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The stratigraphic organisation of incised-valley systems

R. Boyd[1], B.A. Zaitlin[2] and R.W. Dalrymple[3]
[1]University of Newcastle
NSW 2308
[2]Pancanadian Petroleum Ltd
PO Box 2850
Calgary Alberta
Canada T2P 2S5
[3]Queen's University
Kingston Ontario
Canada K7L 3N5

An incised-valley system consists of an incised valley eroded during a relative sea level fall, and a valley fill which accumulated during one or more relative sea level cycles. Incised-valley systems provide the most complete, and at times only, evidence of lowstand to early-transgressive deposition in shelf and/or shallow ramp depositional settings.

The fill of incised-valley systems is divisible in three segments: i) the seaward reaches of the incised-valley (SEGMENT 1) is characterised by backstepping (transgressive) fluvial and estuarine deposits, overlain by transgressive marine sands and shelf muds; ii) the middle reaches of the incised-valley (SEGMENT 2) consist of the drowned-valley estuarine complex that is developed at the time of maximum transgression, overlying a lowstand to transgressive succession of fluvial and estuarine deposits like those in segment 1; and iii) the innermost reaches of the incised-valley (SEGMENT 3) is developed headward of the transgressive marine limit. Segment 3 is characterised by fluvial deposits throughout its depositional history; however, the fluvial style may change systematically due to changes in accommodation. A sequence stratigraphic approach to the study of incised-valley systems results in a model for the predictable organisation of facies and surfaces based on the interaction of sediment supply and relative sea level.

Recognition of incised-valleys and their segments is critical for successful hydrocarbon exploration in many areas. For example, recognition of the Segment 1 valley fill of the Senlac heavy oil pool in the Cretaceous Lloydminster Formation of Saskatchewan enables an understanding of production history in a wave dominated incised-valley sand plug, with increased production resulting from tidal inlet facies and low production in distal flood tidal delta units. The Glauconite Formation of Southern Alberta is an example of a compound Segment 2 incised-valley fill where basal fluvial channel sands are overlain by transgressive tidal channel sands and mudstones. The fluvial channel sands are the best reservoirs, the tidal channel sands have low vertical permeability and the mud filled channels of a younger age act as seals to the underlying reservoirs. The Hunter Valley of eastern Australia exhibits multiple cycles of fill from Tertiary to Quaternary in age, and preservation of all incised-valley segments. Studies of high resolution sequence stratigraphy in Quaternary examples such as the Hunter Valley enable the prediction of reservoir and seal architecture in ancient incised valleys, and an establishment of the criteria for their successful recognition.

Information—how to access your company's most valuable asset

P. Burke
Convergent Group Asia Pacific
Level 1
101 Sussex Street
Sydney NSW 2000

Today's market place demands continual improvements in the quality of both products and services. The 90s are times of unprecedented change with many companies reviewing the way they do business. They are often working in an extended enterprise comprising suppliers, distributors, and in some instances, are restructuring themselves on a global basis.

In this dynamic, often geographically dispersed environment, the access to, and application of information is critical to success. The adage 'Knowledge is Power' is a key phase in our economy today where companies who know where their data resides and the process involved in capturing, managing, assembly and distribution it, are improving their competitive position.

The challenge is to pool this information, to make it available to those who need it, 24 hours a day, in an accurate and up-to-date format. The benefits of achieving this are substantial; increased productivity, reduced costs; reduced development times and, ultimately, improved bottom line performance.

THE BUSINESS CHALLENGE

The challenges facing every industry are to adapt to new ways of thinking and working; to develop new products and services; to evolve new structural relationships with customers and suppliers and to satisfy increasing stringent regulatory requirements.

In more succinct terminology, today's business challenges are improving:

- customer focus and service;
- product and process quality; and
- innovation and development.

The critical factor in meeting this challenge is the effective management of information and its delivery to those who need it. The challenge of effective information management is very real as we are no longer isolated entities. The term 'global teaming' is being heard more frequently in large companies e.g. North West Shelf and on a more macro level we are seeing project and design teams collaborating on new business opportunities across companies and continents.

In this dynamic, often geographically dispersed environment, the access to, and application of, information is critical. Access to information needs to occur across a matrix of other considerations such as:

- market expansion (geographically and by segmentation);
- budgets; and
- Existing corporate information systems and network.

THE ROLE OF INFORMATION MANAGEMENT IN THE LIFE OF A PROCESS PLANT

Process plants go through an fairly predictable life cycle. The phases that a plant goes through include:

- specification of requirements.
- slant design (with associated reviews and possible modifications).
- slant construction (where the design documentation can change into as built documentation).
- operations and production.
- both major and minor plant modifications and rejuvenations; and
- plant decommissioning.

Each phase in the life of a plant generates and uses documents. The trail from one phase to the next is found in the documentation. It is therefore not surprising that proper management of the plant documentation can generate tremendous benefits.

This article will discuss how document software management (and related technology such as workflow and full text search) has been used to greatly improve the safety and efficiency of plant operations.

WHAT IS DOCUMENT MANAGEMENT?

Document management is any system that controls the creation/capture and storage of documents, controls the distribution of those documents, allows user access to these documents, and controls the process by which documents are updated. This includes control over document check-out, check-in, and revision control.

A variety of documentation is needed to operate a process plant. These include:

- piping and instrumentation diagrams (P&IDs);
- plot plans;
- facility drawings;
- process flow diagrams;
- standard operating procedures;
- engineering drawings;
- electrical diagrams;
- vendor manuals;
- material safety data sheets;
- maintenance manuals;
- test certifications;
- inspection reports;
- training records;
- correspondence;
- purchase orders;
- incident reports;
- emergency action plans;
- specifications;
- maintenance history files;
- work orders;
- ISO procedures;
- manufacturing processes;
- parts lists;
- company engineering standards;
- design codes; and
- standards employed.

To be effective, a document management system must not only manage all of the document types, but it must also make it easy for a user to understand the inter-relationship between the individual documents.

An operator using a maintenance procedure should automatically have access to the latest vendor manuals, related material safety data sheets, and any other documentation related to the procedure.

While there are many possible ways to manage documents, most companies have concluded that the only cost effective long-term solution is the use of electronic document management systems. There is well documented evidence that paper-based systems deteriorate in accuracy at a rate of 20–30 percent per year, requiring expensive labor to update, or running the risk of using out-of-date documentation.

Understanding the documentation relationships in a facility, together with the need to manage drawings and redlines, make document management in process industries a highly specialised application. A document management system for general office application will not meet the needs of these plant operators.

SPECIFICATION, DESIGN, AND CONSTRUCTION OF A PLANT

The early phases of the plant evolution are typically characterised by coordination of activities by a diverse group of individuals, often geographically dispersed. These include personnel from the parent company together with subcontractors from the architecture, engineering, and construction industries. The work of the various design specialists must be coordinated as the design evolves.

Once into the construction phase the plant design is moved from the paper (or electronic) representation into the physical manifestation of the plant.

As the construction evolves, problems with the theoretical design manifest themselves. This results in intense communications between the construction site and the engineers. A large number of the original design drawings must be modified to so that construction can proceed.

Speed of turning these design documents around directly effects the construction and production schedule. Proper management of the resulting revisions directly effects the quality of the resulting facility.

PRODUCTION START-UP OR COMMISSIONING

The hand over of the plant from the construction group to the operating group is a critical transition in the plant lifecycle.

A number of petrochemical, oil and gas companies has taken major steps to improve the document hand over at this point in the plant's life. They have found that they can greatly improve the early operation of the plant, and reduce costs substantially if they use an electronic document management system during the design and construction phases. They specify to their subcontractors the document types, document formats, and metadata that they require, and they insist that the documents are deposited, by the subcontractors, in the electronic document management system before the plant is commissioned.

Before they started to use the document management system in this way it often took up to two years to catalogue, organise, and distribute the documents that would come in from the various designers and contractors that were involved in building the plant. So the resulting savings was not only many man-years of cataloguing and organising of documents, but the immediate availability of the documents to the plant operations personnel.

PLANTS IN THE PRODUCTION PHASE

Newly designed plants have the option to insist that their document management systems are in place and populated when the plant comes on line. For existing plants it is usually a different story.

For an operating plant it is reasonable to ask: 'Is there a document management problem in my plant?'

Anyone who has seen engineers, operations personnel, or maintenance personnel searching for the information to perform their job would think that, indeed, there is problem.

Not only is it difficult to locate the information needed (which is usually contained in a document), but a potentially catastrophic problem may arise if the documentation found does not contain the latest revisions to accurately reflect the current plan configuration.

WHY SHOULD YOU CARE IF THERE IS A PROBLEM?

In an industry where safe operation of potentially hazardous products and processes is the highest priority, out-dated documentation can be a real hazard.

The parameters by which success is measured in the plant can be seriously undermined if document management issues are unresolved. Operational procedures must be in place to ensure that information is readily available, accurate, easy to locate in an emergency, and relevant to the work being performed.

The measurable benefits of document management include:

- on-time project completion;
- efficient scheduled and unscheduled maintenance execution;
- reduced cost for document distribution;
- compliance with critical quality accreditation such as ISO 9000; and
- safe operations in compliance with regulatory mandates (license to operate, avoids liability, and keeps insurance costs low).

A quick test to see whether a plant is out of control is to walk up to specific piece of equipment (valve, pump, turbine, etc.) and ask the operators for all of the relevant information about that piece of equipment. In a well run plant, the operator should be able to quickly produce information such as:

- related piping and instrumentation diagrams (P&IDs);
- equipment specification;
- installation instructions;
- maintenance procedures;
- standard operating procedures;
- maintenance history;
- vendor manuals; and
- material safety data sheets.

If this information can not be located within a few minutes the plant is operating inefficiently and the document management system currently in place needs to be re-evaluated.

KEEPING DOCUMENTS ACCURATE AND UP-TO-DATE

Ensuring documentation is up-to-date is a major effort. A familiar model to plant operators is the process of change to 'controlled' documents. These include:

- an update to a drawing to correct an error, or record a change to the 'as built' plant; and
- an update to an operating procedure or maintenance instruction, reflecting a change in plant configuration or vendor specification.

Changes affecting process chemicals, technology, equipment, or facilities must be documented. The management of change process is intended to ensure that changes are:

- properly reviewed by personnel;
- incorporated into relevant documents such as piping and instrument diagrams, operational and training manuals; and
- communicated to affected employees via coordinated training programs prior to implementation of the change.

This documentation is essential to regulators such as OSHA, H&SE, etc, or the quality auditors who certify whether the operation meets standards like

ISO 9000. Management of the change process is what introduced the concept of workflow into document management.

COMPARING ELECTRONIC DOCUMENT MANAGEMENT TO OTHER METHODS

- **Paper as the primary means to communicate information.** The paper process typically relies on the interoffice mail system to transport information. Tracking paper files is often an inefficient and slow the process. A workflow based system, with electronic documents could substantially change the method of routing for approval.
- **Moving paper files is a serial process.** A physical file must be moved in a serial fashion; however, many of the required activities are independent, and can thus be performed in parallel. With parallel electronic routing it is possible to simultaneously perform safety and health reviews, environmental reviews, hazard analyses, and mechanical integrity reviews.
- **Researching related information is difficult.** When asked to approve a change it is often necessary for the worker to review other, related information. Documentation is often in numerous locations including offices, libraries, trailers, and personal files. Relevant information is often ignored since it is not readily available. With all information available on an EDMS it is easy to use feature such as full text search to search the entire document base so that all implications of a change can be determined.

INTEGRATION WITH OTHER INFORMATION SYSTEMS

A document enabling interface is needed to integrate various information systems into the document management system so that documents can be obtained directly from other systems.

Generation and delivery of the work order packages can be accomplished by integration of the maintenance system with the document management system.

THE BENEFITS TO PROCESS MANUFACTURING

The ability to get information, insuring the integrity of the information, controlling the management of change of the plant and related information, and ensuring process integrity has many potential benefits to the operation. Benefits include:

- Increasing the availability and accuracy of process safety information;
- Reducing the cost of locating and distributing documents;
- Significantly reducing the errors in data and documents that are inherent in paper based distribution and control systems;
- optimising return on plant investment by increasing plant availability;
- increasing sales through Quality Accreditation;
- implementing an efficient process to execute and track management of change; and
- integrating document management into existing maintenance management and enterprise management systems

WHERE TO FROM HERE

The intellectual capital or application of managed information is rapidly becoming a business imperative. Today's business challenges are improving:

- customer focus and service;
- product and process quality; and
- innovation and development.

This can only be achieved by two connected items:

- document control; and
- policies and procedures.

Document management facilities these items, but to grow a business must apply knowledge strategically to its processes. These processes must be reviewed and revised on a consistent basis to capture the true capital of the information.

Intranets will provide a major vehicle for companies to disseminate quickly information to their staff in a controlled and user accepted format without the problems normally associated with software products.

If knowledge is power why is it not considered more often in an economic sense? The answer is it will be as more companies strive to meet the business challenges of today.

Application of diamondoid hydrocarbons to maturity assessment of the oils from Western Australia

J. Chen, G.A. Logan and R.E. Summons
Australian Geological Survey Organisation
GPO Box 378
Canberra ACT 2601

Thermal maturity is a very important parameter for assessing petroleum generation in sedimentary basins. However, the maturity parameters based on biomarker ratios cannot be applied to highly mature oils (Ro>1.0%) or over-mature oils (Ro>1.3-1.4%). Diamondoid hydrocarbons (admantanes and diamantanes) are rigid, three dimensionally fused ring alkanes which have a diamond-like structure and have much higher stability than conventional biomarkers. Diamondoid ratios have been used to rank the maturity of highly mature oils and condensates(Chen et al, 1996).

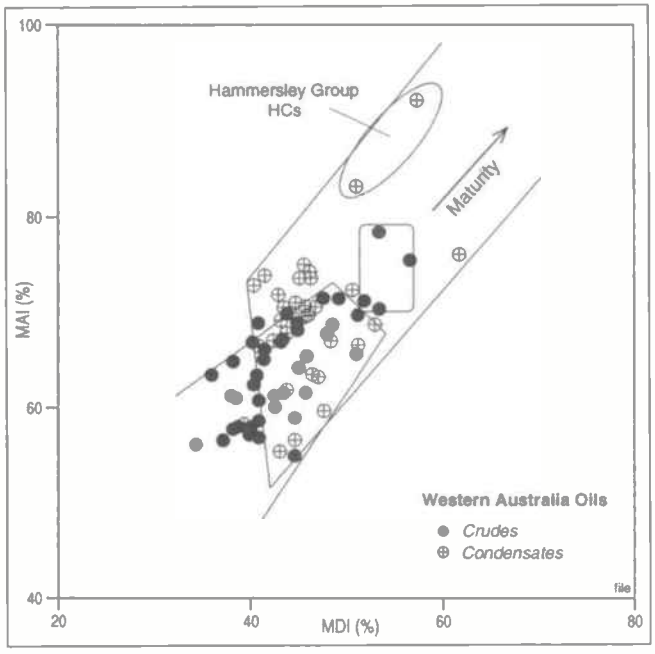

Figure 1. Western Australia oils—Hamersley Group.

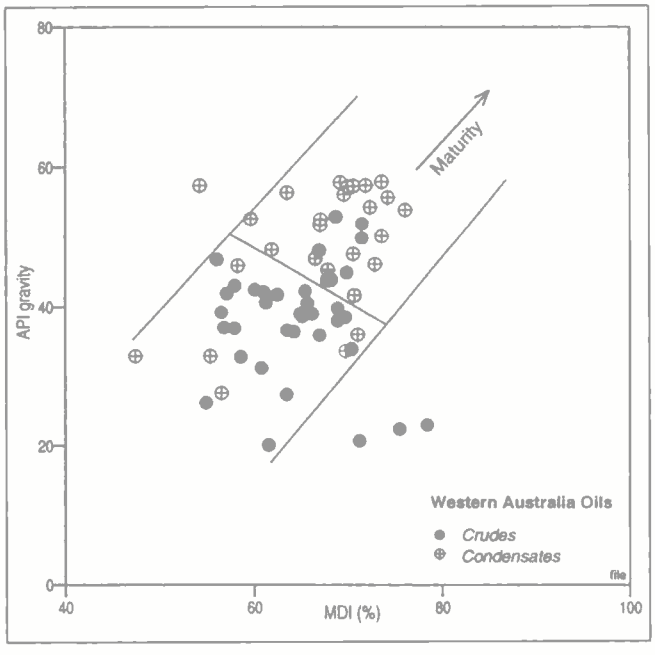

Figure 2. Western Australian oils.

About 80 oil samples from Western Australia (Carnarvon, Canning, Bonarparte, Browse and Perth basin) have been analysed by GC-MS to measure the values of MAI (Methyl Admantane Index) and MDI (Methyl Diamantane Index). The results indicate that crude oils generally have the lowest values of MAI and MDI while condensates have higher values (Fig.1). Almost all the condensates in Western Australia have

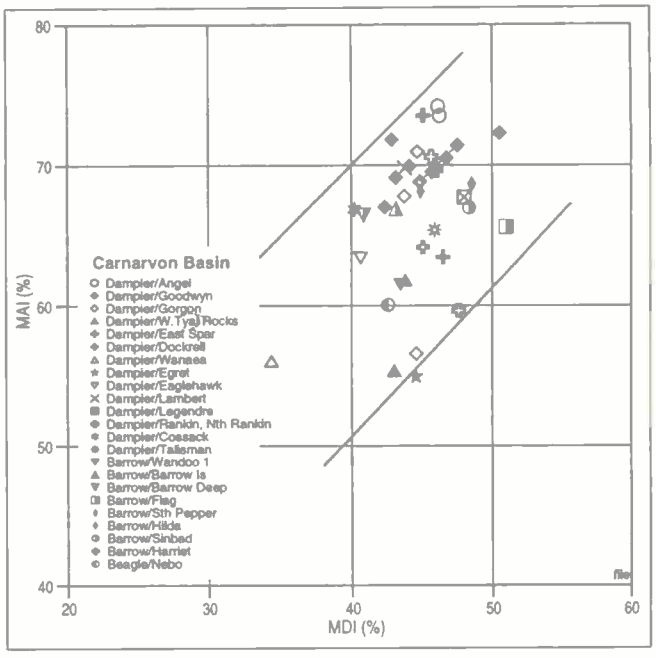

Figure 3. Carnarvon Basin.

indicative Ro values ranging from 1.3% to 2.0%, corresponding to the maturity stage of wet gas and condensate. This is consistent with the fact that vast volumes of natural gas and condensate have been found in the basins of the Northwest Shelf and that these gas/condensate deposits are located close to the large deep faults which could serve as effective upward migration pathways from deeply buried source kitchens.

It was found that most condensates have higher values for MAI and API gravity, while most crudes have lower values (Fig.2). This is an expected result given that the hydrocarbons become lighter with the increasing thermal maturity.

The crude oils have values of Ro between 1.1-1.6% based on MAI and MDI (Fig. 1). These values may not represent the maturities of all hydrocarbons in a single reservoir. An interpretation of the data for conventional biomarkers in oils and condensates (GeoMark-AGSO, 1996), which are normally used to assess thermal maturity, suggests Ro values in the range 0.6-1.2% (Peters and Moldowan, 1993). This observation of inconsistent or ëmixedí maturity signals implies that some reservoirs may contain charges of different thermal maturities. The components of different maturies may be derived from the same source but released at different times during burial. More likely, the highly mature components have been sourced from older and more deeply buried strata. For example, Fig.3 displays the maturity cross-plot of oils and condensates from the most prolific hydrocarbon province, the Carnarvon Basin. The majority of oils in the sample set are likely to have Late Jurassic Dingo Claystone as their predominant source. Most of the

Carnarvon condensates and crudes fall in the area with the values of 40-50% for MDI and 60-75% for MAI, equivalent to 1.3-1.6% Ro. The condensates from gas fields such as Angel, Goodwyn, Gorgon/North Gorgon/ Central Gorgon, East Spar, Rankin/North Rankin generally have higher values for MDI and MAI and hence, are more mature than the oils reflecting the likely contribution from Triassic source units. Figure 3 shows a Lambert oil as anomalously mature and hence indicating possible contribution from older source units.

Two condensate samples from the Hammersley Group, McRae Shale and Bee Gorge Shale in Mt Tom Price Mine were also analysed. These shales have been dated at approximately 2,600 ma and could be regarded as the most ancient source rocks so far identified. The values for Ro of these shales are about 2.0% based on organic matter reflectance (D. Taylor, pers. common.). Based on the values of MAI and MDI, the condensates collected from these shales have quite similar values for Ro, 2.0% and 1.7% for these two samples respectively. The consistency of maturity of condensates and their host source rocks indicates that these condensates are indigenous and derived from the associated kerogen. Actually, these two Archean condensate samples are the most mature condensates from Western Australia that have been analysed (Fig.1).

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A new characterisation of bulk-volume irreducible using magnetic resonance

G.R. Coates[1], D. Marschall[1], D. Mardon[1] and J. Galford[2]
[1]NUMAR
Houston
Texas
[2]NUMAR Australia
Perth WA

Irreducible water volume from the new Magnetic Resonance (MR) logging tools provide the log analyst with insight into a formation's permeability and its water-cut potential. However, the traditional T2 cutoff method to determine the bulk volume of irreducible water (BVI), currently in wide use, has been found to be inadequate for some formations and fluid conditions.

A new method to characterise bulk volume irreducible is presented in this paper that addresses these issues. The method is based on the premise that each pore size has its own inherent irreducible water saturation. Given that relaxation time is related to pore size, this method core MR measurements to relate each relaxation time to a specific fraction of capillary bound water. Thus, the bulk volume irreducible determined becomes a direct output of the inversion of the echo data utilising the entire T2 distribution.

Core data are presented that demonstrate the Spectral Bulk Volume Irreducible (SBVI) petrophysical model and the method used for its characterisation. Log examples of SBVI implementation are presented to demonstrate the improvements brought by this development.

Environmental issues in pipeline facility abandonment

L.R. Denis[1] and J.B. Hinwood[1,2]
[1]Australian Marine & Offshore Group Pty Ltd
19 Business Park Drive
Notting Hill Victoria, 3168
[2]Department of Mechanical Engineering
Monash University
Clayton, Victoria 3168

A condition of offshore production licences in Australia, as in most countries, is that the operator undertakes to remove all facilities including pipelines. Frequently the operator will seek to leave the pipelines in place to avoid the costs of removal, but must then satisfy regulatory authorities that they pose no hazards to the environment or to recognised beneficial uses of the offshore zone. Wastes may be released into the

environment by release of the contents of the pipe and by the degradation of the pipe walls and coatings by mechanical and chemical action. Consideration of these issues is necessary for approval to be granted.

Mechanical or physical effects to be considered include:

- burial or exposure within bed sediments;
- detachment of weight and anti-corrosion coatings;
- breakup of the pipe (generally following corrosion);
- displacement of the pipe;
- provision of new hard substrate available for marine biota; and
- obstruction of shipping lanes or fishing grounds.

Chemical and water quality aspects to the considered include:

- release of hydrocarbons from within the pipeline or its lining;
- release of additives from within the pipeline or its lining;
- release of corrosion products from the pipe walls; and
- release of breakdown products from the pipe coatings and linings.

Ecological effects to be considered include:

- potential impact of water quality changes; and
- retention/loss of land substrate.

In reaching a recommendation in a particular case the above factors must be addressed, and it must be shown with reasonable certainty that recognised beneficial uses will not be disadvantaged. A strategy for reaching this position is outlined.

Greensand reservoirs in siliciclastic shoreline systems: facies models for hydrocarbon exploration

I.A. Dyson
National Centre for Petroleum Geology and Geophysics
University of Adelaide
Adelaide SA 5005

Greensand reservoirs are particularly significant in siliciclastic shoreline systems. Formation of autochthonous glauconite is restricted almost exclusively to the rising limb of the relative sea level (RSL) curve. Depositional environments that are typically developed in response to a rise in RSL are estuaries, barrier bars and shoreface sands. In this setting, the greensands are diachronous and exploration for hydrocarbon reservoirs should ideally be based on a sequence stratigraphic framework. These deposits are characterised by a number of significant surfaces that differ greatly in their origin, geographic extent and chronostratigraphic significance, and their thickness will depend on the rate of RSL rise and sediment supply. The identification of significant surfaces bounding or contained within depositional sequences is critical, especially where drillhole samples are either unreliable or not available for geochemical and palynological analysis. Abrupt physical and chemical changes often occur on or across these surfaces, e.g. porosity, permeability and the presence of Fe-rich authigenic minerals such as glauconite and siderite.

Greensands often overlie unconformities and disconformities that are associated with estuarine and storm-dominated shoreface deposits. The sequence boundary, transgressive surface, tidal ravinement surface and wave ravinement surface are readily identifiable on well logs and cores. The Mardie Greensand (Early Cretaceous) and South Maslin Sand (Early Tertiary) are excellent examples where greensand is best developed on ravinement surfaces. Sands overlying the tidal ravinement surface are favourable sites for early post-depositional precipitation of glauconite and locally can be quite thick (e.g. 10-20m) where they are erosional into thick, lowstand estuarine facies. Glauconite ideally forms from slightly alkaline marine water under reducing conditions and where the oxic-anoxic boundary is located close to the surface. Siderite is often associated with greensands where it is found within tidally-influenced shoreface sands beneath wave ravinement surfaces and high-frequency sequence boundaries. Within individual sequences, ($\delta 13C$ and ($\delta 18O$ display an abrupt increase across the sequence boundary and flooding surface, suggesting a strong meteoric influence on the formation of siderite. Storm-dominated shoreface sands overlying the planar wave ravinement surface are typically sheet-like and relatively thin. If the transgression is rapid and step-like, coupled with an abundant sediment supply, there is potential for development of barrier reservoir sands. Preservation of transgressive barrier bars during erosional 'shoreface retreat' and 'in-place-drowning' may occur under different rates of sea level rise, sediment supply and coastal subsidence. Periods of rapid RSL rise and low sand supply favour in-place drowning, whilst conditions of slow RSL rise and high sand supply favour shoreface retreat. If the rate of RSL is slow compared with the rate of landward erosion, almost all of the barrier system will be destroyed because of wave reworking and only a pebble lag overlying a wave ravinement surface will be present. When high-frequency forced regressions are superimposed on the low-frequency transgression, a series of stacked high-frequency incised valley fills may form above the wave ravinement surface. Deposition of storm-dominated shoreface sands may occur during a stillstand, slow rise or slow fall in RSL. In siliciclastic shoreline systems dominated by active subsidence and abundant sediment supply, a fall in RSL is most likely to have occurred in a series of punctuated events, resulting in deposition of erosive attached and detached shoreface sands. The development of such bodies is attributed to forced regression.

Ancient estuary, barrier bar and shoreface complexes deposited on the rising limb of the RSL

curve have excellent oil and gas source potential. These sand bodies are typically very well sorted. They are replaced updip by lagoonal shales and are overlain by transgressive marine mud rich in organic matter that together provide impermeable barriers necessary for the development of stratigraphic traps. The channelised morphology of the tidal ravinement surface is an excellent stratigraphic trap. Shoreface sands overlying the wave ravinement surface may be prospective if high subsidence created enough accommodation for vertical stacking of several individual reservoirs. These sand bodies are best developed in the transgressive and forced regressive systems tracts where multiple pay reservoirs are with potential hydrocarbon source units. Recognition of estuarine, shoreface and barrier bar deposits is dependent on the correct identification of facies and the subsequent interpretation of the bounding discontinuities. Vertical facies successions can indicate the type of shoreline being transgressed, whether it is tide or storm-dominated, whether there may be thick shore-normal or shore-parallel sand bodies along depositional strike, or whether extensive estuarine channel or valley-fill deposits are likely to be present. It is necessary to map the distribution, diagenesis and facies of individual parasequences or high-frequency sequences to understand differences in reservoir quality within the greensand succession. Radiometric dating of glauconite has the potential to provide calibration of biozones and age-dating of specific depositional sequences.

This is an abstract of a paper being prepared for presentation at the APPEA Conference. The final paper will appear in Part 2 of the 1998 APPEA Journal.

The South Tasman Rise—a frontier petroleum province south of Tasmania

N.F. Exon, P.J. Hill and A.M.G. Moore
Australian Geological Survey Organisation
GPO Box 378
Canberra ACT 2601

The 200,000 km^2 South Tasman Rise (STR) is a continental fragment, surrounded on three sides by Late Cretaceous and Palaeogene oceanic crust, which assumed its present configuration in the Palaeogene. The western margin of STR is the 2,000 m high Tasman Escarpment, the northernmost part of the Tasman Fracture Zone. The three structural blocks of STR, separated from Tasmania by thinned continental crust, moved southward with Antarctica from Tasmania in the Late Cretaceous and Palaeogene. All were affected by northwest-southeast strike-slip motion initially, and north-south extension in the Eocene and Oligocene. The western block, which moved from west of Tasmania and suffered the most tectonism, consists of large basement highs and the complex Ninene Basin. Basins on all three blocks are generally fault-controlled and are believed to contain Late Cretaceous to Early Oligocene detrital deltaic sedimentary rocks, and Late Oligocene and younger bathyal to pelagic chalk and ooze. The Ninene Basin is more extensive and generally somewhat thicker (up to five kilometres) than basins on the other two blocks.

No commercial exploration has been carried out, although there is a cored Deep Sea Drilling Project hole. About 10,000 km of seismic data and a number of dredge hauls and surface cores make up most of the database. All three blocks on STR have some petroleum potential, with thick sediments and structures. Deltaic Eocene mudstones are known to have source-rock potential, as may older deltaic sequences identified seismically. Geochemical analysis of Quaternary sediment cores has shown that hydrocarbons are being generated. Because deep, isolated rifts developed early in the basin history, there is a good chance that anoxic source rocks are present at depth. Potential reservoir rocks may include Late Cretaceous and Palaeogene turbidite sands.

The western block contains narrow basins, trending west-northwest to west, that wrap around the basement complexes in the north. Further south, in the Ninene Basin, many structures trend north-south or northwest, apparently reflecting the two shear directions, and transpressional features are evident. The long history of basin formation explains the relatively thick sequences interpreted as Late Cretaceous to Early Eocene.

Because of the great water depths over the Ninene Basin and the eastern block, any pioneer petroleum exploration would concentrate on the shallower central block, where water depths are 800–1,500 m. The central block is characterised by basement highs cut by narrow faulted basins that were probably localised by the older northwesterly strike-slip faults, and later further developed in response to north-south stretching between Australia and Antarctica in the Early Tertiary. However, there is also some evidence of transpression in the north. The Late Cretaceous to Early Oligocene detrital deltaic sedimentary sequence is up to 4,000 m thick, and unconformably overlain by less than 200 m of younger chalk and ooze. Although comparatively little is known about the basins on the eastern block, the available data suggest that they are similar to those on the central block.

PRINCE—managing E&P and data

G.R. Farebrother
Pacific Resource Information Centre
68 Pineapple Street
Zillmere Qld 4034
gfarebro@prince.qld.gov.au

By making seismic data and related information readily accessible, the Pacific Resource Information Centre (PRINCE), a joint venture between the Queensland department of Mines and Energy (DME) and the CSIRO, is designed to increase exploration and production activity. Once data is easy to retrieve, it can be periodically reprocessed using more effective algorithms and techniques. This has the potential to reveal overlooked hydrocarbon traps.

The PRINCE databank has a highly scalable infrastructure. Scalability enables the facility to handle virtually any quantity of data over the long term while maintaining or improving the databank's performance and preserving PRINCE's hardware and software investment.

The databank has a current storage capacity of 28 terabytes scalable to 300 terabytes by fully populating the robotic silo. By adding silos and tape drives PRINCE can further scale the system's capacity to thousands of terabytes. However, the current capacity can hold all of Queensland's current E&P data with ample space for the storage and management of other interested parties data.

PRINCE faces a daunting challenge. About 50,000 reels of 1/2-inch 9-track tape holding roughly four terabytes of seismic data need to be accurately data based, transcribed and RODE (Record Oriented Data Encapsulation) encapsulated. The Department's Exploration Data Centre, that houses PRINCE, also stores well logs, maps, film and sepia sections, company reports and other documents and artefacts pertaining to Queensland E&P projects conducted over the past century. This support data is being scanned, databased and logically linked to the digital data.

The transcription of data began in February 1996 and the first 30,000 tapes should be completed by early 1999. Field and processed data are being stored in the format in which they were originally recorded (RODE encapsulated), including SEGB, SEGD, SEGY and UKOOA. There is also LIS and LAS format well data, and CGM+ files submitted in lieu of film or sepia sections.

E&P data management remains a significant stumbling block to efficient geoscience, imposing major costs on explorers. However, emerging terabyte databanks such as PRINCE are integrating often-chaotic legacy data sets to make valuable information readily accessible.

Geologically based stochastic models: the best answer for reservoir modelling?

A. Galli[1] and C. Ravenne[2]
[1]Centre de Geostatistique-Ecole National Superiere des Mines de Paris
35, Rue St Honoré
77305 Fontainbleu
France
[2]Institut Francaise du Petrole-Service Geologie
1 et 4 av. de Bois Préau
92852 Rueil Malmaison Cedex
France

By the late 1980s, it was widely acknowledged that geology was one of the key factors controlling heterogeneities in reservoirs. Consequently, the petroleum industry has been increasingly using two-step stochastic models. The first step replicates the geology, then the petrophysical values (porosoties, permeabilities) are generated in accordance with simulated geology.

After reviewing the main types of stochastic models (in particular, pixel versus object models), we address he following questions:

- which geological data and information have a marked impact on the geometry of the internal architecture of the reservoir? For example, the size and type of channels are very important, as is their position in the sedminatry sequence.
- is there any way to determine these parameters from the data available on the subsurface field?
- how does outcop information help us? How can statistics calculated on outcrops be used on an actual field?

Then we discuss some of the available models showing their potential for respecting these features. Finally, we illustrate the imact of upscaling permeabilities on different models.

Structural restoration across the Timor Sea: implications for fault-style, basin formation and uplift

K.C. Hill[1], G.T. Cooper[2], G. Chen[1] and G.W. O'Brien[3]
[1]Australian Geodynamics Cooperative Research Centre
VIEPS School of Earth Sciences
La Trobe University
Melbourne Victoria 3083
[2]Santos Ltd
101 Grenfell Street
Adelaide SA 5000
[3]Australian Geological Survey Organisation
GPO Box 378
Canberra ACT 2601

In the Timor Sea area, balancing of sections, using Geosec™ has demonstrated that an interpretation of listric faults is not valid and that steep-dipping planar faults are more likely. In the areas of domino faults, as on the Ashmore Platform, these planar faults appear to pass into a ductile zone at 4–8 km. Many of the significant Miocene faults are related to underlying Late Jurassic extensional faults, although the relationship is often not a simple one. The Miocene fault extension is small (1–2 per cent) so the reactivated faults pass up into the Miocene section as overlapping vertical and lateral relay faults. Thus the offset of a single fault is likely to be small such that the risk of breaching may be small.

Our section restoration suggests that in the early Mesozoic, the Ashmore Platform was buried by an additional 2.5–3 km of Triassic-?Jurassic strata, consistent with the Vulcan sub-basin and Timor Trough on either side. This leads to the following Mesozoic geological history: Minor regional Triassic extensional faulting (1-2 per cent) was followed by a more significant faulting event by the Late Jurassic, with 10 per cent extension across the Ashmore Platform, but <1 per cent across the Cartier Trough-Jabiru-Challis area. Initial down-faulting of the Swan Graben and Skua Syncline occurred in the Callovian and may have been related to uplift of the Ashmore Platform at that time. The steep-dipping, planar faults observed do not appear to detach at a constant horizon, but rather at a common intial depth of 4–6 km, perhaps controlled by water depth in the adjacent new ocean basins, but locally by a suitable incompetent horizon (e.g. Mount Goodwin).

Balancing and restoration of a further six regional lines across the Vulcan Sub-basin is placing constraints on some of the pre-Callovian structure of the area and the timing and amounts of uplift and erosion. Linking of these sections in three dimensions using 3D Geosec will aid in determining migration paths, changing trap morphology in time and potential sites of breaching.

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The frontier west Tasmanian petroleum province

P.J. Hill[1], N.F. Exon[1], W. Lodwick[2], A.J. Meixner[1] and A.M.G. Moore[1]
[1]Australian Geological Survey Organisation
GPO Box 378
Canberra ACT 2601
[2]Bureau of Resource Sciences
PO Box E11
Kingston ACT 2604

The continental margin off west Tasmania is a 100,000 km^2 frontier petroleum province that contains the Sorell and southernmost Otway Basins. It has a thick fill of late Mesozoic and Cainozoic sediments. Petroleum exploration dates back to the 1960s. Recent industry activity (early 1980s, Amoco; early 1990s, Maxus) has concentrated in the Strahan Sub-basin off the central west coast. Only four exploration wells have been drilled on the margin, two of which (Clam–1 and Cape Sorell–1) are in the Sorell Basin.

To better understand its tectonic evolution and basin development, and hence its petroleum potential, the Australian Geological Survey Organisation (AGSO) has, since 1994, acquired substantial and diverse new data sets off west Tasmania through multibeam sonar swath-mapping, deep seismic, aeromagnetic and geological sampling surveys. Integrated interpretation of these various new data sets, with pre-existing survey data and satellite gravity imagery, has significantly advanced our knowledge of its geological framework and the processes leading to its formation.

The margin has a 30–55 km wide continental shelf, a continental slope with variable relief due to canyon development and uplifted fault blocks, and an abyssal plain at about 5,000 m depth underlain by Palaeogene oceanic basement. Cretaceous depocentres on the shelf and upper slope are typically of half-graben or v-shaped geometry, deep and narrow, and appear to be transtensional. These depocentres are surrounded by relatively shallow Precambrian to early Palaeozoic basement and are 2–4 s twt (approximately 2–5.5 km) thick. Sediment thickness beneath the continental slope is generally 2–5 s twt. The lower continental slope is a highly-faulted, 60 km wide zone of uplifted basement

blocks with considerable igneous intrusion. A strong, angular mid-Cretaceous (?Cenomanian) unconformity is coeval with uplift of the Otway Ranges and the eastern Otway Basin. The Late Cretaceous and older section has been considerably deformed, mainly by normal faulting generally dipping seaward, ranging from near-vertical to low-angle listric. Reverse faulting and gentle to moderate folding are also evident. Though most faults extend only to the top Cretaceous, minor faulting extends into the Palaeogene in some areas, particularly nearshore and adjacent to the Tasman Fracture Zone.

The Sorell Basin evolved by continental wrench tectonics during initial rifting between Australia and Antarctica in the latest Jurassic to earliest Cretaceous. In the Late Cretaceous, left-lateral strike-slip developed into transtension; seafloor spreading began to propagate eastward into the Otway-Sorell rift in the latest Cretaceous. At this time (Late Cretaceous) marine deposition first commenced—within elongate downwarps and in narrow, fault-controlled depocentres on the upper margin. The last major wrenching episode was Maastrichtian-Paleocene, coinciding with breakup off west Tasmania. Thick Palaeogene prograding sequences were deposited, first in the north and then farther south, as the margin collapsed and spreading moved relatively south. Minor wrenching, mainly by reactivation of older structures, continued into the Palaeogene as the Australian and Antarctic continental plates separated by shearing in a north-south direction. The Palaeogene wrench reactivation was confined mainly to the upper margin (including the Sorell Fault Zone), and was associated with transform movement along the Tasman Fracture Zone and its northerly extension.

More than half the margin has sediment thicker than two kilometres, and at least six kilometres of Cretaceous-Tertiary section is present in places. Petroleum has been generated in the Sorell Basin, at least in the Strahan and Sandy Cape Sub-basins. Indications include live oil in Cape Sorell–1, high concentrations of thermogenic hydrocarbons recorded in surface geochemical surveys, and direct hydrocarbon indicators (flat-spots) in Strahan Sub-basin seismic sections. Untested prospects and leads exist where early depocentres may well have been restricted and poorly oxygenated, favouring the formation of petroleum source rocks.

Experiences with lithology and fluid prediction from seismic data, offshore Western Europe

A.C. Kemp, J.W. Gallagher, N. Steinsland and O. Riise
Statoil
4035 Stavanger
Norway
acke@statoil.no

Recent licensing rounds have made increasing demands on techniques for the prediction of lithology and fluid variation from seismic data, leading to wide use of the analysis of amplitude variation with offset (AVO) in prestack seismic data, the conversion of poststack seismic traces to impedance logs (inversion), and the modelling of the anticipated surface seismic response based on well log data.

AVO analysis, inversion and modelling techniques are constantly being refined to improve the prediction of lithology and fluid type from seismic data and, while one technique can often give significant results on its own, the integration of these methods in a combined study of the seismic response both before and after stack imposes significantly greater constraints on the modelling process —thus reducing the inherent ambiguity and improving the quality of the predictions.

Recent experience with lithology and fluid prediction has given encouragement to the use of such techniques, while uncovering pitfalls which can be avoided by careful processing and analyses of the original data. With the large volumes involved in 3D data sets and prestack seismic analyses, a balance has had to be made between efficiently analysing these large volumes of seismic data and taking into account the need to look in detail at the data contributing to any sophisticated analysis. AVO analysis, for example, has many useful techniques for compressing the volume of data to be analysed but to decrease the risk associated with such interpretation there is no substitute for going back to the individual gathers and checking the source of promising anomalies.

The increased use of multiple versions of 3D datasets allows the interpreter to directly compare and analyse alternative versions of the data, each optimised to highlight a particular attribute. By comparing results from the different volumes a powerful discriminator can be provided in the search for anomalies which may indicate lithology and/or fluid changes.

Cases will be shown demonstrating the benefits and pitfalls associated with these techniques.

A petro-acoustic study of Cooper Basin sandstones

A. Khaksar[1] C.M. Griffiths[1] and C. McCann[2]
[1]National Centre for Petroleum Geology and Geophysics
Thebarton Campus
University of Adelaide
Adelaide SA 5005
[2]Postgraduate Research Institute for Sedimentology
University of Reading
Whiteknights PO Box 227
Reading RG6 6AB United Kingdom
akhahsar@ncpgg.adelaide.edu.au
cgriffit@ncpgg.adelaide.edu.au
c.mccann@reading.ac.ac

To date more than half of the proven and probable estimated conventional gas has been exploited from the sandstone reservoirs in the Cooper Basin. Hydrocarbon production causes changes in dynamic reservoir properties such as pressure and fluid saturation. Knowledge of the magnitude of such variations is essential for the exploration of unaccessed reserves and the optimising of the performance of existing fields.

A petro-acoustic study carried out to investigate the influence of effective pressure and fluid saturation on the compressional and shear wave velocities on a set of representative samples from gas producing fields in the Cooper Basin. The suite of samples consists of 22 sandstones from 1,917 to 2,564 m depth with porosity ranging from 2.6 to 16.5 per cent. A reflection technique was used to measure the ultrasonic wave velocities in dry and water saturated cores under effective pressures of 5 to 60 MPa.

Both Vp and Vs in the Cooper Basin sandstones increase non-linearly with effective pressure with the pressure influence being stronger below 40 MPa. The increase of velocity with effective pressure is due to the closure of crack-like pores which hardly affects the porosity but significantly increases the bulk and shear moduli of the samples. For water saturated rocks the finite modulus of the water increases the bulk modulus of the rock and resists the closures of cracks. Vp in dry samples shows the greatest stress sensitivity whilst there is no significant difference between the pressure dependency of Vs in dry and water saturated samples.

The stress sensitivity of the Cooper Basin rocks appears to be large when compared with data in the literature. A 10 MPa increase in the in situ effective pressure causes up to 12 percent increase in the wave velocities in the studied samples. A wire-line sonic log could detect such a change of velocity with effective pressure. At 2,500 m depth in the study area, a gas producing reservoir may show effective pressure of ranging from 28 (non-depleted) to 50 MPa (highly depleted). There are examples of apparent low sonic porosities in partially pressure depleted gas fields in the southern Cooper Basin. Combining field data with the results of laboratory acoustic measurements confirms that the velocity anomaly due to higher effective stress causes the sonic log to read too low in pressure depleted reservoirs. Neglecting this pressure effect results in anomalously low sonic porosities if the porosity is calculated by conventional sonic porosity methods. A mechanism is proposed to calibrate the sonic tool response to the reservoir pressure variations for the Cooper Basin rocks.

The strong stress sensitivity and the distinct Vp/Vs values for dry and water saturated Cooper Basin cores suggest that the dynamic changes in pressure and saturation of the reservoir rocks may also be detectable from other field velocity data such as VSP and time-laps seismic (4D) surveys. Our petro-acoustic study also has implications for direct hydrocarbon detection techniques and seismic reservoir characterisation in the Cooper Basin and similar regions.

The total management of NORM in the offshore petroleum industry

J. Kvasnicka
Radiation Detection Systems
10 Allendale Grove
Stonyfell SA 5066

ABSTRACT

Naturally Occurring Radioactive Materials (NORMs) in the offshore petroleum industry are generally associated with the formation of scale in pipes and vessels. As scale and sludge contain radioactive isotopes of radium they are in the category of Low Specific Activity (LSA) NORMs. Handling of NORMs creates issues involving occupational health and safety, environmental protection and radioactive waste management and waste disposal. Barium (Radium)Sulfate scale is highly insoluble and can create serious production problems by clogging pipes and valves.

The paper discusses the external gamma radiation monitoring at the external surfaces of well and oil production pipes which assists in establishing the scale thickness patterns in pipes and in identifying the optimum location of a scale inhibitor injection point.

In order to minimise radiation doses of workers special NORM handling Work Procedures and Instructions supported by radiation protection training are to be developed. Provided facility personnel are trained in radiation protection and Work procedures and Instructions are adopted it is possible to manage personal radiation exposures below the public limit of 1 millisievert per year. Under such conditions no personal radiation monitoring during routine operations is required and the assessment of routine annual external radiation doses may be carried out through yearly external gamma radiation surveys of

offshore petroleum production facilities.

The NORM waste can not be disposed of onshore with general non radioactive waste. Only the NORM waste generated in Western Australia can be disposed of onshore in an official low level radioactive waste disposal facility. Considering that the NORM waste generated by operators outside Western Australia canít be disposed of onshore it is important that relevant Governments and regulations address this NORM waste disposal option. The regulations should also address a screening method for scrap metal contaminated by MORMs to be released for smelting.

This is an abstract of a paper being prepared for presentation at the APPEA Conference. The final paper will appear in Part 2 of the 1998 APPEA Journal.

The Heavitree Quartzite, Amadeus Basin, central Australia—a neoproterozoic (c.800-760 Ma) tidal association with reservoir potential

J.F. Lindsay
Australian Geological Survey Organisation
GPO Box 378
Canberra ACT 2601

The Neoproterozoic Heavitree Quartzite is widespread in the Amadeus Basin and has correlatives in all of the major central Australian intracratonic basins. The origin of the formation is enigmatic, not only because of its widespread distribution and uniformity of composition, but also because intense silicification makes facies studies difficult. Recently discovered exposures in a major cliff section on Limbla Station at the eastern end of the basin are relatively free of diagenetic quartz allowing for the first time a more detailed study of sedimentary structures and an understanding of the architecture of the formation.

The formation was deposited as a series of stacked tabular sand sheets the architecture of which is defined by at least four depositional sequences. Planar cross beds are the most abundant sedimentary structure although horizontal lamination is present in many sand bodies. Herring-bone cross stratification, recumbent cross-stratification, abundant reactivation surfaces and mudcracks all provide support for a largely high energy tidal origin for the formation.

Deposition was controlled, to a large degree, by basin subsidence, sediment supply and eustatic cycles. In the early stages of deposition, mud-dominated tidal-flat environments alternated with higher energy sand-dominated subtidal settings. However, in the later stages of deposition a major eustatic fall moved base-level basinwards. As a consequence, earlier sediments were reworked by streams, gravel was carried well into the basin and fines largely disappear from the environment. Gravel deposition was followed by a return to high-energy, subtidal sand deposits including large sand waves. Upward change to shallow-marine, anoxic deposits of the Bitter Springs Formation is gradational and reflects increased accommodation concomitant with reduction of the clastic flux as slightly deeper marine conditions overtook large areas of the basin.

In the past, the Heavitree Quartzite was regarded as having poor potential as a hydrocarbon reservoir on the basis that it was seen to be heavily silicified. The occurrence of relatively unaltered sandstone in the Limbla cliff sections suggests that the observed diagenetic alteration of the formation in the MacDonnell Range may be anomalous and the result of fluid movement along deep thrust faults associated with the development of the MacDonnell Homocline by the Palaeozoic Alice Springs Orogeny. If this is so, the formation, because of its extent, may well have considerable hydrocarbon potential especially since it is overlain by an anoxic shale interval at the base of the Gillen Member of the Bitter Springs Formation. The shales and overlying evaporites could provide an ideal source and seal.

Quantitive simulation of variability of the sequence stratigraphic model with examples from the North West Shelf, Australia

K. Liu[1], C.M. Griffiths[2] and L. Patterson[3]
[1]School of Earth Sciences
James Cook University
Townsville Qld 4811
[2]APCRC and National Centre for Petreoleum
Petroleum Geology and Geophysics
Thebarton Campus
The University of Adelaide
Adelaide SA 5005
[3]APCRC and CSIRO Petroleum
PO Box 3000
GlenWaverley Victoria 3150
Keyu.Liu@jcu.edu.au
cgriffiths@ncpgg.adelaide.edu.au
Lincoln.Paterson@dpr.csiro.au

Two computer programs, SEDPAK and SEDSIM, were employed to quantitatively model the influences of the basic parameters (sediment, flux, eustasy, tectonism and basin physiography) that control facies distribution and stratal architecture in depositional sequences and sedimentary basin fill. SEDPAK is a 2D empirical computer program based on geometric rules that govern gradients and stacking patterns of sedimentary strata. SEDSIM is a 3D process-driven computer program based on equations governing

sediment-water fluid dynamics and constrained by conservation of energy and momentum.

The simulation results were presented in an atlas format. They provide various useful 2D and 3D graphic templates that can be used directly by exploration geologists and reservoir engineers to envisage various possible scenarios given a set of input parameters.

The quantitative simulation and analysis of the variability of the sequence stratgraphic model was accompanied by case stidues from the Barrow and Dampier Sub-basins, North West Shelf, on both basin and reservoir scales. This paper has demonstrated that such a quantitative stratigraphic modelling approach can play an important role during various stages of hydrocarbon exploration. The programs are able to provide geologists and reservoir engineers with a quantitative and yet deterministic alternative to their conventional seismic and stratigraphic approach.

Potential impact of greensand mineralogy on reservoir quality: An example from the Eocene South Maslin Sand in the St. Vincent Basin, South Australia

J. C. Matthews and I. Dyson
National Centre for Petroleum Geology and Geophysics
Thebarton Campus
University of Adelaide
Adelaide SA 5005

A major study at the NCPGG is currently focussed on the nature of the Cretaceous greensands of the North West Shelf and their potential as hydrocarbon reservoirs. Of particular interest is the mineralogy of greensands and its effect on reservoir quality. A key to understanding the nature of these greensands is comparison with similar units in other basins. The Middle Eocene South Maslin Sand (SMS) is a potential outcrop analogue for the Mardie Greensand reservoirs.

The SMS was deposited in the intracratonic St Vincent Basin of South Australia under estuarine and shallow marine conditions. At Maslin Beach, it overlies fluvial and estuarine sediments of the North Maslin Sand with an erosional disconformity. Standard petrography, XRD and SEM combined with elemental analysis indicate that there are a number of authigenic clay types present in the SMS. With continued burial, the potential impact on reservoir quality for each type of clay is quite variable. The most common clays are a 10 to 20 micron-thick compact layer of glauconitic illite coating quartz grains and a green clay-matrix filling some pores or associated with iron-oxyhydroxide-rich ooids or pisoliths. The glauconitic illite has a fairly restricted composition and probably contains a few percent of expandable layers. Whether this type of grain-coating clay would transform with increasing burial depths into illite, into chlorite or remain unchanged is unclear. By its compact nature and the fact that is completely coats quartz grains, it should inhibit quartz overgrowths at depth. The green matrix-clay has a more variable composition and may contain berthierine or iron-rich smectite. Either clay would be likely to transform toward an iron-rich chlorite, although by different reactions.

Less abundant clays in the SMS include kaolin and smectite. Lenses of kaolin found in the estuarine facies are interpreted to be re-sedimented clay clasts that probably formed under the influence of acidic, meteoric water. These clasts are not volumetrically significant and will have little impact on reservoir characteristics. Thin millimetric stringers of iron-rich smectite are also found in some of the estuarine deposits. With increased burial they may be plastically deformed and injected into pore space in the adjacent sand stringers and eventually transform into iron-rich chlorite, possibly through a corresite-type mixed-layer clay. Clay coatings on quartz grains will inhibit quartz cementation and this can preserve reservoir quality to great depths. On the other hand, matrix clay will reduce effective permeability as a function of its abundance. The iron-rich nature of the sediments and clays in them would certainly require care in drilling and development.

These results for the SMS are compared to the mineralogy of the Mardie Greensand.

Concept of FSPO (Floating Storage and Production Operations) telecommunications

J. Meehan
TELEMATIKA (Australia) Pty Ltd
185 Pinjarra Road
Pinjarra Hills Queensland 4069
berridge@bigpond.com

The telecommunications networking of an FSPO tanker with other off-shore facilities such as fixed production platforms calls for unique solutions. There are several issues involved. The integration of voice, fax and data on one link calls for a high bandwidth radio signal normally accommodated utilising microwave frequencies. Such high bandwidths are not recommended on UHF or VHF frequencies due to the limited spectrum available in these bands. Utilising microwave links off-shore however, can have it's own problems such as multipath reflections resulting in deep fades and loss of traffic. Issues like height of tide, fetch, wave shape and form, all come into play. An FSPO by nature does not only rise and fall with the tide relative to the fixed production platforms, but it also can revolve 360 degrees around the mooring presenting a constant changing bearing in relation to the platform. Standard microwave links cannot cope with this

movement as the signals have a very narrow, fixed beam.

Two methods used in an attempt to overcome these problems are: (i) use of omni-directional antennas, which must be mounted clear of any superstructure obstruction, and (ii) to mechanically track the microwave directional parabola antenna on the FSPO respective to the fixed platform. Both solutions continue to have problems with issues such as omni antenna gain inefficiencies, continued multipathing effects, long expensive waveguide or foam filled cable runs from the high antenna to the below deck equipment and the subsequent signal losses, the installation and maintenance implications of antenna tracking equipment, and obtaining the traffic capacity the user requires.

A solution which overcomes all of these problems is now available.

The significant point is the use of the UHF band. This eliminates the potential of multipath reflections. Further, UHF frequencies are not so sensitive to feeder cable attenuation compared to microwave, and reasonably priced, low loss heliax cable can be run from the below deck equipment to the highest point on the FSPO with minimal loss. A UHF omni-directional antenna is also quite efficient yet easily mounted and would not present any great difficulty with installation compared with a tracking unit and parabola antenna. The spectrum efficiency problems can now be addressed using multiplexers with compression capabilities which can achieve the same traffic capacity on one eighth of the spectrum previously required. For example, up to 30 quality voice/fax channels, or a combination of voice and data channels, can now be provided.

For one TELEMATIKA project the customer was provided with four voice channels and still had 48 Kb of data capacity available. Another major advantage of this solution is a complete, state of the art, digital switch (PABX) is provided at both ends allowing total control of each individual channel and it's onward/inward connection into the network. Four data ports are provided (expandable), these can be independently configured for various interfaces and bit speeds which is only limited by the overall data capacity allocated.

Higher data speeds can be accommodated, but only with the loss of voice channels. The data circuits are completely separate from the voice channels on an electrical level and can be connected to a bridge, router, server or any common DTE directly from the back of the multiplexer. The digital signal representing the voice channels has a standard E1 telephone interface which connects directly into the PABX. Individual voice channels are not available at the output of the multiplexer.

TELEMATIKA has provided the overall telecommunications planning and fit out for several FSPOs, including the Udang field as the first FSPO and the first off-shore production from the Indonesian sector of the South China Sea.

Distribution, organic richness, maturity, and timing of hydrocarbon generation in the Cretaceous source rocks of the Otway Basin

K. Mehin[1] and A.G. Link[2]
[1]Minerals and Petroleum Victoria
3/115 Victoria Parade
PO Box 2145 MDC
Melbourne Victoria 3000
[2]Department of Civil and Geological Engineering
Royal Melbourne Institute of Technology
Melbourne Victoria 3000

Analyses of cores and drill cuttings from the Cretaceous interval at exploration well-sites across the Otway Basin included determinations of organic richness (Total Organic Carbon), maturity (vitrinite reflectance, Rock-Eval pyrolysis), organic material (organic petrology, bulk composition, gas chromatography) and biomarkers. If it can be established that about-to-be-drilled reservoir rocks are in close proximity and hydraulically connected to good source rocks, the costs and risks of exploration drilling may be minimal.

Results of studies of Early Cretaceous sections of the basin indicate that generally mature shaley rocks accumulated in the Portland Trough, and in both the Tyrendarra and Port Campbell Embayments. Although gas-prone macerals were shown to be abundant and wide-spread, oil-prone macerals which accumulated in mainly lacustrine environments in parts of the basin are locally abundant. Lateral variations in the thickness of rocks within floral time zones, such as in the *C. hughesi* (Aptian/Albian) zone, indicate that the various fault blocks within the basin subsided at different rates. This led to thick shaley sections accumulating in the most rapidly and deeply depressed blocks thus providing the best 'kitchens' as well as the largest volumes of organic matter content in these locations (Mehin and Link, 1995; 1996 and 1997).

Studies of the Late Cretaceous sequence showed that the sections in onshore areas are not as organically-rich as those in the offshore areas. Indeed, some of the richest horizons in the offshore areas contain more than four per cent total organic carbon. The offshore sections are also thicker and more mature. Although gas-prone vitrinitic macerals predominate, oil-prone liptinitic macerals may be locally abundant, as at Eric The Red–1 in the eastern offshore area of the basin. Oil-proneness is noticeably greater in rocks of *P. mawsonii* (Turonian/Cenomanian) age in the Voluta and Shipwreck Troughs.

Current studies of hydrocarbon generation in, and expulsion from Cretaceous rocks have so far indicated

that, for much of the Otway Basin, the organic-rich shales of Early Cretaceous age, rather than those of the Late Cretaceous age have been the main source of the known oil/gas shows and discoveries. The primary period of oil generation and expulsion occurred at 100--95 Ma. In western Victoria oil has also been expelled since 55 Ma and is probably still being expelled from source rocks. The initial pulse of gas expulsion occurred between 95–85 Ma; the overlapping second phase of gas expulsion has been in progress in offshore eastern Victoria since 90 Ma and is probably continuing at present (Mehin and Link, 1997).

Arafura Sea—Tertiary, Mesozoic, Palaeozoic and weathered basement plays

S. Miyazaki[1] and B. McNeil[2]
[1]Bureau of Resource Sciences
PO Box E11
Kingston ACT 2604
[2]Technology Research Center
Japan National Oil Corporation
1-2-2 Hamada Mihama-ku Chiba Japan 261
Shige.Miyazaki@brs.gov.au
mcneil-b@jnoc.go.jp

Substantial potential for petroleum accumulations exists in the Arafura Sea, the northern-most part of Australian waters. Exploration targets range from Tertiary, Mesozoic and Palaeozoic sandstones or carbonates to the weathered Pre-Cambrian basement.

Carbonates and clastic rocks of the Arafura Basin were deposited in various marine environments during the early to late Palaeozoic time. The northwest-trending Goulburn Graben emerged towards the end of the Palaeozoic. After having been deformed, block-faulted and then eroded, the Palaeozoic formations left with a peneplain over the graben in the Early Jurassic.

The deposition of sediments of the Money Shoal Basin began in the Middle Jurassic when the Arafura Sea transgressed over the smoothed, erosional surface of both the Arafura Basin and, in the inshore terrace, the Pre-Cambrian basement. These marine formations are generally monoclinic and undeformed, giving a sharp angular unconformity at the base.

Significant oil shows were encountered from Upper Jurassic, Carboniferous and Devonian sandstones and Carboniferous and Ordovician carbonates in four wells. Bitumen strandings have been known for many decades on southern shores of the Arafura Sea. Oil slicks were identified extensively at sea surface over the Goulburn Graben during an airborne laser fluoresence survey.

Both lenticular claystones interbedded with Jurassic sandstones and Early Cretaceous claystones have good potential for oil generation. The Jurassic section is mature, and the Early Cretaceous section is marginally mature for oil generation in the western Money Shoal Basin.

Organic-rich shaly units are present in the Cambrian, Devonian, Carboniferous and Permian sections of the Arafura Basin. Many source rocks of this basin are mature for oil generation determined by vitrinite reflectance or thermal alteration index.

Our new research on fluid inclusions has revealed that fairly immature liquid hydrocarbons are contained with gaseous hydrocarbons in fractures within Ordovician dolostones. These hydrocarbons have the same fluorescence characteristics as the oil shows, suggesting that the fractures were used as a transport pathway to reservoirs or leakage from them. The results confirm also that Palaeozoic source rocks still retain oil generative capability.

Jurassic and Early Cretaceous sandstones have good porosity, while Palaeozoic reservoirs (dolostones, limestones and sandstones) tend to be of low porosity. However, the Palaeozoic reservoirs are often fractured as shown on core samples and wireline borehole resistivity images. The Ordovician dolostones are so vuggy that they often caused drilling breaks and lost circulations.

We have identified six distinctive play types in the Arafura Sea:

1. Jurassic, Cretaceous or Tertiary fault rollovers;
2. Jurassic, Cretaceous or Tertiary subtle low-relief anticlines;
3. a 400 km long Tithonian and basal Cretaceous channel;
4. large-scale fault rollovers of Palaeozoic carbonates and sandstones in the Goulburn Graben;
5. northern outer Arafura Basin plays; and
6. onlapping Jurassic sandstones and weathered basement with secondary porosity on the inshore terrace.

Otway Basin deepwater margin

A.M.G. Moore and H.M.J. Stagg
Australian Geological Survey Organisation
GPO Box 378
Canberra ACT 2601

The northwest-trending Otway Basin straddles Australia's southeastern margin for some 500 km from Cape Jaffa in South Australia through Victoria to the northwestern tip of Tasmania, and covers an area of 150,000 km^2. While petroleum exploration has been confined to the onshore and shelfal areas, major sediment accumulations underlie the continental slope.

The Australian Geological Survey Organisation has acquired a range of innovative data sets in the basin to enhance understanding of its tectonic framework and petroleum potential. In 1994-5, a regional grid of more

than 3400 km of deep-seismic data (16 s record length) was acquired, from relatively unextended crust in the northeast to oceanic crust in the southwest. Refraction data recorded at land stations enable the crustal velocity structure to be determined. These data are providing our first look at the structural foundations of the Otway Basin, down to Moho depths.

Interpretation of the evolution of the Otway Basin has long been a contentious subject. In particular, the timing and extent of rifting, and the azimuth(s) of extension, have all been matters subject to disagreement. These disagreements may have arisen from the combination of the lack of high-quality regional data with the complex regional setting of the basin within a dominantly strike-slip margin.

The basin developed as an intra-cratonic rift in eastern Gondwana from the Tithonian through the Maastrichtian, as the crust between Antarctica and Australia extended. Initially, the rift was dominated by SE–SSE extensional transport, which produced WSW-trending extensional half-graben (e.g. Crayfish Platform, Robe Trough, Torquay Sub-Basin) and NW-trending oblique extensional features such as the Penola and Ardonachie Troughs. Elsewhere on the southern margin, this extension produced strike-slip basins and pull-apart troughs on the west Tasmanian margin and South Tasman Rise, but more-orthogonal extensional basins in the western Great Australian Bight. Slow-spreading oceanic crust may have been emplaced in the Great Australian Bight and westwards as early as the Valanginian. Sinistral relative lateral motion between the plates continued through the Cretaceous and into the Paleogene. Intra-basinal structural complexities were introduced where irregularities in the plate boundary alternately locked-up or released, causing transpression or transtension.

Transtension dominated, allowing extension between WNW-trending normal faults, and occasional submergence during the Late Cretaceous and Paleocene. This process was interrupted briefly by episodes of transpression at about 120-117 Ma, at about 85 Ma and in the latest Maastrichtian (about 67 Ma), which uplifted and eroded the extension-produced fault blocks. The progressive oblique separation of Antarctica along this margin during the Cretaceous and Paleocene results in an effective younging of the margin from Maastrichtian in the northwest Otway Basin to Early Paleocene off northern Tasmania. This is also reflected in the relatively late collapse of the outer margin of the Otway Basin when compared to the accepted timing of Australia-Antarctic separation. Outbuilding of a carbonate dominated shelf succeeded the collapse of the margin that followed the onset of fast sea floor spreading in a nearly north–south direction in the mid-Eocene.

New potential field and bathymetry grids in the Timor Sea

M. Morse and P. Petkovic
Petroleum and Marine Division
Australian Geological Survey Organisation
GPO Box 378
Canberra, ACT 2601

As part of the Australian Geological Survey Organisations (AGSO) Timor Sea Project, a major upgrade of the marine ship-track potential field and bathymetry data which have been acquired on the north-west Australian margin since 1963 has been undertaken. AGSO and Desmond Fitzgerald and Associates have developed techniques for correcting crossover and other errors in these data, thereby enabling the production of high quality images for interpretation.

The offshore data in the zone of interest, 9°–18° S, 120°–132° E, include BMR Continental Margins Survey (1970-73), AGSO Continental Margins Programme (1985-97), open-file company data, foreign surveys, and RAN Hydrographic Office data. Additional data from other sources were used in areas of sparse ship-track coverage. The wide range of data sources and variable navigation accuracies inherent in data of different vintages result in crossover errors being a dominant feature of any grid created from such unlevelled data. Images produced from such data are difficult to interpret as they are dominated by linear features which coincide with ship's tracks. Furthermore, AGSO's regional approach to data acquisition and integration has resulted in a marine shiptrack data-set with quite an irregular line distribution.

To integrate these data into a more useable form for accurate geological interpretation required development of specialised techniques. These new techniques now allow data which are irregularly distributed in space and time, and of varying quality, to be used to produce meaningful images. The offshore data were grided in conjunction with existing onshore databases to produce a suite of images of Bouguer anomaly, magnetic anomaly, and bathymetry/topography. These grids have been filtered and manipulated to produce various derivatives and composites to enhance the interpretability of the data. Enormous improvements upon the usefulness of the original data-sets have resulted from this approach.

Using Airborne Laser Fluorescence (ALF) on the North West Shelf: why, what and how?

A. Murray[1], G.W. O'Brien[1], D.S. Edwards[1] and P. Quaife[2]
[1]Australian Geological Survey Organisation
GPO Box 378
Canberra ACT 2601
[2]Resource Management Pty Ltd
Perth WA 6000
amurray1@agso.com.au

Airborne Laser Fluorescence or 'ALF' is one of a family of reconnaissance remote sensing techniques used to detect offshore hydrocarbon seepage. Despite its high sensitivity and relatively low cost, ALF has had a chequered history in the exploration industry, mainly due to lingering doubts about its ability to discriminate between seep oils, pollution and algae, and the difficulty in synthesising the results with other geochemical and geological information. In collaboration with companies and World Geoscience Ltd (the licensee of ALF), the Australian Geological Survey Organisation (AGSO) has carried out an evaluation of ALF and its application to Australia's North West Shelf petroleum province.

In order to resolve some of these perceived problems, the fluorescence spectra of ~60 Australian oils have been measured using a laboratory fluorescence spectrometer. These fluorescence results were then compared to the aromatic hydrocarbon distribution for the same oils, as measured by gas-chromatography/mass-spectrometry. This allowed interpretation of spectral features in terms of molecular parameters traditionally used to indicate maturity, source and degree of biodegradation and water-washing. The laboratory spectra were also compared with those obtained using the airborne system, which explained the red-shift commonly seen in the airborne spectra and allowed its true significance to be understood.

The high sensitivity of the fluorescence method means that very minor hydrocarbon seepage can be detected on the sea surface, whereas such subtle seepage would not be easily recognised in either satellite imagery or in bottom water geochemical sniffer data. For example, image processing of high resolution geochemical sniffer data from the Timor Sea has revealed the presence of areas of (previously unnoticed) very low levels of hydrocarbon seepage which relate directly to prominent (i.e. obvious) and large ALF anomalies.

In contrast to earlier models, ALF Mark III uses a 266 nm laser to excite fluorescence from the aromatic hydrocarbons in oils. Most of the light North West Shelf oils have peak emission wavelengths between 310 and 340 nm and are essentially invisible to the longer wavelength lasers used in the previous versions of ALF. Furthermore, density of data acquisition and efficiency of processing are also much improved. The capabilities and limitations of ALF, and its proper place in the hierarchy of reconnaissance remote sensing techniques, are shown, with particular reference to the North West Shelf petroleum systems.

Combination of horizontal well technology and multiple stage transverse fracturing—a new strategy to exploit tight, naturally fractured formations in central Australia

D. Naseby, S. Narayan, Z. Yang, and S.S. Rahman
The School of Petroleum Engineering
University of New South Wales
Sydney NSW 2052
sheik.rahman@nsw.edu.au

ABSTRACT

Vast, relatively untapped gas resources exist in formations of low permeability in Central Australia. In many such formations, natural fractures are most likely the primary production mechanism. These tight gas resources are already exploited to a large degree by hydraulic fracture stimulation, though fracture lengths and conductivities remain disappointing due to high prevailing in-situ stress conditions. The use of horizontal well technology is seldom practiced. However, the hydraulic fracturing of horizontal wells has the potential to further unlock tight gas resources more efficiently than currently practiced

In this study, we recommend a strategy that combines horizontal drilling and the creation of multiple stage transverse fractures in order to enhance wellbore productivities to achieve commercial gas production rates. It has been demonstrated that horizontal wells that take advantage of permeability anisotropy and localised high permeability zones ('sweet spots') can make a significant contribution to gas production from tight gas reservoirs.

A horizontal wellbore that is drilled in the minimum horizontal principal stress direction is most likely to encounter permeable naturally fractured zones, and may itself be economical. If the productivity of the well is not high enough, hydraulic fracture treatments in multiple isolated zones can be carried out, increasing productivity even further. When correct treatment procedures are employed, transverse fractures

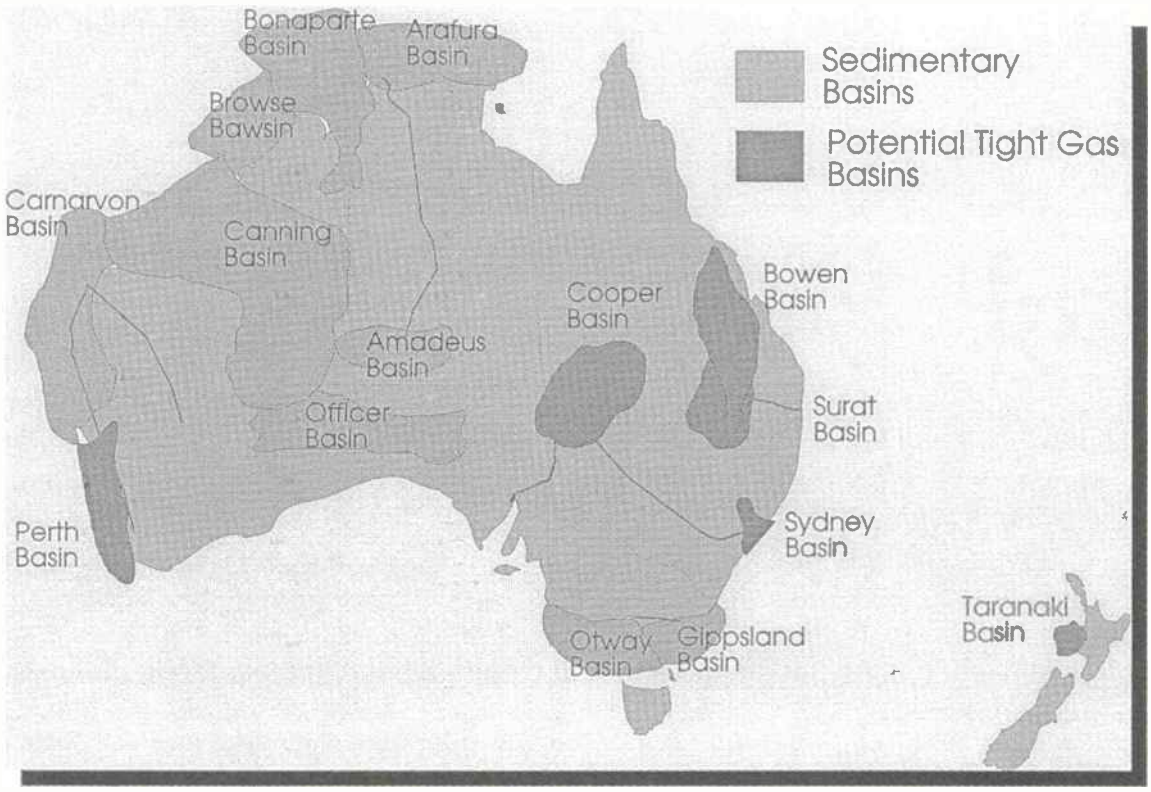

Figure 1. Potential tight gas resources in Australia and New Zealand.

(propagating perpendicularly to the wellbore) are initiated from a horizontal wellbore aligned parallel to the minimum horizontal principal stress.

INTRODUCTION

The Cooper Basin, in Central Australia, has vast, relatively untapped gas resources locked up in tight reservoirs. A tight gas reservoir is defined by the US Federal Energy Regulatory Commission as having a permeability of less than 1 mD, and a specified unstimulated gas flow rate. A reservoir is considered 'tight' in the Cooper Basin if it cannot be economically produced with the prevailing technologies and gas prices, predominantly due to the low reservoir permeability.

Traditionally, tight gas resources are exploited by hydraulically fracturing vertical wells. High in-situ stresses complicate the fracturing programs in some of these reservoirs, resulting in disappointing fracture lengths and conductivities. There is a great commercial potential throughout Australia (Fig. 1) for the successful production of tight gas fields, if producers can take advantage of new technologies that have been designed to exploit tight gas in the US in the last 20 years.

This study examines the issues related to tight gas production, including in-situ stresses and hydraulic fracturing, and discusses alternative methods to produce the resource economically.

Introduction to fractured horizontal wells

Hydraulic fracturing has been the major tight gas production tool for 25 years. New technologies have been developed in this period that have the potential to increase both the production rate and the ultimate recovery from tight gas reservoirs. Most important amongst these for application for Australian conditions is the horizontal well, and the logical next step, the fractured horizontal well (Figure 2).

The Central Australian tight gas reservoirs are excellent candidates for production from horizontal wells, as they have low permeability, with natural fractures that provide occasional moderate permeability 'sweet spots' ranging to tens of millidarcies. It has been demonstrated that horizontal wells that take advantage of permeability anisotropy and localised high permeability zones ('sweet spots') can make a significant contribution to gas production from tight gas reservoirs.

The fracturing of horizontal wells is an obvious

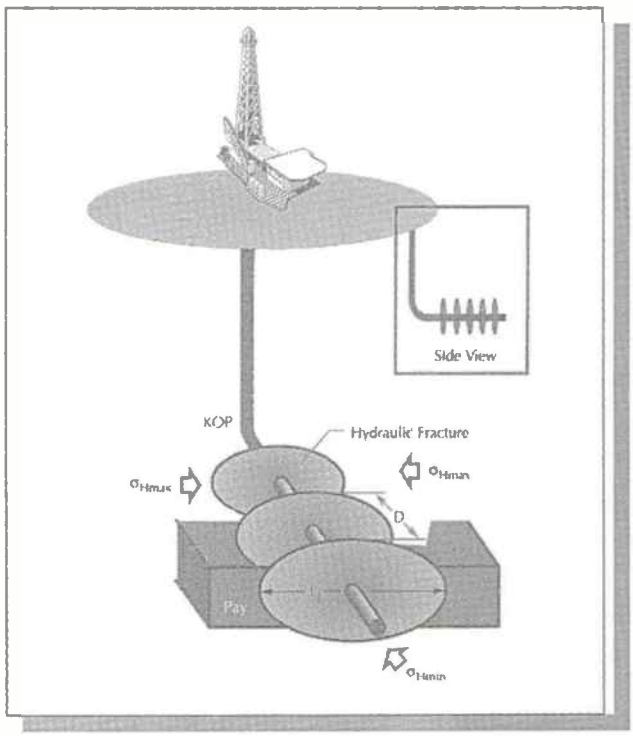

Figure 2. Fractured horizontal well.

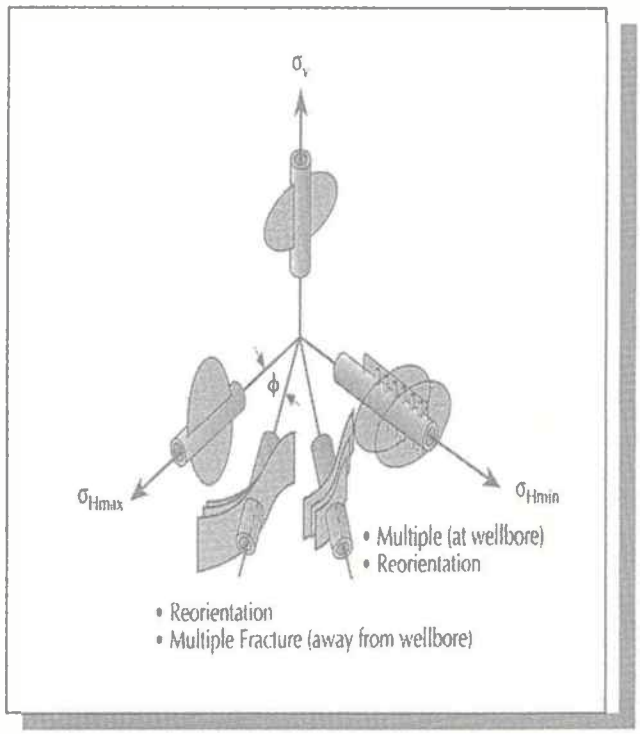

Figure 3. Fracture type according to orientation of well.

technological advancement over horizontal wells, providing even greater benefits to production. Hydraulic fracturing of horizontal wells should be considered if the productivity of the well is not high enough. Fracturing of horizontal wells is, however, the source of significant technical difficulties, such as multiple fracture initiation and re-orientation of the fracture during propagation, which must be solved before the tremendous potential that this technique promises can be realised.

Horizontal well and fracture orientation

Horizontal wells may be transversely or longitudinally fractured, according to the orientation of the well with respect to the prevailing in situ stresses (Figure 3). It is important to accurately determine the stress orientation when planning the trajectory of the well, as it must be oriented parallel to either the maximum or minimum horizontal principal stress in order to avoid shear effects that re-orient fractures and thereby cause a number of stimulation and production problems.

Transverse fractures occur when a horizontal well is drilled in the direction perpendicular to the maximum horizontal stress and the wellbore is later pressurised for a fracture treatment. Transverse fractures initiate and extend laterally away from the wellbore. Transverse fractures are usually quite small, and so have the advantage of not extending far beyond the formation of interest. They allow increased production rates, and multiple transverse fractures from a single wellbore can increase the total recovery. The major drawback of using transverse fractures is the level of precision required, as any miscalculation of stress orientation can result in a rough surface at the face of the fracture as it turns to re-orient itself with the direction of the least principal stress. Proper fracture initiation is also difficult, and so due attention must be paid to the orientation of the perforations and the length of the perforated interval.

Longitudinal fractures form and propagate parallel to the longitudinal axis of the wellbore, and they occur when the well is drilled perpendicular to the direction of minimum horizontal in-situ stress. They have the advantage of being able to create a series of fractures that span the entire length of the horizontal portion of the well. The stress orientation when planning this type of fracture is less critical than with transverse fractures, but it remains important. A longitudinal fracture will most likely not have as high a production rate as a transversely fractured well.

Issues to be addressed prior to application to central Australia

In order to progress with the study, a lot of data from Central Australian fields has been gathered and is being analysed at UNSW. Stress data is obtained from well logs and fracture tests. Geological and structural

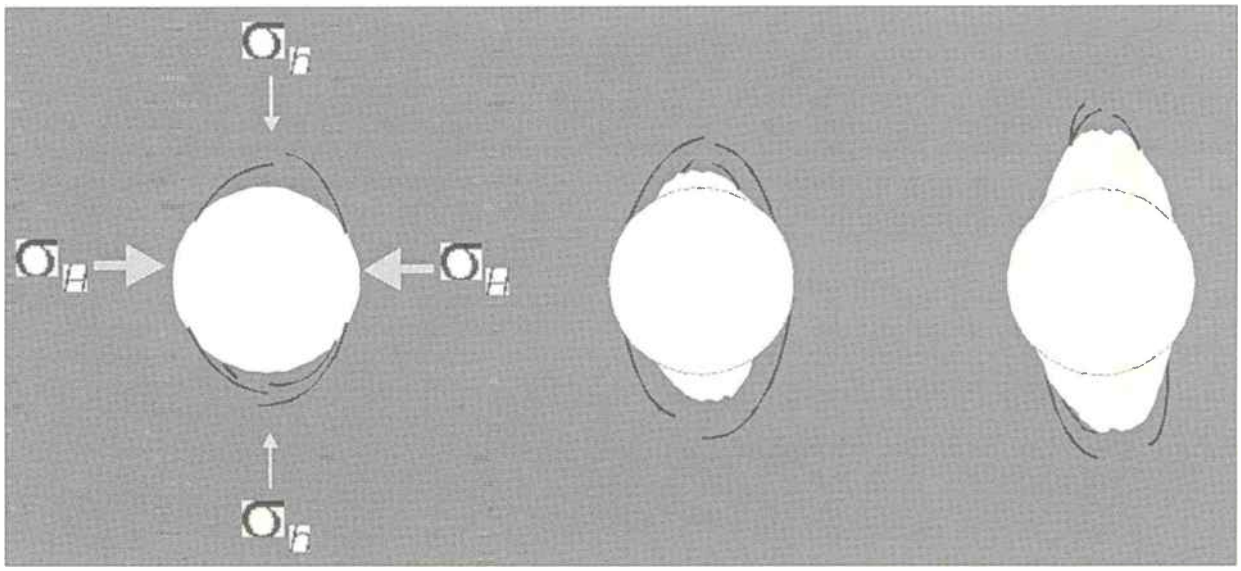

Figure 4. Development of borehole breakouts.

data must be analysed to determine the structural controls on in-situ stress magnitudes and orientations.

This data is processed and incorporated into numerical and analytical models that are aimed at studying and solving the wellbore completion and fracture treatment issues that have plagued some Central Australian tight gas fields.

Problems that have been observed when fraccing wells under high in-situ stress conditions in Central Australia include premature screen-out and high treating pressures, and low in-place proppant concentrations. Several theories have been developed to explain these difficulties, and they are currently being tested through modelling work.

Stress orientations in central Australia from wellbore breakout analysis

Wellbore breakouts are a mode of wellbore failure caused by compressive failure of the rock due to inadequate mud support in weak formations (Figure 4). Breakouts occur preferentially on the side of the wellbore wall parallel to the minimum in-situ stress. Thus, from a study of wellbore breakouts, the in-situ stress orientation may be determined.

The orientation of the maximum horizontal principal stress in Central Australia as determined by the study of breakout orientation is east-west trending. Local structural features appear to play some part in the orientation of the stress. Imaging tools are being employed in the next stage of the study as a result of their improved accuracy over four arm caliper techniques.

In situ stress magnitudes

The magnitudes of in-situ stresses in the Cooper Basin show a high degree of structural correlation. Figures 5 and 6 show in-situ stress magnitudes divided into several regions. The correlation between the trends in magnitudes of the stresses and the depth for each region is very good, and clearly delineates the broad trends in the stress regime. For instance, Region 1 (Figure 5) is a normal faulting regime bordering on strike slip, whereas Region 2 (Figure 6) has a marked reverse faulting stress regime.

Work is currently being undertaken at UNSW to further define the effects of local structures upon the regional stress field, and results are expected to be the subject of future papers.

Hydraulic fracturing of horizontal wells

Fractured horizontal wells are considered highly susceptible to localised multiple fracturing from the same perforated interval. Multiple fracturing is extremely problematic, causing a reduction in fracture width, proppant blockage and screenout and increased treatment pressures.

Experimental, numerical and analytical studies are being carried out at UNSW into understanding the processes leading to multiple fracture initiation and propagation from horizontal wellbores.

Transverse fracture initiation from horizontal wellbores

Multiple stage transverse fracturing is the major focus of this study as it has enormous potential to accelerate the rate of hydrocarbon production from

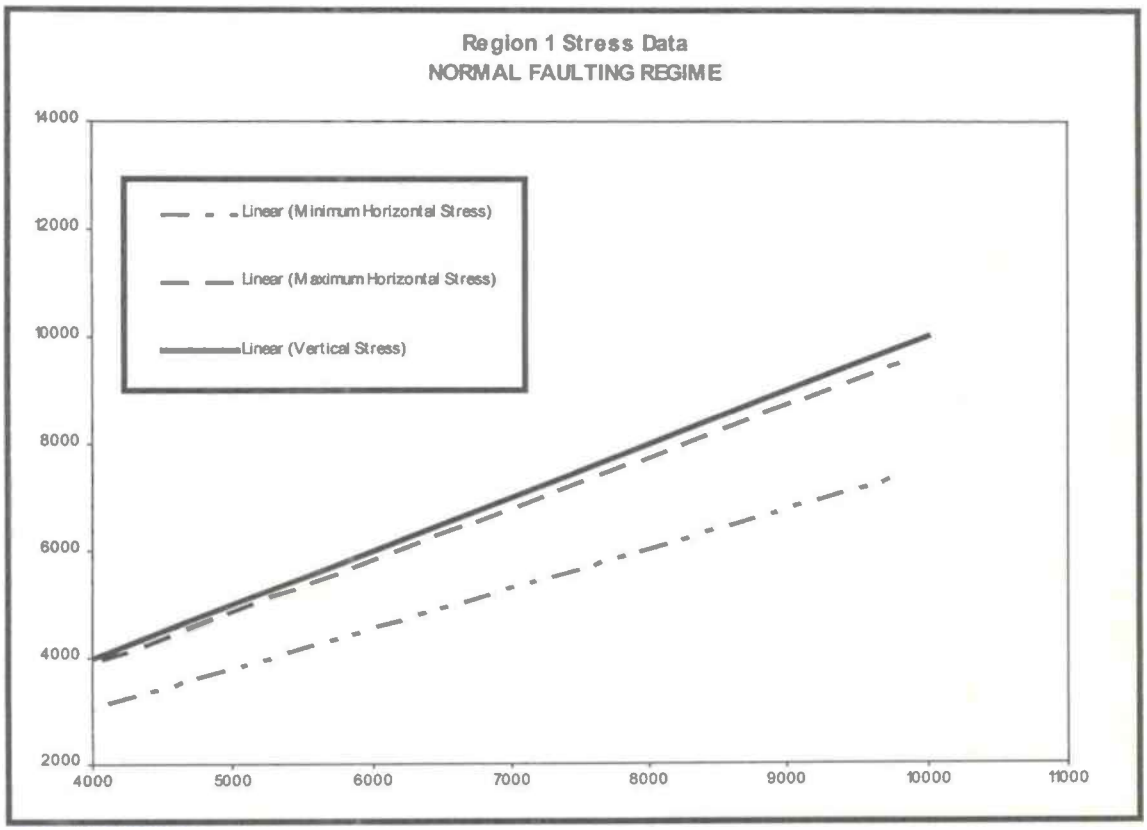

Figure 5. Region 1 stress data.

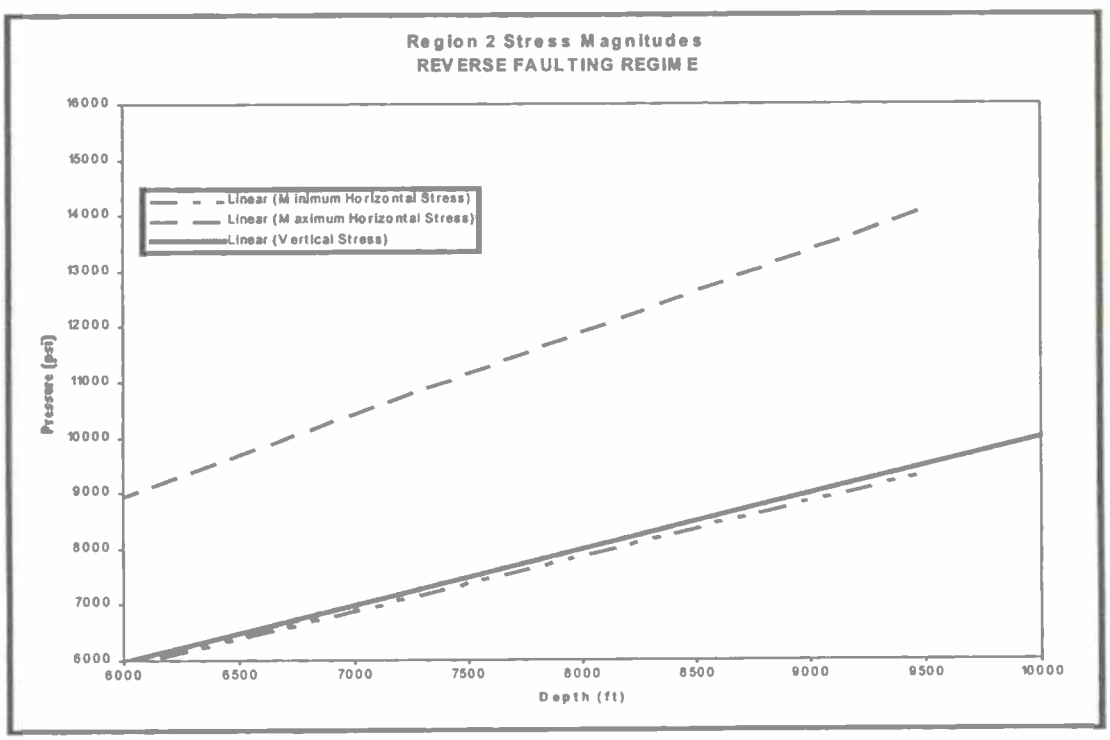

Figure 6. Region 2 stress magnitudes.

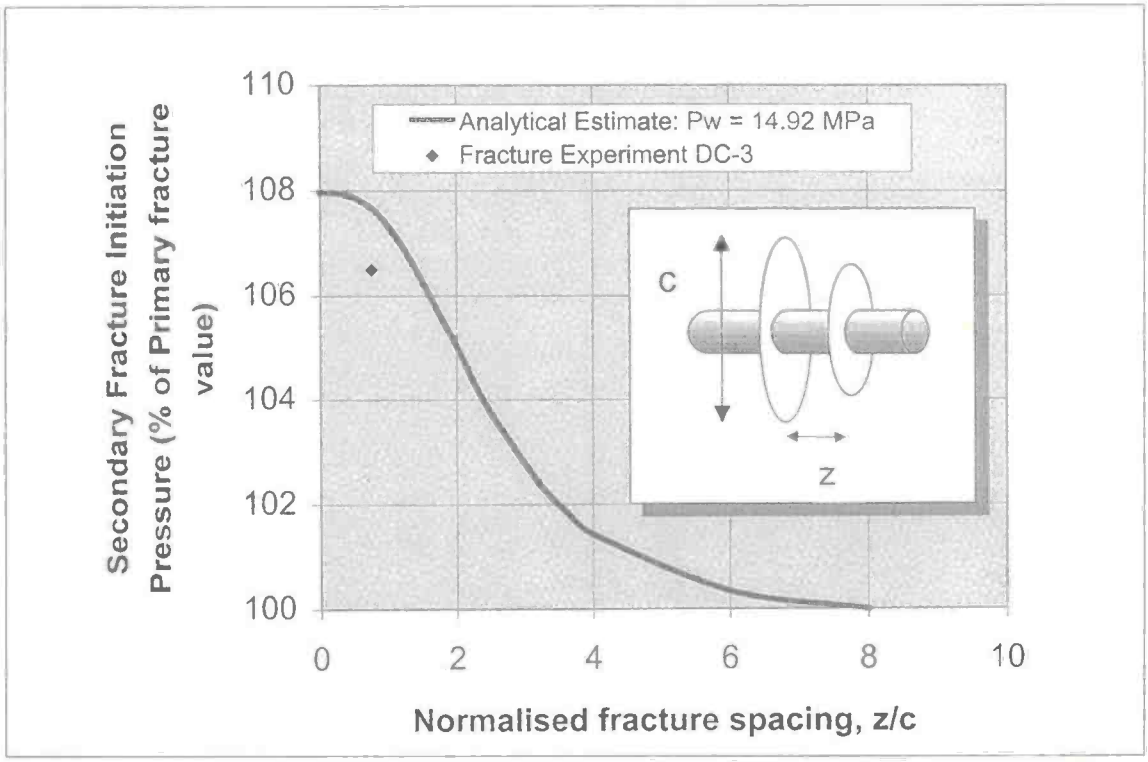

Figure 7. Distance between multiple fractures.

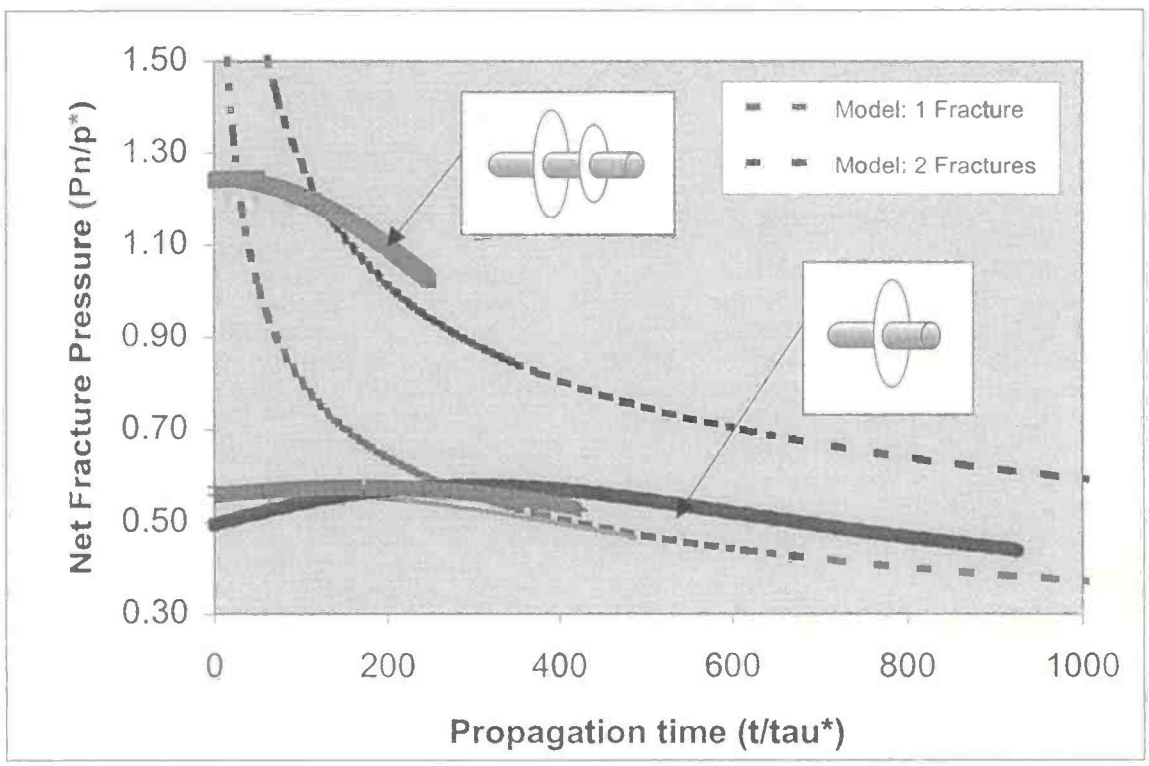

Figure 8. Multiple fracture pressure.

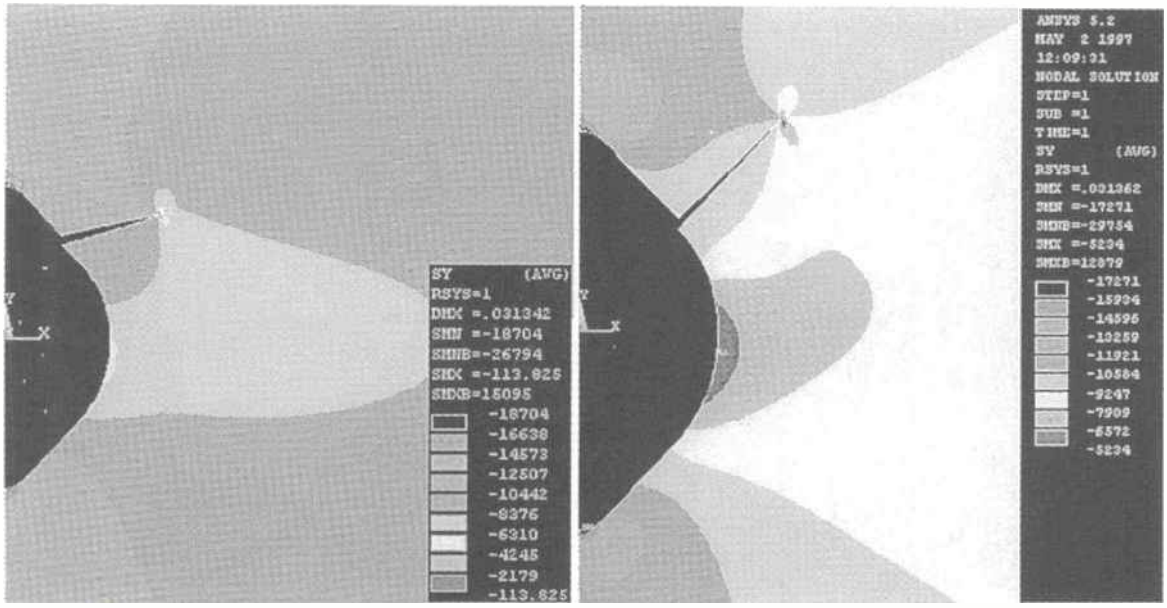

Figure 9. Initiation of hyrdaulic fractures from natural fractures.

tight gas reservoirs to commercially viable levels. Research efforts have been directed towards some of the common problems anticipated in transverse fracturing operations in Central Australia, namely twisting fractures, multiple fractures and fracture initiation in naturally fractured rock.

Fracture twisting occurs as the result of fractures initiated at an angle other than the preferred propagation angle, as the fracture will realign perpendicular to the minimum principal stress. It is considered a problem for transverse fracturing as the conventional Hubbert and Willis breakdown criteria suggests that fractures initiate longitudinally with respect to the wellbore regardless of in-situ stresses and wellbore orientation.

Stress analyses of perforated horizontal completions have been made to assess the likelihood of a transverse fracture initiating from a wellbore, in order to avoid fracture twisting effects. Results indicate that under certain in-situ stress conditions, a perforation will break down independently of wellbore fluid pressure and initiate a transverse fracture directly. In a well oriented in the direction of Sh, a transverse fracture will initiate directly with in-situ stress conditions such that:

Sh (SH ñ Sv/3 (1)

with vertically oriented perforations, or

Sh (Sv ñ SH/3 (2)

with horizontally oriented perforations.

Equation (1) will be commonly satisfied in strike-slip faulted stress regimes, such as those found in parts of Central Australia. Equation (2) will rarely be satisfied, only occurring in extremely relaxed formations with very small horizontal stresses compared to the overburden stress. The practical significance of these simple studies is that at least under certain stress conditions, transverse fractures may be propagated directly from horizontal wells without any twisting, thus greatly increasing the chanced for the successful placement of proppant.

Figure 7 shows the wellbore pressures required to initiate an additional multiple fracture a distance z away from a pre existing fracture of diameter c. This figure highlights the discovery that horizontal wellbores have extremely limited capacities to resist the initiation of additional near-by hydraulic fractures.

Excessive treatment pressures, observed in Central Australian conventional fraccing operations, are often indicative of the initiation and propagation of multiple fractures. Figure 8 shows the experimental and analytical match with the prediction of the treatment pressures that indicate multiple fractures.

The initiation of fractures in naturally fractured rock can be a problem, as the fracture may initiate from a natural fracture tip, and re-orient itself from shear effects as it propagates away from the wellbore. Numerical studies have been performed to better understand the conditions under which fractures may initiate from a natural fracture tip. Figure 9 shows the effect of natural fracture orientation on the initiation site. Clearly, the further a natural fracture is from the preferred borehole wall fracture initiation site, the more likely the fracture will initiate from the borehole wall.

CONCLUSION

Tight gas reservoirs hold vast amounts of gas resources, but pose significant production and completion difficulties to economically exploit. Multiple stage transverse fracturing of horizontal wells provide a viable and economic alternative for achieving commercial levels of production from tight gas reservoirs.

To this end, work has been carried out designed to assess the viability of this production option in the context of Central Australian tight gas fields. In-situ stress magnitudes and orientations have been determined throughout the region, and problems regarding fracture initiation and propagation have also been studied.

Simple studies conducted thus far in the research program have shown that at least for some in-situ stress conditions, clean transverse fracture initiation is possible from a horizontal wellbore oriented in the direction of the minimum horizontal stress.

Permo-Triassic prospectivity of the Londonderry High region, Timor Sea

V.L. Passmore[1], D.S. Edwards[2] and J.M. Kennard[2]
[1]Bureau of Resource Sciences
PO Box E11
Kingston ACT 2604
[2]Australian Geological Survey Organisation
GPO Box 378
Canberra ACT 2601

The Londonderry High, a present day structural feature that extends northward from the Kimberley Block, is flanked by depocentres to the southwest (Browse Basin), west (Vulcan Sub-basin), north (Sahul Syncline) and east (Petrel Sub-basin) which have sourced numerous oil and gas discoveries in the Timor Sea region (e.g. Cornea, Challis, Jabiru, Laminaria, Bayu-Undan, Petrel and Tern). Most of these discoveries occur within or immediately adjacent to these depressions, and are sourced from Early Cretaceous (Browse), Jurassic (Vulcan and Sahul) or Permian (Petrel) organic-rich facies.

Hydrocarbon shows in porous Permian and Mesozoic sediments on the southern portion of the Londonderry High, such as oil at Torrens–1, gas at Ascalon–1A, minor gas at Plover–1, 2, and minor oil and gas at Whimbrel–1, indicate the presence of oil and gas in this region and the occurrence of an active petroleum system. However, since Cretaceous organic-rich facies are immature, and potential Jurassic source rocks are absent or have been largely eroded from the Londonderry High, such hydrocarbon shows imply either long distance migration from the adjacent depressions, or an active older petroleum system on the Londonderry High similar to that in the Petrel Sub-basin. In Torrens–1, for example, significant oil shows occur within Carboniferous-Permian sandstones, and the structural setting of this well implies that these shows have been sourced from pre-Jurassic sediments.

Seismic and well data show that Triassic, Permian and Late Carboniferous sediments extend across the Londonderry High and comprise facies similar to those deposited in the Petrel Sub-basin. Rock-Eval pyrolysis data indicate that organic-rich rocks with both gas and liquid hydrocarbon potential occur in Triassic marine shales in the Sahul Group and Mount Goodwin Formation at Crane–1, Peewit–1 and Whimbrel–1. Although immature in these wells, these Triassic units are expected to be mature in the more deeply buried sections in the eastern portion of the Londonderry High. The underlying Late Permian marine shales of the Hyland Bay Formation (e.g. Plover–1, Torrens–1 and Whimbrel–1) are gas-prone, whereas shales of the Early Permian Keyling Formation, as intersected at Torrens-1, have the potential to generate both oil and gas. These Permian organic-rich intervals are analogous to the inferred source of the Petrel and Tern gas accumulations in the Petrel Sub-basin (Edwards et al, 1997).

Potential reservoirs include shallow marine-deltaic sandstones and limestones of the Late Permian Hyland Bay Formation, as well as Triassic and Jurassic-Early Cretaceous sandstones (Sahul, Plover and Flamingo units, respectively). Regional seals are provided by the Early Triassic Mount Goodwin Formation and Early Cretaceous Darwin Shale.

Palaeozoic structuring and later tectonic events have created several trap types, including horst blocks, tilted fault blocks and erosional truncations, and have locally placed Late Permian reservoir rocks in juxtaposition with Early Triassic source and seal facies. The Permian and Triassic organic-rich lithofacies identified in this study are widespread across the Londonderry High area, and have probably generated and expelled sufficient hydrocarbons to migrate updip and along fault conduits to charge these traps.

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The New Caledonia Basin: deep-water frontier of the Taranaki Basin, New Zealand

C.I. Uruski[1], P.A. Symonds[2], R.A. Wood[1] and I. Borissova[2]
[1]Institute of Geological and Nuclear Sciences Ltd
PO Box 30 368
Lower Hutt New Zealand
[2]Australian Geological Survey Organisation
GPO Box 378
Canberra ACT 2601
C.Uruski@gns.cri.nz
psymonds @agso.gov.au

During late 1996, the New Zealand Ministry of Commerce and the Australian Geological Survey Organisation (AGSO) acquired the first modern seismic line (TL1) linking the Taranaki Basin off eastern New Zealand, to its deep-water equivalent, the southern New Caledonia Basin (NCB). This strike line, which runs along the axis of the NCB from Wainui–1 well on the Taranaki Shelf to DSDP hole 206 in the central NCB, was acquired by RV *Rig Seismic* during collaborative Law of the Sea surveys in the Lord Howe Rise–Norfolk Ridge region. TL1 ties existing AGSO, IGNS and industry seismic dip lines back to the Taranaki Basin, and was designed to image basement structure and provide as complete and continuous imaging of the sedimentary fill of the NCB as possible. The new data will enable assessment of the hydrocarbon potential of the deep-water frontier adjacent to the Taranaki basin, and will allow dating of regionally significant basin-forming and -modifying tectonic events

NNE–NE directed extension began throughout the region in the mid-Cretaceous (Albian), and breakup and seafloor spreading probably commenced in parts of the NCB and then in the Tasman Basin in the Late Cretaceous (Campanian). During and following breakup, NNE–NE oblique extension formed the West Coast and Taranaki rift systems of western New Zealand, and this system may have linked divergence in the NCB to Tasman Basin seafloor spreading.

The southern NCB, adjacent to Taranaki, is dominated by basement rift blocks, probably initiated during the mid-Cretaceous. The total sedimentary fill may be up to 5,000 m, and is commonly up to 4,000 m along much of TL1. At Wainui–1 and DSDP 206, a relatively thin Paleogene section is overlain by thick Neogene. However, the thin Late Cretaceous section at the base of Wainui–1 thickens into deeper water as a syn-rift section up to about 1500 m thick. Elsewhere along TL1, the Paleogene and Late Cretaceous section is more than 1,500 m thick. The stratigraphic succession encountered in DSDP 206 shows that this part of the NCB was at bathyal depths by the Paleocene. A significant episode of compressional tectonism deformed the pre-Neogene section of the NCB and probably culminated with the onset convergent tectonism along the eastern margin of the Australian plate in the Late Eocene to mid Oligocene.

Ties to Wainui–1 indicate that similar basal successions to those in Taranaki, and probably parts of the Bass Strait basin system, may be present throughout the NCB, particularly in the south. These basal successions may contain Cretaceous coal measures and could be a significant source rock for hydrocarbons. This rift fill section is at depths of approximately 3,000 to 5,000 m and is likely to be mature. Another possible source rock is the Waipaua Formation, a Paleocene deep-water marine black shale, which is widespread on the Northland peninsula of North Island and elsewhere around New Zealand. Potential Paleocene source rocks could also be mature, particularly in the part of the NCB adjacent to the Taranaki Basin.

Reservoir facies appear to be common throughout the succession, as reflector patterns suggest the presence of channel and fan units, which are likely to be sand-rich and may be analogous to such reservoirs in the Taranaki Basin. For example, the reservoirs of the Maui and Kapuni fields are terrestrial and marginal marine sands of Eocene age and there are likely to be deeper-water low-stand fans and channels of the same age in the NCB. The Oligocene Tikorangi limestone is a prolific reservoir in places and similar formations may occur in deeper water. Recent exploration targets in Taranaki include Miocene fan and channel systems and lateral equivalents of these are undoubtedly present. Traps are formed by drapes across extensional fault blocks and by minor basin inversion, possibly associated with the onset of convergent tectonism in Northland, New Caledonia and PNG in the Oligocene.

The internal Fold and Thrust Belt Play, PNG

P.K. Webb[1] and P. Woyengu[2]
[1]British Geological Survey
PO Box 1846
Port Moresby Papua New Guinea
[2]Petroleum Division
Department of Petroleum and Energy
Private Mail Bag
Port Moresby PNG

In contrast to the moderately well explored, oil and gas productive Papua Fold and Thrust Belt (PFTB) adjacent to the Fly Platform, the hinterland side of the PFTB is almost completely unexplored. It contains numerous potential reservoirs, source rocks and seals. It has been affected by rifting, passive margin, and compressional tectonics and is likely to contain a variety

of trap types therefore. Oil and gas seeps testify to the presence of active petroleum systems.

The PFTB lies on the northern edge of the Australian Craton. Overlying a Paleozoic crystalline basement is a Late Permian through Bathonian sequence of clastics, carbonates and volcanics which forms the Gondwanaland Syn-Rift Sequence. Reef limestones and arkosic sandstones offer reservoir potential, while black shales could provide source potential.

The overlying Gondwanaland Post-Rift Sequence is Bathonian through Albian in age, and comprises marine shales with interbedded thick massive sandstones, most likely deposited as turbidites on a north-facing passive margin. This sequence is laterally equivalent to the producing interval in the fields and discoveries of the Platform side of the PFTB. The sandstones have significant reservoir potential, while the shales offer both sourcing and sealing potential.

The Coral Sea Syn-Rift Sequence consists of thick marine mudstones with minor coarse clastics. It offers no major reservoir potential, but the mudstones may be source quality. Age is Cenomanian through Maastrichtian.

The Coral Sea Post-Rift Sequence, Paleocene to Early Oligocene in age, comprises a massive basal sandstone overlain by thick shelf limestones. Both the sandstone and limestone are potential reservoirs.

The Darai Back-Arc Sequence marks the end of the passive margin tectonic regime and the start of the compressional to transpressional tectonics resulting from convergence between the Australian and Pacific plates. Rocks laid down in this phase, which lasted from Late Oligocene to the Middle Miocene include shallow marine limestones and laterally equivalent clastics and volcanics.

Overlying this is the Foreland Sequence, thick limestones overlain by shallow marine to continental clastics deposited in rapidly subsiding unstable troughs. Quaternary volcanics and clastics complete the stratigraphic column to the Present Day.

The Late Oligocene through Present Day convergence of the Australian and Pacific Plates has resulted in the uplift of the Kubor and Om Massifs, and the formation of numerous parallel synclines and anticlines, the latter offering attractive exploration targets.

A review of geostatistical simulation algorithms for lithofacies architecture modelling

L. Wang[1], P.M. Wong[1] and S.A.R. Shibli[2]
[1]School of Petroleum Engineering
University of New South Wales
Sydney NSW 2052
[2]Landmark Graphics (M) Sdn Bhd
Suite 22–04
Menara Tan and Tan Jalan
207 Tun Razak
50400 Kuala Lumpur Malaysia 50400

Accurate modelling of reservoir heterogeneities is a well-known problem in most clastic reservoirs. Understanding the spatial distribution of major lithofacies and their connectivity is a key factor for successful characterisation studies. The architecture of lithofacies serves as a guidance for subsequent assignment of lithofacies-specific hydraulic properties such as porosity and permeability.

Today, geoscientists and engineers are faced with diverse techniques to generate detailed geological models. This paper provides a review of stochastic simulation algorithms for lithofacies architecture modelling in the oil and gas industry, namely sequential indicator simulation (Bayesian and conventional); truncated Gaussian and pluri-Gaussian models; simulated annealing; and marked point processes. Such techniques provide an uncertainty measure for both project reserves and future fluid performance (e.g. water and gas breakthrough times), thereby facilitating the assessment of the risk associated with a project.

We discuss the strengths and limitations of the above techniquees, as they relate to:

1. the ability to generate geologically realistic looking facies distributions (e.g. curvilinear features);
2. speed and ease of use; and
3. the ability to incorporate multiple sources of information, both hard (e.g. core and log data) and soft (e.g. seismic attributes and subjective geological knowledge).

We find that object-based methods have a broader appeal among geoscientists, being both fairly intuitive and realistic. Marked point processes models or Boolean models can be used in facies modeling with high effectiveness, because these models not only can incorporate soft data conveniently, but also provide a realistic distribution pattern of sandbodies. Also some new techniques have appeared that combine both the marked point process model and the Bayesian model.

In contrast, pixel-based methods, although flexible, have some difficulty in generating curvilinear shapes, but this is expected to be offset by current progress in adapting these techniques for such purposes (e.g. via

multivariate moments or incorporation of directions of continuity). For example, in simulated annealing, different directional multiple-point statistics can be used as constraints in the objective function. Bayesian models can also be very useful for facies modeling, both for pixel-based methods and for object-based methods.

The following issues remain a great challenge to lithofacies modelling in reservoir characterisation:

1. incorporating detailed geological analyses in terms of sedimentary and diagenetic patterns;
2. transforming qualitative geological expert 'rules' into quantitative numerical inputs to the simulation models;
3. handling data in multiple-dimensions; and
4. handling data with different spatial resolutions ('support' problem) and quality ('hard' and 'soft').

Darling Basin seismic interpretation

J.B. Willcox[1] and J.D. Alder[2]
[1]Australian Geological Survey Organisation
GPO Box 378
Canberra ACT 2601
[2]NSW Department of Mineral Resources
PO Box 536
St Leonards NSW 2065

The Darling Basin occupies a large portion (approximately 100,000 km^2) of western New South Wales, ringed in the north by the towns of Broken Hill, Wilcannia and Cobar, and stretching southward to the region of the Murray River. Although poorly defined, basin development is believed to have been controlled by a sub-basinal architecture that stemmed from terrane dispersal in the Late Proterozoic–Early Cambrian (Adelaide and Kanmantoo Fold Belts), through docking and terrane convergence in the Late Cambrian–Early Silurian. The basin itself, is predominantly a Devonian–Early Carboniferous feature. Its present configuration comprises both depositional and residual structural troughs, some containing 8,000 m or more of section. Darling Basin sedimentation may once have been continuous with other depocentres in Queensland and in central Australia (e.g. Adavale, Amadeus, Officer Basins). The basin-fill has undergone continued convergent deformation, translating into major thrust and wrench-related structures.

A regional seismic interpretation of the Darling Basin is being carried out by AGSO/New South Wales DMR as part of a new National Geoscience Mapping Accord project-Central Australian Basins Gas Project (CABGAS). About 10 seismic megasequences have been recognised and are being mapped but, as yet, the available well data has not allowed unambiguous age identification. Tentatively, the mid-basinal section is believed to comprise:

- the ?Proterozoic/Early Cambrian 'basement' complex;
- an Early Palaeozoic (?Silurian–Early Devonian) marine sequence;
- a Late Devonian terrestrial, largely 'red-bed' sequence; and
- a Tertiary veneer.

The seismic geometry indicates that deposition probably commenced within a synrift environment, followed by younger, largely layer-cake deposits. The section has been subjected to as many as four episodes of compressional/thrust-related movements, probably from mid Devonian–?Early Carboniferous times. Major thrusted anticlines with bounding growth faults and numerous antithetic faults are evident; these control the range country through the region. Correlation of sequences across these thrust structures is, at present, based on imprecise character correlations, since the seismic profiles do not form an effective grid around them.

In its initial phase, petroleum exploration waned though a lack of shows, the likelihood of a gas-prone source, and the presence of a thick, red-bed dominated and organically lean, Late Devonian sequence. As discussed by Alder and others (this volume), red-bed deposition is now considered to have been contemporaneous with marine deposition, at least during part of the Early Devonian. A probable marine section of about this age, and up to 3,000 m thick, is interpreted from the seismic profiles.

The few exploration wells in the basin have been sited, either, on the basis of gravity 'lows' to gain stratigraphic information, or more commonly, near the crest of thrusted anticlines, but with poor structural control. The thrust faults associated with the anticlines generally extend, by way of continual reactivation, to the level of the Tertiary veneer. Although many of the anticlines are dramatic and have provided obvious primary targets in early exploration efforts, they may well have been associated with leakage to surface of any migrating hydrocarbons. Subtle, lower amplitude folds with minimal faulting may provide more efficacious prospects.

With a currently projected shortfall in gas supplies to the Sydney market from around the Year 2000, and the basin's proximity to the Moomba-Sydney pipeline infrastructure, the Darling Basin now has renewed appeal and is in need of a thorough re-assessment.

Ultrasonic technology improves dispotal of drilling cuttings

G. Young
Expro Pty Ltd
3rd Floor
78 Mill Point Road
South Perth WA 6151

A new method has been developed by The Expro Group for efficiently reducing the particle size of drill cuttings, resulting in the enhancement of various disposal techniques.

It is widely acknowledged throughout the oil and gas industry that during drilling operations, a number of environmental challenges are becoming more significant. One such challenge is the effective disposal of drill cuttings subsequent to the separation of drilling fluids from the cuttings. It is accepted that the preferred drilling fluids are low toxicity mineral oil-based muds (LTOBMs). Unfortunately, LTOBMs contain a variety of different deleterious solids which, coupled with the hydrocarbons, impregnate the cuttings and inevitable contaminate them. When they are discharged onto the seabed floor, it leads to a degree of localised environmental damage which has the potential to promote rates of mutation for organisms that are exposed to these toxins.

The essential features of a single ultrasonic slurrification system is a bank of four processors linked together in series by hollow steel tubing. Each processor consists of a tubular section which has a 5" through bore diameter with 40 piezoelectric crystals located on the external surface of the processor.

The crystals transmit sonic waves through a medium (sea water) which also acts as the agent for the cuttings to be transported through the system. The source of energy is produced from a generator which employs a novel frequency sweep oscillating up to a frequency of 40 Khz which is regarded as the optimum frequency band for destructive cavitional energy.

The size reduction performance of the ultrasonic system developed by The Expro Group recognised as being second to none, in comparison with existing technologies. The ultrasonic system is capable of reducing drill cuttings of almost all known types of formation to levels as low as 50 microns if required.

The performance parameters of ultrasonics are dependant upon a number of variables and these have to be calculated and analysed to achieve the desired particle size reduction, these being:

- residence time through the processors (which increases the exposure time to the ultrasonic waves)
- ROP—volume of cuttings;
- type of formation; and
- cuttings to water ration (slurry mix).

The treatment of drill cuttings by ultrasound prior to disposal now offers oil and gas operators around the world a new dimension in performance enhancement towards their existing techniques. Ultrasonics is a highly efficient slurrification system in the areas of natural dispersion into the water column when synthetic or water-based mud systems are employed, for re-injection into the wellbore and disposal on-shore when ship-to-shore operations are being conducted with oil based mud.

Petroleum system of the Mentawai-Bengkulu forearc basin, West Sumatra, Indonesia

B. Yulihanto[1] and B. Situmorang[2]
[1]R&D Centre for Oil and Gas Technology
LEMIGAS
[2]Australia-Indonesia Joint Authority for the Timor Gap Zone of Cooperation
GPO Box 2059
Darwin NT 0801

The Mentawai and Bengkulu forearc basins are located in the southeastern part of the Sumatra Island Indonesia. The most extensive hydrocarbon exploration activities are mainly focussed in the offshore part of the Bengkulu Basin. Recent geological and geophysical studies of the Mentawai-Bengkulu Forearc Basin indicated that two distinct phases of basin development can be distinguished. In the south, development of the Bengkulu Sub-basin is characterised by the formation of the NE–SW oriented Paleocene graben system, followed by the formation of a N–S orientated Late Oligocene-Early Miocene graben system. In the north, development of the Mentawai Sub-basin is typified only by the formation of N–S orientated Late Oligocen-Early Miocene graben system

Tertiary petroleum systems comprise organic matter deposited in deep lacustrine-open marine environment in the NE-SW graben system of both Bengkulu and Mentawai Sub-basins, with sufficient maturity level reached since the Middle-Upper Miocene. Recent geochemical studies in the Bengkulu Basin indicate the Eocene lacustrine sediments are poorly documented on the surface and no single well within the basin penetrated the lacustrine sediments. We believe the lacustrine sediments to be most prolific hydrocarbon source rocks in the other Sumatra basins (i.e. Jamb Sub-basin, Ombilin Basin). Moreover, since the Eocene lacustrine sediments within the Bengkulu Basin have been buried very deeply in the basinal areas, they may have reached middle to late maturity and may have generated medium to light oils and some gas. The Late Oligocene-Early Miocene Sequences in the onshore basin are also prospective petroleum source rocks. Gas chromatography analysis generally reveals a high

pristane/phytane ratio and alkane in composition attributable to kerogen rich waxy material derived from terresstial plant with a slight odd over even indicative of medium maturity oil prone kerogen.

Potential reservoir rocks occur mainly in the non-marine sediments which were deposited during the early phase of graben formation (Eocene and Late Oligocene-Early Miocene) consist of fluvial-alluvial fan sediments, and also during the later phase of graben formation coinciding with the final stage of the Oligo-Miocene transgressive period to form carbonate facies and also shallow marine sandstones. Other potential reservoir rocks are the early Middle Miocene carbonates which are comprised of neritic limestone, with some locally reefal limestones, as clearly seen in the Mentawai Sub-basin.

Hydrocarbon traps in this basin include anticinal, fault and stratigraphic traps, which may have occurred along the NE–SE and N–S wrench faults. Those traps are sealed regionally by the upper MiocenePliocene transgressive shales. Hydrocarbon exploration in those basins appears to be attractive. Future exploration activities should be focussed on detailed structural and sedimentolocal studies of those two graben systems in order to understand the basin evolution in more detail.

APPEA