and Landsat imagery.

By classifying all Australian estuaries, we have been able to identify those with similar behavioural properties (i.e., similar sedimentary environments, circulation pathways, ecology, and nutrient cycling processes). This information is useful for estuary management.

The data have been compiled into a series of management recommendations for understanding regional, estuarine and coastal waterway behaviours. The report was delivered to the Audit for government to identify future work programs to improve the quality of Australia's estuaries and coastal waterways.

Future directions

Next financial year the Urban and Coastal Impacts program will be divided into two main components. Work for the Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management will focus on converting scientific data into 'tool kits' for environmental managers. The other component (UCI Research and Development) is the sedimentology and biogeochemistry research that supports the CRC work.

'Tool kits' convert the science into indicators that can be readily understood and used by the community to identify an estuary's condition and monitor its ecological health.

The indicators include measurements of water quality (occurrences of hydrogen sulphide which kill fish), habitat integrity (mangroves and sea grasses have been removed from estuarine sediments), and eutrophication (enriched in nutrients, choked with green plants and weeds).

For the research component, UCI's geomorphologists will measure and map habitats and determine threats to ecosystem integrity. They will also look at sedimentation of estuaries, or how quickly estuaries are infilling from catchments and the sea. The geochemists will study areas that could become eutrophic because of nutrients, and identify toxicant input into estuaries.

Results of these science activities will be added to 'OzEstuaries', the web database managed by the UCI team, which has information about every estuary and coastal waterway in Australia.

For more information phone David Heggie on +61 2 6249 9589 or e-mail david.heggie@ga.gov.au

Move on mangroves

Mangroves may not be as beneficial to the environment as first thought. They are taking over other important habitats for plants and animals, such as salt marsh.

A recent workshop at the Homebush Bay Field Studies Centre on management strategies for coastal wetlands, focused on the rapid expansion of mangroves in estuaries of New South Wales. Researchers from NSW Fisheries and a number of universities described how mangrove areas have significantly increased at the expense of salt marsh since the 1930s (when the first aerial photographs of Australian estuaries were taken).

Salt marshes have a much greater diversity of flora and fauna than mangroves, and provide important habitats for a range of birds and juvenile fish. Loss of salt marsh to mangrove could mean a reduction in biodiversity.

Historical evidence

Historical evidence indicates that mangrove expansion is greater than that measured in time-series aerial photographs. For example, much of the foreshore of Sydney Harbour comprised tidal flats and salt marsh when first settled by Europeans.

Mangrove expansion appears to be related to large-scale clearance of land surrounding estuaries and the subsequent large influx of sediment into estuarine channels. It is also influenced by other factors including increased nutrient loads, subsidence of the salt marsh deposits, modification of estuary inlets, and a possible rise in sea level.

Local councils and environmental managers need to know the condition of the estuary before European settlement to decide whether to move on mangrove expansion. Sedimentological data can provide historical evidence of habitat changes, but very little has been gathered in Australian estuaries to date.

Geoscience Australia work

Geoscience Australia's Urban and Coastal Impacts group is involved in examining sediments from Australian estuaries (many of which are not covered by time-series aerial photographs). The sediment cores can be analysed for evidence of habitat change.

Also useful are the environmental management tools that Geoscience Australia is generating as part of its research. These include the spatial database the UCI is building about estuaries around Australia (OzEstuaries), habitat/facies maps, and the satellite imagery prepared by Geoscience Australia's National Mapping Division.

UCI staff Brendan Brooke, Emma Murray and David Ryan attended the coastal wetlands workshop. Workshop discussions have helped the UCI refine its investigations into estuary sedimentation, because mangrove expansion may be linked to changes in the rate and character of sediments that have been infilling estuaries over the past two centuries.

For more information phone Emma Murray on +61 2 6249 9019 or e-mail emma.murray@ga.gov.au

DATA BUILDS FOR OZ ESTUARIES

If you need reliable data or information about an Australian estuary or coastal waterway, go to the web and tap into 'OzEstuaries' before you look anywhere else (www.ozestuaries.org). It will save you time and effort.

OzEstuaries is a scientific database with information about more than 960 Australian estuaries and coastal waterways, including an assessment of their condition. The data were collected and compiled by Geoscience Australia as part of the National Land and Water Resources Audit.

OzEstuaries includes geometric data on each estuary (maximum length and width, perimeter, water area, entrance length and width), geomorphic classification (pristine, altered), areas of key sedimentary environments/habitats (mangrove, salt marsh, central basin, tidal sandbanks), and wave height and tidal range at the entrance. The database also includes sediment geochemical data where available. There is a Landsat image (jpg file) for most estuaries.

The web interface allows users to perform complex queries and view specific data from selected estuaries. Anyone can search the database for information. To ensure the data are current, user feedback is encouraged.

The database is a secure store for scientific information. It is managed and maintained by Geoscience Australia. State agencies and other researchers are being asked to submit data that add to its usefulness and make it comprehensive.

Some future developments that will expand the database include additional sedimentary, chemical and biological fields, and photographs. Also to be developed is a GIS component that incorporates sedimentary environment/habitat data. This will enable users to spatially correlate geomorphic data, geochemical data and satellite imagery.

CSIRO's Simple Estuarine Response Model (SERM) will be linked to the database so that 'real' data can be used. SERM predicts an estuary's response when there are changes to its inputs and conditions.

For more information or to provide feedback on data phone Craig Smith on +61 2 6249 9650 or e-mail craig.smith@ga.gov.au

Catchment clearing impacts on estuaries

Most of the 50 wave-dominated estuaries in south-western Australia have been modified or severely modified by human activity.¹ Increases in sediment, changes in sediment oxygen levels, and excessive plant and algal growth are serious environmental concerns for these estuaries.

Estuary sediments analysed

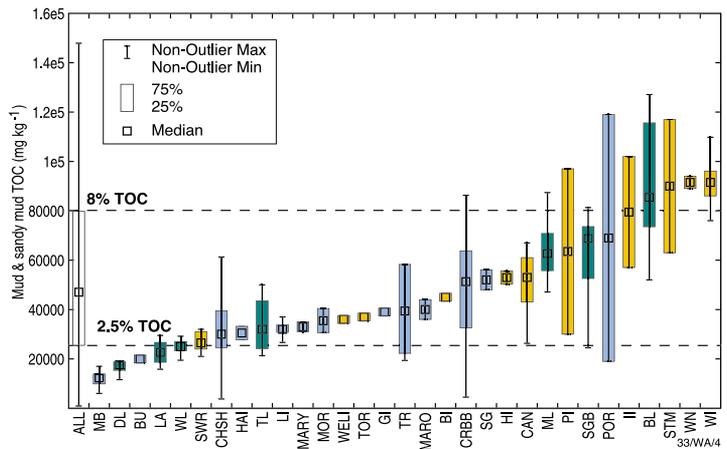
Geoscience Australia's Urban and Coastal Impacts (UCI) group collected grab samples of surface sediment from the central basins of 13 estuaries in south-western Australia. The sediment was analysed for major elements (including sulphur), nutrients (TN, total nitrogen & TP, total phosphorus), total organic carbon (TOC) and the $\delta^{13}\text{C}$ signature of the organic matter.

The sampled estuaries 'occupy a disturbance gradient', which is determined by how much native vegetation has been removed from the catchments.

Organic content elevated

Median sediment TOC (and TN) contents of some south-western wave-dominated estuaries (e.g. St Mary's, Walpole-Nornalup, Irwin and Wilson Inlets) are elevated in comparison to known TOC concentrations from different waterways around Australia (figure 1). Strangely, the sediment TOC contents appear to be inversely proportional to how much native vegetation has been removed (figure 2a), even though Loh and others showed that dissolved nutrient concentrations in streams are higher in cleared catchments.²

For example, Walpole-Nornalup is a relatively unmodified estuary with a median TOC content of approximately 10 per cent. The Swan River estuary, however, is severely modified and has a median TOC content of only two per cent (figure 2a).



▲ Figure 1. Mud and sandy-mud sediment TOC contents from Australian coastal waterways. The typical range varies from 25 500 to roughly 80 000 mg/kg⁻¹. Medians above the 8% TOC line are anomalously high.

The south-western, wave-dominated estuaries are shown in orange and New South Wales wave-dominated estuaries are shown in green. This data was assembled during the National Land and Water Resources Audit.³ Abbreviated names are as follows:

Moreton Bay (MB)	Moruya River (MOR)	Myall Lake (MYL)
Durras Lake (DL)	Wellstead Inlet (WELI)	Parry Inlet (PI)
Burnett River (BU)	Torbay Inlet (TOR)	St Georges Basin (SGB)
Lake Alexandrina (LA)	Gordon Inlet (GI)	Port River (POR)
Wallis Lake (WL)	Tomaga River (TR)	Irwin Inlet (II)
Swan River (SWR)	Maroochy River (MARO)	Burrill Lake (BL)
Crookhaven-Shoalhaven River (CHSR)	Beaufort Inlet (BI)	St Mary's Inlet (STM)
Hardy Inlet (HAI)	Clyde River-Bateman's Bay (CRBB)	Walpole-Nornalup Inlet (WN)
Tuggerah Lake (TL)	Spencer Gulf (SG)	Wilson Inlet (WI)
Lake Illawarra (LI)	Hammersley Inlet (HI)	
Mary River (Mary)	Canning River (CAN)	

The best explanation for these results at this time is that (mineral) sediment transport, enhanced by catchment clearing, dilutes the organic matter concentrations in the estuaries. This interpretation is substantiated by the TOC accumulation rate data (figure 2a). These limited data show that Swan River sediments have higher TOC accumulation rates than Wilson Inlet sediments, despite having much lower TOC concentrations (figure 2a).

Disturbed catchment findings

Another interesting finding is that the lowest sediment C:S (carbon to sulphide) ratios tend to be found in estuaries with the most disturbed catchments (figure 2b). Sediment sulphide results from sulphate reduction. In this process, sulphate (SO_4^{2-}) oxidises organic matter within oxygen-depleted zones in the sediment and produces hydrogen sulphide gas (H_2S). The H_2S then reacts with iron to form FeS and FeS_2 , thus increasing the sulphur content of the sediment. As more and more sediment becomes anoxic, sulphur contents increase and C:S ratios decrease.

Low C:S ratios ranging from 5.0–1.5 typify most of the south-western estuaries. They are indicative of anoxic sediment underlying oxic bottom waters.^{3,4}

But C:S ratios of less than 1.5 can be found in Hardy Inlet and the Swan-Canning estuarine system. These indicate anoxic sediment underlying anoxic bottom waters.^{3,4} Anoxic bottom waters are an environmental concern. Under these conditions more nutrients are released from sediments, and these nutrients promote algal blooms.



GA *nose* about smelly lake

Something stinks in Lake Wollumboola and local residents don't like it. The local council and the Department of Land and Water Conservation have commissioned Geoscience Australia's Urban and Coastal Impacts group to determine what processes in the lake are causing the smell.

The odour is hydrogen sulphide gas (H₂S or rotten egg gas) and the human nose can detect H₂S at very low concentrations (0.06 µM). H₂S can also dull silverware to a splotchy dark brown as it combines with silver to form silver sulfide.

Small towns affected

Lake Wollumboola is a saline coastal lake in the Shoalhaven region, 170 kilometres south of Sydney on the New South Wales south coast. The lake is broad, shallow and intermittently open to the ocean.

The lake's catchment is largely undeveloped except for the small town of Culburra on its northern shore. Sometimes the smell of rotten egg gas reaches Vincentia, 10 kilometres south of the lake. The lake is used for such recreation as swimming, sailing and bird watching.

Natural process

Estuarine sediments can produce H₂S through the action of sulphate-reducing bacteria.¹ The bacteria break down organic matter using sulphate (SO₄²⁻), which is available in the water, to produce H₂S, water and carbon dioxide. This only occurs under anoxic conditions. When oxygen is present, other sorts of bacteria will break down the organic matter using more easily available dissolved oxygen. (See figure 1 on page 8.)

Odour production in the lake is a natural process that has not been enhanced or caused by human activity.^{2,3} It has been suggested that odour events could be related to periods of destratification in the lake.³

Normally the bottom waters of the lake do not interact with the surface water (stratified) and H₂S is contained within the bottom waters.

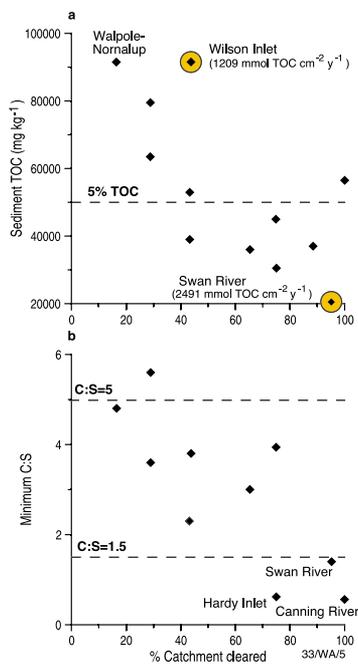
Lowered oxygen levels

Eutrophication is excessive plant and/or algal growth caused by nutrient run off from agricultural land and urban settlement. It is a major concern for some of the region's estuaries. Eutrophication may be responsible for the inferred lower oxygen status of the more disturbed estuaries, and for higher TOC accumulation rates in the Swan River estuary compared with Wilson Inlet.

However, increased sedimentation alone can influence sediment oxygen status. For example, high sedimentation rates can reduce the abundance of benthic macro-invertebrates that irrigate the sediment with oxygen as they burrow. High sedimentation rates can also reduce the contact time between organic matter and oxidising water, and promote sediment anoxia.⁵

Sediment studies continue

The UCI group continues its work on the impacts of sedimentation on south-western Australian estuaries in collaboration with the Waters and Rivers Commission of Western Australia. The work is part of a broader initiative (carried out with the states and the Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management) to develop geochemical indicators of sediment condition for use in monitoring Australian estuaries and coastal waterways.



▲ **Figure 2a.** Median TOC in sediment versus the percentage of cleared catchment. TOC accumulation rates are indicated for Wilson Inlet and the Swan River Estuary.

Figure 2b. Minimum C:S versus the percentage of cleared catchment

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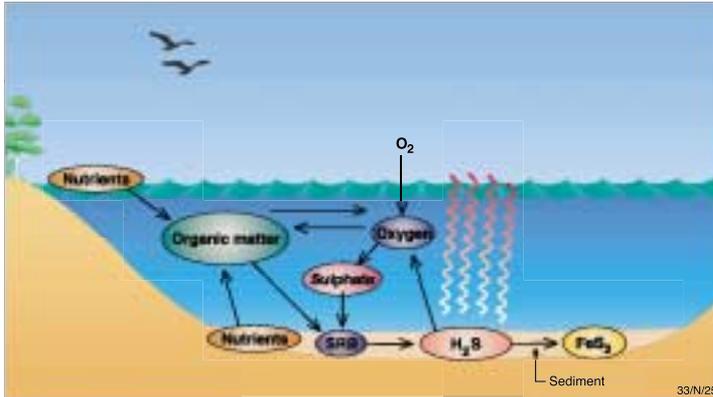
For more details phone Lynda Radke on +61 2 6249 9237 or e-mail lynda.radke@ga.gov.au



When there are strong winds, these layers are churned up (destratification) and H₂S is mixed with the entire water column and escapes to the atmosphere.

Lake surveyed

UCT's investigation is the first to measure H₂S concentrations in Lake Wollumboola. It confirms the presence of H₂S, and shows the distribution of H₂S concentrations across the lake (figure 2). The data allow sites with high H₂S concentrations to be compared with those of low H₂S concentrations, to determine what is influencing H₂S production.



▲ Figure 1. Diagram showing H₂S production in estuarine waters



▲ Figure 2. Aerial photograph of Lake Wollumboola showing H₂S concentrations in sediments measured at 12 sites. The circle size is proportional to the concentration of H₂S averaged over three depth intervals (0–2 cm, 8–10 cm and 16–18 cm). The H₂S concentration in μM is also shown.

During a four-day field survey in November 2001, the following were measured at three depths (0–2 cm, 8–10 cm and 16–18 cm) down cores taken from 12 sites that spanned the three different sedimentary facies of the lake (sandy marine delta, central mud basin and fluvial delta):

- bottom water and pore water concentrations of H₂S, Fe²⁺, Cl⁻, NH₄⁺, PO₄³⁻, SO₄²⁻ and SiO₂²⁻
- grain size, total iron (TFe), total sulphide (TS) and total organic carbon (TOC) concentrations of the solid phase.

Bacteria, reactive iron

Sulphate reduction occurs extensively in Lake Wollumboola, with pore water concentrations of H₂S up to 10 000 μM. (No wonder residents complain about the odour, when they can smell H₂S at concentrations of 0.06 μM.)

H₂S concentrations were generally highest in the central mud basin and fluvial delta (average about 3000 μM), and lowest in the marine delta (average about 158 μM). TOC, the fuel for sulphate reduction, was highest in the fluvial delta and central mud basin (~6.0 Wt%) and lowest in the marine delta (~1.3 Wt%).

Surprisingly, two sites in the central mud basin had relatively low levels of H₂S (<346 μM) but high rates of sulphate reduction, as indicated by the pore water sulphate to chloride ratios in the top 10 centimetres of sediment. Sulphate is depleted in relation to chloride, indicating that the sulphate is involved in a reaction—probably sulphate reduction.

The sediment of these two central basin sites had the highest concentrations of TS in the lake, indicating the presence of sulphide minerals. It seems that at these sites, the availability of reactive iron has resulted in extensive precipitation of H₂S as iron sulfides.

In Lake Wollumboola, high levels of TOC, a lack of oxygen and the availability of pore water sulphate, result in the bacterially mediated production of H₂S. However, in some places reactive iron appears to control the amount of free H₂S in sediment pore waters.

Conservation value

The natural ecological processes of the lake are sensitive to, but remain largely unaltered by human activity. The Healthy Rivers Commission Inquiry into Coastal Lakes considers the lake to be of very high conservation value.⁴ It proposes that Lake Wollumboola, along with eight other south coast lakes, be protected as reserves, and considered for World Heritage listing.

A Commission of Inquiry for Environment and Planning rejected a proposed subdivision for the lake's north-west shore (Long Bow Point).⁵ The Inquiry stated that the 'highest levels of protection from pollution or impacts are required for the important Lake Wollumboola to protect habitat and fauna, including threatened species'. Threatened species that use the lake include the Little Tern and the Green and Golden Bell Frog.

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For more information
phone Emma Murray on
+61 2 6249 9019 or e-mail
emma.murray@ga.gov.au ✉

Teachers: For ideas on how to use this article in the classroom see www.ga.gov.au/education

ESTUARY NITROGEN controlled with *nature's help*

The Urban and Coastal Impacts program has been examining the processes controlling nutrient cycling in sediments, and discovered that nature has its own way of dealing with nitrogen.

Nitrogen is an essential nutrient for life, and is thought to control plant productivity in estuaries and waterways. Too much nitrogen encourages algae and plants, eventually resulting in eutrophication (excessive plant growth and clogged waterways).

The environment (if allowed to function properly) has a mechanism for controlling nitrogen in sediments.

Sediment denitrification

Much of the organic matter (from the catchment, algae, macrophytes and faecal pellets) in estuary waters sinks to the bottom and is incorporated in the sediments. Bacteria in the sediments use oxygen and degrade the organic matter, releasing dissolved carbon, nitrogen, phosphorus and other elements into the sediment pore waters (water in the interstitial space between sediment grains).

Sediment denitrification occurs in sub-oxic environments that are found, for example, in oxygen-poor niches in surface sediments, and around irrigation tubes caused by burrowing animals. The denitrification processes use nitrates in sediment pore waters to convert solid nitrogen into nitrogen gas, which is lost to the atmosphere and therefore generally not available to encourage additional plant growth.

Denitrification efficiency

Denitrification efficiency depends on how much of the nitrogen that falls to the sediments is converted into nitrogen gas. When only 40 per cent (or less) of the nitrogen that reaches the sediments is converted into nitrogen gas, most of the nitrogen will be returned to the overlying waters as ammonia. Ammonia complements the nitrogen added from catchments and other sources.

Ammonia release will drive additional productivity and bring changes to the estuary. These include increased algal growth and decreased water clarity, incidences of toxic algal blooms, increased epiphytic growth on seagrass, and loss of human amenity value.

Decreasing denitrification efficiencies are early warnings of impending deteriorations in water and sediment qualities.

Measuring denitrification

One way of measuring the denitrification efficiency of sediments involves benthic chambers. These look like a perspex cylinder that encloses an area of sediment and overlying water.

The chambers act as 'incubators'. They are placed on the floor of the estuary for periods of eight to 24 hours to measure the rates of oxygen consumed, organic matter re-mineralised, and nitrogen and phosphorus released to the overlying waters as organic matter breaks down.

The rate of denitrification is determined by measuring the amount of nitrogen gas (N_2) released. The N_2 released is only a few per cent of the total N_2 inventory in estuaries. The technique used requires very high precision and accuracy to detect the amount of metabolic N_2 released.

Geoscience Australia has this capability in its Urban and Coastal Impacts project, and is exploring simpler ways to measure denitrification for environmental managers.

For more information phone David Heggie on +61 2 6249 9589 or e-mail david.heggie@ga.gov.au ✉

Conceptual models for national approach to estuary management

Geoscience Australia's Urban and Coastal Impacts (UCI) group is developing conceptual models of Australian estuaries and coastal waterways with input from other science disciplines, engineers, fisheries and the public, as part of a national approach to managing Australia's coastal habitats. The work is for the Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management (also called the Coastal CRC).

Vast differences

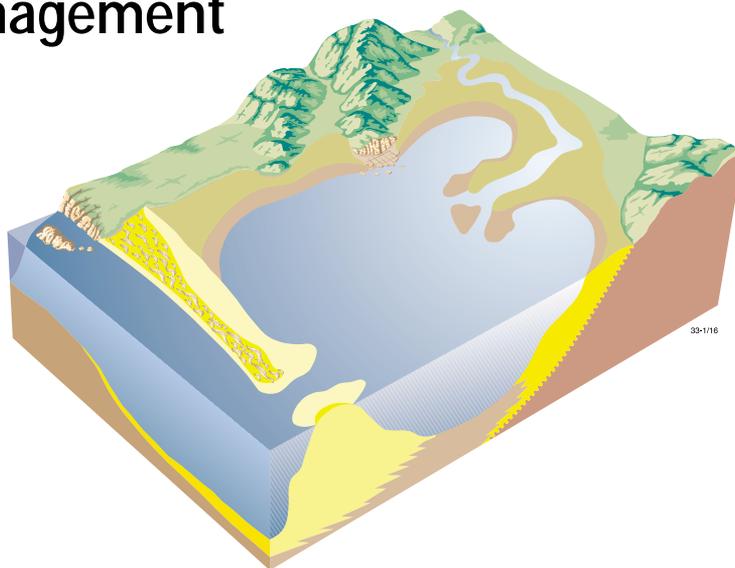
The Australian coastline is almost 70 000 kilometres in length, spans 34 degrees of latitude, and includes tropical, subtropical, and temperate environments.¹ The continent has roughly a thousand estuaries and coastal waterways, set in a wide range of geological, climatic and topographic conditions. The physical characteristics (or morphologies) of these estuaries vary greatly.

Australia is a dry continent and many of its estuaries and coastal waterways are fundamentally different from Northern Hemisphere estuaries.² Attempts to classify and model Australian estuaries must consider the diversity and uniqueness of the continent's environments.

Climatic, geological, topographic, biological and sedimentological factors are therefore being considered by UCI in its work to divide the Australian coast into estuarine regions and develop models for those regions. This 'regionalisation' will be compatible with, and draw upon pre-existing classifications of the coastline, such as the Interim Marine and Coastal Regionalisation of Australia.³

Continent classified

UCI has previously analysed aerial photographs, Landsat TM imagery, scientific literature, and compiled data for wave, tide and river power, to create an Australia-wide classification of estuaries and coastal waterways for the National Land and Water Resources Audit.⁴ It was the first occasion that estuaries of an entire continent had been classified using a systematic, quantitative geomorphological approach.



▲ Figure 1. A 3-D geomorphic conceptual model of a wave-dominated estuary

Geomorphic characteristics are key to understanding the function (or behaviour) of a waterway. These include marine and fluvial flushing, distribution of habitats (such as mangroves, salt marshes and intertidal flats), sedimentation, eutrophication, and persistence of pollutants in the estuarine environment.

Seven main waterway types were identified on the basis of their wave, tide and river power characteristics. These include embayments, wave-dominated estuaries, wave-dominated deltas, coastal lagoons (intermittently closed and open lakes and lagoons), tide-dominated estuaries, tide-dominated deltas, and tidal creeks.

Graphic summary

A 'conceptual model' is a graphic that collates the information and perspectives of many disciplines (see figure 1). UCI's conceptual models provide a framework in which the physical form (classification) and ecological function of estuaries and coastal waterways can be visualised and compared. They explain natural processes, and communicate complex ideas, knowledge and data in a visual form that all stakeholders can understand.

Sound understanding, and communication of the key processes operating in any particular water system are important for prioritising and effectively managing the competing needs of stakeholders (such as commercial and recreational fishing, aquaculture, ports and navigation, environmental protection, urban and rural development, scientific research, and human amenities).

Collaboration vital

In the estuarine environment, the disciplines of geoscience, ecology, hydrology and geochemistry all play critical roles. Integrative scientific understanding is vital for sustainable management, and collaboration is needed for an effective approach.

UCI is collaborating with other partners of the Coastal CRC, state governments, and the scientific community for a better perspective on Australia's estuaries and coastal waterways. Other partners in the Conceptual Models work include the University of Queensland, CSIRO, Queensland Department of Primary Industries, the Environmental Protection Authority, and Griffith University.

Products developed

UCI recently presented the Coastal CRC with 3-D geomorphological models of the seven key waterway types found in Australia. Drafts of these figures will soon be available from the OzEstuaries database.

Other products under development include an interactive map of estuarine regions around the Australian coastline; overlays of hydrodynamic, sediment and nutrient process models; links to biological impact models developed by the University of Queensland, and links to the CSIRO Simple Estuarine Response Model. There will also be a web-based communication product for stakeholders.

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**For more information
phone David Ryan on
+61 2 6249 9257 or e-mail
david.ryan@ga.gov.au**

ESTUARY CHANGES cored



How quickly sediments have been infilling estuaries both before and since European settlement is unknown for most Australian estuaries. Such information is crucial for proper management of estuaries and for predicting the impact of proposed coastal developments and changes to catchment land-use.

One way to gauge how estuaries have been altered over the past few centuries is to look at their sedimentary records. By analysing sediment cores, scientists can determine the chronology of deposition and identify changes over time in the characteristics of sediment.

In March, the Urban Coastal Impacts project started collecting sediment cores from estuaries in the south-west corner of Western Australia. The work is being undertaken with the Waters and Rivers Commission of Western Australia and in tandem with UCI's ongoing estuarine sediment nutrient cycling program.

Core samples

UCI will collect cores from a range of estuary types around Australia (from both muddy and marginal sandy environments) using shallow-water coring equipment. Core lengths will range from 0.5-1 metre in the mud basins to approximately three metres in marginal settings where sediment infilling has been more rapid.

Estuaries are often dynamic depositional environments. Terrestrial sediment intermittently is transported to the open coast and waves rework the deposits within the estuary. Sediment core sites therefore must be carefully selected to ensure samples comprise detailed depositional records of the past 200 years and not just recent sediment build-up.

Dating methods

The most common method of sediment dating is the ^{14}C technique. This method is unsuitable for obtaining accurate chronologies of deposition over the past 200 years. An alternative, the ^{210}Pb method is also a problem. Although it can provide an estimate of the rate of sediment accumulation over this period, estuarine sediments often contain a relatively low proportion of ^{210}Pb that is difficult to measure.

Direct cross checking of the results is not possible, because their age ranges do not overlap.

New techniques

To overcome these problems, UCI will be using relatively new dating techniques called Optically Stimulated Luminescence (OSL) and amino acid racemisation (AAR). The OSL method determines a deposit's age by measuring the amount of natural radiation that quartz grains have been exposed to while buried. In the AAR method, the age of marine shells is calculated from the degree of interconversion of structural amino acids that occurs after the organisms' deaths.

The dating will be done in collaboration with specialist dating laboratories at CSIRO Land and Water and the University of Wollongong.

In addition to the dating, a range of physical and geochemical analyses will be undertaken. These analyses will indicate changes in the type of sediment entering the estuary (e.g. grain size, porosity, mineralogy, major and trace elements, mollusc assemblages), nutrient loading (e.g. TOC, TN, TP, TS) and sources of organic sediment (stable isotopes of carbon, nitrogen and specific biomarkers).

The sediment data will be a quantitative measure of human impact on estuarine habitats, and will provide a geoscientific basis for environmental decision-making.

**For more information phone Brendan Brooke on +61 2 6249 9434 or
e-mail brendan.brooke@ga.gov.au**

At GREAT DEPTHS for petroleum question

Much of the northern half of the Fairway Basin in the Tasman Sea has petroleum potential. But nobody knew whether the area far south of New Caledonia in the Australian part of the basin had similar prospects.

In an attempt to end the speculation, a multinational group led by Geoscience Australia's Neville Exon and Peter Hill set sail on Research Vessel *Franklin* late last year for the deep waters of the Fairway Basin. Neville Exon outlines early findings of the *Franklin* survey FR9/01.

Recent geophysical investigations by Geoscience Australia (mostly under the FAUST program) and New Caledonian and French scientists show that much of the northern half of the Fairway Basin, on the eastern Lord Howe Rise, could contain petroleum. The evidence consists of thick sedimentary sequences, sediment diapirs like those that form major hydrocarbon traps around the margins of the Atlantic Ocean, gas hydrate and probably free gas. Water depths are largely 1500–3200 metres, which is the present-day limit of exploration drilling.

The primary aim of survey FR9/01 (FAUST 3) was to study potential petroleum resources in the deep-water Fairway Basin. The work started in 1998 on *Rig Seismic's* last deep-seismic cruise (FAUST 1), and was continued in 1999 on *L'Atalante* (ZoNéCo 5). The latest survey involved seismic mapping, coring and dredging for seafloor samples (figure 1). More specifically, RV *Franklin* was used to:

- continue seismic mapping of basin sequences, sediment diapirs and bottom simulating reflectors (BSR) within the Australian and New Caledonian/French seabed jurisdictions;
- take cores to determine the origin and composition of gas on the Lord Howe Rise, especially in any identified seafloor structures above sediment diapirs;
- ground-truth seismic data by sampling older outcropping sequences; and
- take cores to establish the composition, character and climate history of shallow sediment of Holocene and Pleistocene ages.

Already the cruise data are providing insights into this complex region of Cretaceous and Cainozoic subduction and back-arc rifting in the south-west Pacific. At this stage, the whole Fairway Basin appears to have some long-term petroleum potential, but its remoteness from land is a logistical problem.

Not all plain sailing

The survey experienced a few difficulties with equipment. But old-fashioned ingenuity allowed Geoscience Australia technician, Craig Wintle, and the ship's engineers to overcome seismic compressor problems that would have crippled the survey program.

A new deployment system that allowed two airguns (the seismic energy sources) to be towed at eight knots increased productivity considerably. It was designed and built by Geoscience Australia's Engineering Services Unit.

Fair weather minimised seasickness and allowed good data to be gathered.

Seismic program

The seismic program gave 2790 kilometres of 24-channel profiles, which shipboard processing showed were of excellent quality. Two, new east-west cross-sections were obtained in the north of the central Fairway Basin (largely in New Caledonian jurisdiction). These found more diapirs, evidence of a BSR indicating the presence of gas hydrates, and young faulting. (The diapirs are very obvious on line four, figure 2.)

In the south, the multi-channel seismic profiling provided six, east-west cross-sections in an area of Australian jurisdiction where there were previously none. These show that the deeper water, north-south extending depression south of 26° 20'S is a southern extension of the Fairway Basin. The main difference is probably a thinner continental crust. The basin is limited by the Lord Howe Rise to the west and the northern extension of the West Norfolk Ridge to the east. It is roughly 700 kilometres long and 100 kilometres wide.

The South Fairway Basin is 70 000 square kilometres in area (roughly the size of Tasmania), and about 40 per cent is in the Norfolk Island Exclusive Economic Zone. It contains sediments more than two seconds thick in places, deep diapirs, and a BSR in some regions. Water depths are 1200 metres to 3600 metres. The South Fairway Basin has some petroleum potential, although the thickness of sediment (<3 km) limits the potential in the small areas surveyed.



Core, dredge samples

Calcareous ooze (consisting of the skeletons of nannoplankton and foraminifera) was recovered in 22 cores, in water depths of 1297 to 3517 metres. These gravity cores averaged 3.6 metres long (and totalled 80 metres), compared with the piston cores of *L'Atalante* in the north and central Fairway Basin in 1998, which averaged 6.3 metres. The much higher velocity of a piston corer (~10 times as high) is a huge advantage in penetrating firm oozes like these, and makes coring of foraminiferal sands quite feasible. Thus piston coring should become a standard deep-water operation when the larger *Southern Surveyor* replaces the *Franklin* in September 2002.

The FR9/01 cores allow the composition, character and climate history of the region to be studied over nearly eight degrees of latitude and 300 000 years. The samples taken aboard will help address petroleum potential, by determining the origin and composition of any enclosed gas. Similar work on the ZoNéCo 5 cores suggested that thermogenic hydrocarbons are present—a plus for petroleum potential.

Only seven dredges were taken (far fewer than planned) because of time constraints and because most possible hard-rock targets were only marginally suitable. The much heavier dredges deployable from *Southern Surveyor* will greatly improve Australia's deep-water dredging capability.

Two dredges were successful, one in recovering volcaniclastic basement rocks and the other Eocene chalk. The basement rocks should provide an insight into the nature of the Vening-Meinesz Fracture Zone, a north-west-trending feature of regional significance.

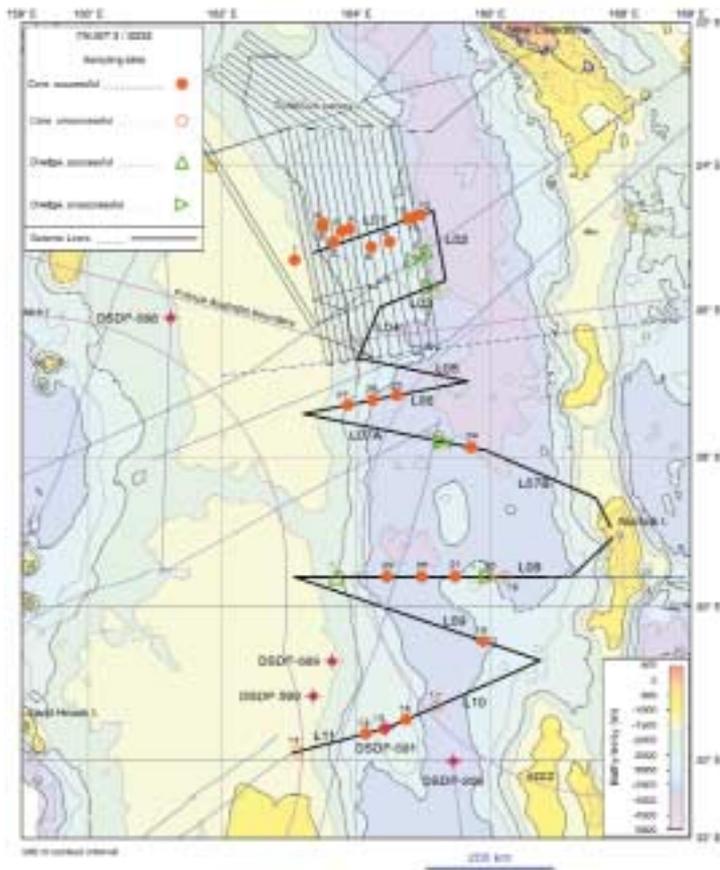
Survey members

The research plan for FR9/01 was designed by Neville Exon, Peter Hill, Jerry Dickens (Rice University, Texas), and Yves Lafoy (Service des Mines in New Caledonia). Jerry Dickens did not join the cruise.

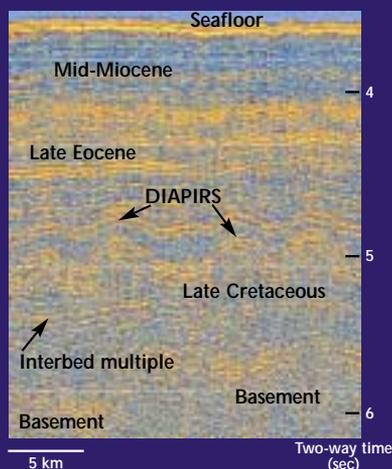
Other scientists aboard were Geoscience Australia's Melissa Fellows and David Holdway, and Australian and American graduate students (Kirsten Perry and Patrick Mitts). Geoscience Australia also provided three technicians: Jon Stratton, Lyndon O'Grady and Craig Wintle. The National Facility *Franklin* was crewed by P&O Maritime Services, under the captaincy of Ian Taylor. CSIRO Marine provided two support scientists.

The data are being evaluated in Australia, New Caledonia and the United States over the next few years. An initial report is available on www.marine.csiro.au/franklin.

For more information
phone Neville Exon on
+61 2 6249 9347 or e-mail
neville.exon@ga.gov.au



▲ **Figure 1.** Bathymetric map of the region investigated north-east of Lord Howe Island, showing new seismic profiles and sampling sites, and pre-existing core holes and multi-channel seismic profiles



► **Figure 2.** A cross-section through the central Fairway Basin from seismic profile 4, showing nearly three kilometres of sedimentary deposits. The diapirs are domes or ridges of sediment (salt or mud) that have flowed under pressure. In some parts of the world they trap oil and gas.

Ancient deltas key to Bight's oil potential

The Bight Basin on Australia's southern margin could be Australia's next big petroleum province. Two large deltas that developed in the Bight 100 million years and 85 million years ago provided the ideal material and conditions for oil and gas formation.

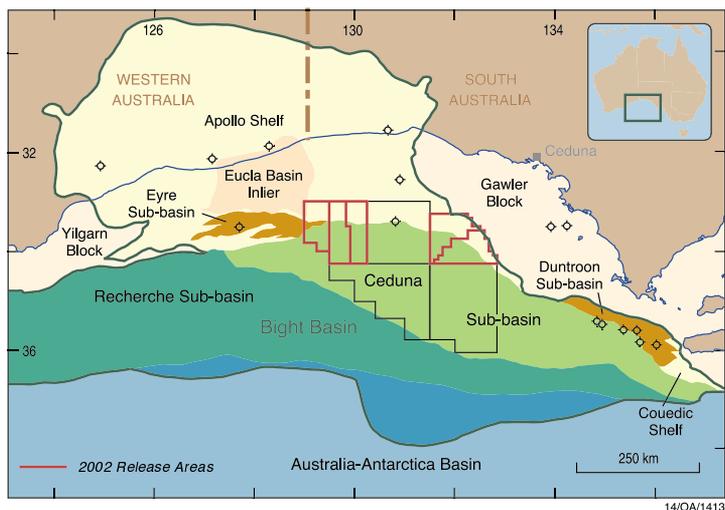
Jennifer Totterdell, one of a team of scientists from Geoscience Australia's Petroleum and Marine Division that has been examining the evolution of the Bight's deltas explains...

Many of the world's most successful and prolific petroleum provinces are associated with large, progradational (built out into the sea) deltas. Examples include the Niger delta of western Africa, the Mahakam delta of Indonesia and the Mackenzie delta of northern Canada. In the evolution of Australia's Bight Basin there were two of these deltas.

Bight Basin deltas

The Bight Basin is a large, mainly offshore basin that lies on the southern Australian margin in the Great Australian Bight (figure 1). The two delta systems occur mainly in the Ceduna Sub-basin. They cover an area of roughly 110 000 square kilometres. The scale and architecture of these delta systems are comparable to deltas of the West African passive margin, particularly the Niger delta and the Orange Basin delta.

Only nine petroleum wells have been drilled in the entire offshore portion of the Bight Basin.



▲ Figure 1. Location map showing Bight Basin, Ceduna Sub-basin and acreage release areas

REGIONAL GEOLOGY

Approximately 100 to 65 million years ago, a series of depocentres developed along Australia's southern margin. The Bight Basin contains four main ones: the Ceduna, Duntroon, Eyre and Recherche sub-basins (figure 1).

Delta deposition was concentrated in the thickest of these, the Ceduna Sub-basin. This basin underlies a broad terrace (Ceduna Terrace) in water depths ranging from 200 to more than 4000 metres. It has a sedimentary section that is more than 12 kilometres thick.

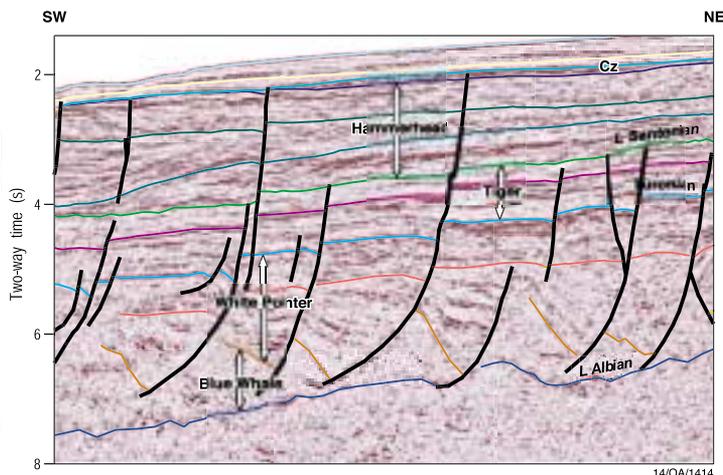
Extension and deposition

The Bight Basin was initiated during a phase (170–140 million years ago) of intracontinental extension that formed a series of extensional and transensional half graben.

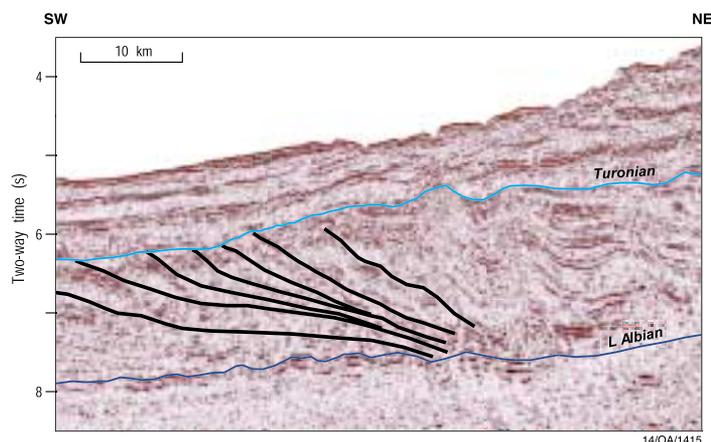
The extensional phase was followed by a period of slow thermal subsidence throughout most of the Early Cretaceous (140–110 Ma). Deposition during this time was largely non-marine.

An abrupt increase in subsidence rate in the mid-Albian (102 Ma) signalled a new phase of basin development. This period, which continued until seafloor spreading started between Australia and Antarctica (85 Ma), coincided with rising global sea level. The sea flooded the basin for the first time and there was widespread deposition of marine silts and shales (Blue Whale Supersequence).

The seaway (called the Blue Whale seaway) would have extended along the southern margin from the open sea in the west towards the Otway Basin in the east. Progradation of delta sediments into this seaway (White Pointer Supersequence) commenced in the Cenomanian (97 Ma) after uplift and erosion along the eastern margin of the continent.



▲ Figure 2. White Pointer growth faults in the northern Ceduna Sub-basin



▲ Figure 3. White Pointer toe thrusts in deep water at the toe-of-slope

Deposition was rapid. This resulted in overpressure in the underlying marine shales, and a short-lived period of shale mobilisation and growth faulting throughout the northern half of the Ceduna Sub-basin.

After continental break up (85 Ma), there was thermal subsidence and the southern Australian passive margin was established. It was during this phase that the second large progradational delta developed (represented by the Hammerhead Supersequence). At the end of the Cretaceous (65 Ma) there was a dramatic drop in sediment supply. Delta deposition stopped and a cool-water carbonate margin developed.

CRETACEOUS DELTAS

The White Pointer delta (108–90 Ma) comprises the sediments of the Blue Whale and White Pointer supersequences. The few petroleum exploration wells drilled in the Ceduna and Duntroon sub-basins intersect the relatively thin, proximal parts of the basin succession. In these wells, the Blue Whale Supersequence generally consists of near-shore or restricted marine siltstone. The overlying White Pointer Supersequence contains dominantly fluvial to lagoonal siltstone and mudstone.

The seismic character of these sequences changes further into the basin. The Blue Whale Supersequence is characterised by chaotic or low-amplitude reflections that are typical of overpressured shale. The White Pointer Supersequence contains bands of highly reflective, relatively continuous reflections that suggest coal.

White Pointer delta

The White Pointer delta is a Niger-style delta due to its mobile substrate, extensive growth faulting and mud diapirism. It has three distinct structural zones. An updip region dominated by extensional growth faults is accompanied downdip by a zone of complex deformation and possible diapirs. Further downdip there is a contractional fold and thrust belt.

Modelling of progradational deltas shows that updip extensional structures are dynamically linked to the downdip contractional structures. The deformation seen in the White Pointer delta is believed to result from gravity sliding and gravity spreading processes. These were caused by the progradation of delta sediments over mobile, over-pressured muds on a gently basinward-dipping decollement.

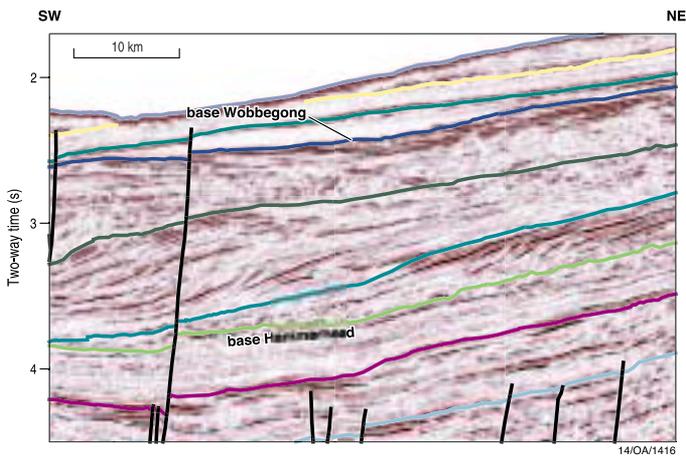
In the Ceduna Sub-basin, the zone of growth faulting is relatively broad, covering more than 150 kilometres across the palaeo-shelf (figure 2). The listric growth faults are dominantly basinward dipping and detach within the underlying over-pressured shales. Shale mobility takes the form of reactive diapirs.

The faults have a generally arcuate trace and a north-west to south-east strike. The downdip belt of folding and diapirism occurs at the outer edge of the Ceduna Sub-basin, and coincides with what has been described as an outer basin high. Further out, in deeper water at the present-day foot-of-slope, is the fold and thrust zone that is characterised by north-east-dipping toe-thrusts (figure 3).

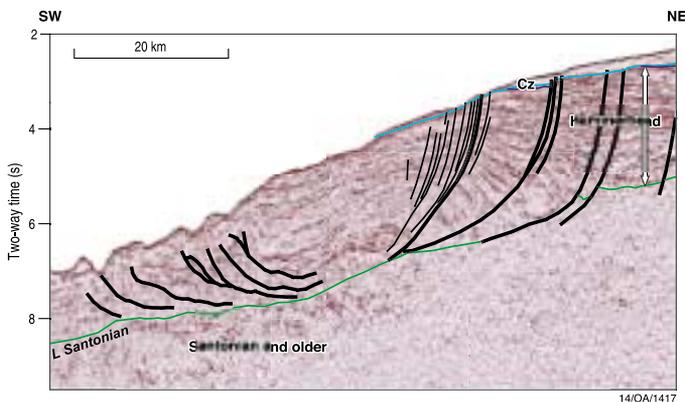
Hammerhead delta

In the lead-up to seafloor spreading, deposition occurred in a rapidly subsiding, restricted marine environment (Tiger Supersequence). Uplift associated with continental break up resulted in widespread exposure and incision of the former shelf. This was followed by the deposition of the Hammerhead Supersequence—a 19-million-year period of sustained delta and related sedimentation.

The Hammerhead delta (85–70 Ma) is very different from the older White Pointer delta. Well and seismic data indicate that it is a sand-rich system featuring strongly progradational stratal geometries, but it lacks the extensive shale deformation of the earlier system.



▲ Figure 4. Classical prograding clinoforms in the Hammerhead delta



▲ Figure 5. Spectacular gravity slide at the outer edge of the Hammerhead delta

The Hammerhead Supersequence comprises three third-order sequences. The lower two sequences exhibit strongly progradational geometries (figure 4), while the upper sequence has a dominantly aggradational geometry, because of a gradually decreasing rate of sediment supply.

In the proximally located wells, the supersequence consists mainly of amalgamated fluvial channel sandstones. In distal parts of the basin, the Hammerhead Supersequence comprises thinning wedges of marine shale at the toe-of-slope.

The most striking structural feature of the Hammerhead delta occurs at the palaeo-shelf margin in the south-western Ceduna Sub-basin. In this region, where the sediment pile was at its thickest, gravitational instability has resulted in localised gravity tectonics, with large growth faults compensated down-dip by folds and toe-thrusts. The growth section on the faults reaches thicknesses of up to 3500 metres. This deformation is a classic example of gravity sliding (figure 5). It appears to have occurred during the strongly progradational phase of delta development (83–73 Ma).

PETROLEUM POTENTIAL

The White Pointer and Hammerhead deltas built out into a narrow, restricted seaway before and immediately after the slow seafloor spreading between Australia and Antarctica. This seaway would have been an excellent environment for the development of organic-rich rocks.

The marine shales of the Blue Whale Supersequence (the mobile substrate to the White Pointer delta) have proven source-rock potential. From geochemical evidence, they could be the source of the asphaltites that are regularly found along the southern margin of Australia.

The White Pointer Supersequence contains marine-condensed sections and coaly deposits. It is potentially an excellent source of oil and gas. The preservation of organic-rich rocks would have been enhanced in the high accommodation setting of the growth-fault controlled depocentres. In addition, seismic indications of thick, shale-prone intervals within the dominantly marine Tiger Supersequence suggest the presence of Turonian-age (90 Ma) source rocks in the basin.

The dominantly progradational Hammerhead Supersequence has excellent reservoir potential, and there is a high likelihood of regionally extensive marine seal facies within the upper aggradational portion of the succession. The basinward thickening geometry (up to 5000 metres) of the Hammerhead is the key to the loading and maturation of successively younger source rocks.

The structural fabric of the White Pointer delta sets up the plumbing system for the basin. Growth faults that have been reactivated several times were the nucleus for new faults.

The Bight is a poorly drilled frontier basin but, from SAR-detected seepage and asphaltite strandings, it shows signs of active petroleum systems. These alone suggest that the Late Cretaceous deltas of the Bight Basin may provide Australia with its next big petroleum province.

**For more information
phone Jennifer Totterdell
on +61 2 6249 9407 or e-mail
jennifer.totterdell@ga.gov.au**