Multi basin usage/cumulative impact

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Background paper for the Office of the NSW Chief Scientist and Engineer (OCSE) providing information and a discussion about the multiple uses of sedimentary basins (e.g. agriculture, communities, energy resources) including potential environmental impacts and synergistic opportunities.

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Summary

As human requirements for water, food, energy and a sustainable environment and climate grow with increasing global population, so do our demands on the shallow portions of the Earth's crust and the services that it provides. For many years now we have utilised these crustal services for our benefit, extracting minerals, oil, gas and coal to meet our material and energy needs and groundwater to service our agriculture, industry and domestic needs. Management and planning for the development of these resources tends to be siloed with resource utilisation governed by a complex web of regulatory regimes and authorities.

With the advent of novel technologies that allow extraction of unconventional resources (such as enhanced geothermal heat, coal seam gas, shale gas and tight gas) and growing needs for geological storage of water, fuel and waste, the demands on sedimentary basins in particular are becoming extreme. As a result there is increasing potential for resource conflict, with the possibility that lack of appropriate planning could lead to reduction in long-term benefit, in the least case, and sterilisation of resources, in the worst case.

This report describes the current way sedimentary basins are used in Australia, along with emerging uses, to set the scene for understanding the challenge around interacting usage regimes.

The paper is structured as follows:

- The Introduction sets the scene for understanding the need for integrated sedimentary basin management
- Section 2 outlines what sedimentary basins are from a geological point of view, and why they are important.
- Section 3 discusses Australia's sedimentary basins and highlights the resource systems that they contain.
- Section 4 discusses the issues arising from development of multiple coexisting basin resources and the implications for sustainable resource management.
- Section 5 analyses the benefits of developing coexisting basin resources.
- Finally, Section 6 provides a synopsis of the challenges, risks and issues associated with developing multiple basin-contained resources.

The essential argument that frames the paper is that there is need to establish better frameworks for integrated management of sedimentary basins, if we are to realise the long-term social, environmental and economic benefit of basin resources, and secure the best value of the full range of services those basins provide to the communities that depend on them. The paper concludes with a discussion about how that might be best achieved.

1. Introduction

Sedimentary basins underpin much of Australia's national wealth. They host the fossil fuel resources that provide for more than 90% of Australia's primary energy production and the great majority of our groundwater resource. They are the locus of most of our agricultural production and rural population centres. They support a significant fraction of Australia's endangered riverine and rangeland ecosystems. Increasingly, our sedimentary basins are being explored for new resources and services, such as unconventional gas, the sub-surface storage of CO_2 waste and geothermal energy.

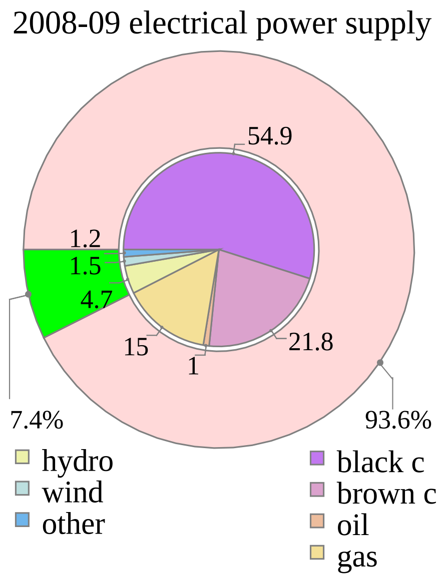

Figure 1. Australian electrical power supply by resource type. Fossil fuels provide ~93.6% (Source Energy in Australia 2011, ABARES[1])

The current scale of investment in our sedimentary basins is unprecedented, and competition for access to basin resources is already raising challenging social, environmental, political and regulatory issues. Past and ongoing practices have the potential to compromise future resource opportunities. With potential for conflict over competing access regimes to sedimentary basin resources, there is a case for new approaches to the management of our sedimentary basins to help reduce adverse environmental and social impacts, reduce the potential for unintended resource depletion and/or sterilisation, and reduce economic risk arising from multiple, interacting and competing resource usage scenarios.

There is a case for more broadly based, harmonised regulatory frameworks and for the development of more meaningful engagement strategies with the rural and regional communities that have a direct interest in the way the sedimentary basins are managed. There are long-term economic benefits to ensuring that

[1] http://data.daff.gov.au/data/warehouse/pe_abares99001789/Energy_in_Aust_2011_13f.pdf

resource and agricultural developments within our sedimentary basins proceed harmoniously without undue impact on already fragile surface environments.

As a backdrop to understanding the challenges and opportunities that come from existing and emerging multi-use scenarios for our sedimentary basin, this report summarises basic scientific issues concerning the geology and economic importance of our sedimentary basins, highlights some emerging new usage scenarios, and some of the key needs in better framing emerging management issues.

2. What are sedimentary basins and why are they important?

What are sedimentary basins?

Sedimentary basins are large, long-lived depressions in the Earth's crust formed by local geological subsidence, subsequently filled with sediments sourced from surrounding (or distal) uplands. The depressions that localise the accumulation of thick sedimentary deposits form in a variety of geological environments. Many form in extensional tectonic environments associated with divergent plate motion within or adjacent to active plate margins, especially during the rifting of continents[2]. Sedimentary basins can also form in convergent tectonic settings[3] and in intra-continental settings at long distances from active plate margins[4].

Sedimentary basins have formed throughout geological time. Depending on the tectonic setting at the time of formation, the nature of the sub-basin crust beneath and the post-sedimentation history, sedimentary basins can host a diverse variety of geological resources. Mineral resource examples include the iron ore deposits of the Hamersley Basin in the Pilbara, base metal deposits such as those now found in the MacArthur Basin in the Northern Territory (as well as those at Mount Isa and Broken Hill[5]), and the mineral sands of the Perth, Murray and Eucla Basins in southern and western Australia. Energy resources include the hydrocarbons (oil and gas) of the Gippsland Basin and the many other offshore basins, particularly along Australia's Northwest shelf, as well as the coals of the Latrobe, Sydney and Surat Basins, and the uranium deposits of the Stuart Shelf. Sedimentary basins are also the primary store of the Earth's groundwater resources, supplying around 20% of the earth's potable water and 17% of Australia's accessible water resources[6].

A distinctive feature of sedimentary basins is the high rock porosity of many of their constituent rock types. The porosity of sedimentary rocks varies significantly as a function of the primary rock forming process and due to subsequent alteration. The "primary porosity" refers to any residual pore space

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[2] Explaining why most continental shelves are covered by thick sedimentary deposits in offshore basins, often with significant accumulations of fossil fuels.

[3] A key example is provided by the Ganges Basin, in the Himalayan foreland.

[4] A key example is provided by the Eromanga Basin in Central Australia.

[5] While our base metal deposits in Mt Isa and Broken Hill now lie with complexly deformed metamorphic tectonic settings, the original deposits were formed in the precursory sedimentary basin as exhalative massive sulphide deposits (Leach et al, 2010).

[6] National Water Commission – Groundwater Essentials - http://www.nwc.gov.au/__data/assets/pdf_file/0020/21827/Groundwater_essentials.pdf - Viewed Aug 2013

formed between sedimentary grains originating at the time of deposition, such as the pore space between individual sand grains. While the collective processes associated with compaction and cementation (collectively referred to as digenesis), typically lead to its reduction through time, primary porosity can persist for geologically significant times. In some sedimentary rocks types such as those with high carbonate content (e.g. limestones); secondary porosity can be created by chemical process such as dissolution within the rock column.

Beneath the water table, the pore filling fluids are often salty. However, they include a wide variety of other species including fresh water, CO_2 and various hydrocarbons including crude oils, tars and methane (natural gas). These naturally occurring pore fluids have a variety of origins, including:

- residual fluids, dating to the time of deposition,
- fluids generated within the sedimentary column through diagenetic processes including mineral reactions, thermal maturation of organic matter and processes mediated by subsurface bacterial communities,
- recharge from hydrological processes into surface connected aquifers, and
- deep sources associated with sub-basin process such as magmatic degassing[7].

When the pores space is connected, creating permeability, contained pore fluids are able to migrate within sedimentary basins. On geological timescales the migration of such intrabasinal fluids allows fluid species to migrate and potentially accumulate. Fluid migration causes redistribution of both heat and chemical mass within basins and can impact on crustal properties such as stress[8]. Such migration occurs through a variety of forcings, including via pressure gradients maintained by surface recharge systems, through the differential buoyancy between phase-separated and differentially heated fluids, and from compaction within the sedimentary column due to digenetic processes including ongoing sediment loading.

The intrinsic permeability of the rocks comprising sedimentary basins varies by many orders of magnitudes. Shales are effectively impermeable, while

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[7] A commercially significant Australian example is the Caroline field near Mt Gambier in the onshore Otway Basin in South Australia, which produces approximately 21,000 tonnes of CO2 derived from degassing of the Gambier Volcanic per year
ww.pir.sa.gov.au/__data/assets/pdf_file/0008/27395/caroline_eir.pdf.

[8] The Great Artesian Basin in central and eastern Australia is one of the largest confined aquifer systems in the world, with flow system extending over almost 2 million km^2 involving aquifer waters that have been dated to more than 1 million years old..

sandstones and conglomerates can be highly permeable[9]. Combined with inherent sedimentary facies variability[10] and subsequent tectonic disturbance (via, tilting, warping and or faulting), basins typically have a complex distribution of permeability. Aquifers with high fluid transmissivity are interlayered with low transmissivity aquitards. Reservoirs are created where sealing aquitards bound porous compartments in such a way that they effectively prevent further fluid migration. Such seals are key to accumulation of liquid hydrocarbons within hydrocarbon reservoirs.

The distribution of porosity and permeability within sedimentary basins evolves naturally in both space and time, through processes such as compaction, mineral reaction and faulting related to natural tectonic activity. In so doing, the degree of fluid connectivity between different parts of the basin changes, with an important consequence being the generation of fluid compartments can in which the fluid pressures show very significant deviations from normal hydrostatic conditions[11]. Fluid overpressures are generated where fluid generation processes, or compaction of the pore space, exceeds the ability for pressurised fluid to migrate (Zoback, 2007).

In large part, the value of sedimentary basins relates to the pore space and our ability to access and manipulate it in order to recover its contained fluids, or store surface derived fluids (usually contaminated and waste fluids) in it.

On short timescales, appropriate to human activities, the permeability is crucial to the utilisation of pore filling fluids, such as hydrocarbons. The mechanism of extraction of fluids from the subsurface pore space varies depending on both the permeability and the fluid pressure. Where fluids are "overpressured" they can flow to the surface naturally. At or below critical pressures, as is expected during reservoir depletion, artificial lifts methods must be used such as pumping, or the reinjection of waters to enhance reservoir pressures. While providing a natural mechanism for venting fluids to the surface, overpressures are a key risk in operating within the subsurface, since any breach in operations can lead to

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[9] For example, intrinsic permeability of gravels and coarse sands with primary porosity intact can exceed 10^6 millidarcys, while the permeability of tight shales can be as low as 10^{-1} millidarcys

[10] The term "sedimentary facies" refers to bodies of sediment recognizably different from adjacent sediment deposited in a distinct depositional environment (for example a river channel or carbonate reef), and which are confined in space and time, making for both lateral and vertical confinement of rock types within sedimentary basins.

[11] Hydrostatic conditions are those that pertain when the pressure in a fluid column is the integral of the product of density of the fluid and gravitational acceleration, from the depth to the surface of the fluid column (e.g. the water table). i.e. $\sigma_{zz} = \int_0^z \rho_z g dz$

blowouts and uncontrolled surface venting. A key emerging issue in the utilisation of sedimentary basin resources is the impact of technologies such as hydro-fracturing designed to enhance natural permeability.

Like most parts of the Earth's crust, sedimentary basins are prone to earthquakes, due to a near critical state of stress (e.g., Zoback , 2007). While the level of natural earthquake activity varies significantly with the tectonic setting, the near critical stress state makes all parts of the crust susceptible to induced earthquakes as discussed in detail in a companion paper[12].

Why are sedimentary basins important?

Sedimentary basins are of crucial importance for a variety of economically significant purposes. Historically, these include:

- as the primary source of groundwater, supporting agricultural commercial and direct human consumption needs,
- as the exclusive source of fossil fuels (oil, gas, coal),
- as a source of several important mineral resources (e.g. Fe-ore, Uranium, various base metals and heavy mineral sands),
- as an important source of industrial materials, such as construction aggregates, limestone for cement production and building stone,
- as a permanent store of waste fluids, such as contaminated surface waters,
- as a temporary storage for hydrocarbons (mainly natural gas[13]) to moderate supply and demand imbalances and mitigate against supply shocks.

Increasingly, sedimentary basins are being investigated for their potential for:

- the secure store of CO_2 waste from energy production,
- recovery of thermal energy from natural geothermal heat, both for electricity generation and for direct heat applications
- novel energy storage options, such as subsurface compressed air storage.

In addition, sedimentary basins provide a variety of important natural services. Key amongst these is the role of basin groundwater systems in sustaining natural surface water flows. Especially in regions subject to drought, such as Australia,

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[12] Gibson, G. & Sandiford, M., Seismicity and induced earthquakes, A background paper for the Office of the Chief Scientist of NSW. June, 2013.

[13] There are four underground natural gas storage facilities in Australia with a total capacity of 1.3 bcm of working gas all located in depleted gas fields (Mondarra, Perth Basin in WA, Moomba, Cooper Basin in SA, Newstead, Surat Basin in Queensland, Iona Field, Otway Basin in Victoria). http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/storagebasics/storagebasics.html

groundwater maintained flows are crucial to the health of riverine and associated wetland ecosystems.

A number of other resources, whist not “contained within” the sedimentary basins are intimately linked to them. For example all of mainland Australia’s high yield arable land and the majority of the medium yield land is located on top of sedimentary basins. The majority of the country’s dairy industry and much of the forestry industry is also located within these basin systems. In the offshore areas fisheries (including the lucrative squid, abalone, scallop, pearl oyster and gillnet shark fisheries) are collocated with submerged and prospective sedimentary basins. Finally many of the nation’s most iconic tourist destinations are also located on our sedimentary basin systems, with the consequence that operational activities designed to access the subsurface can impact the tourist amenity.

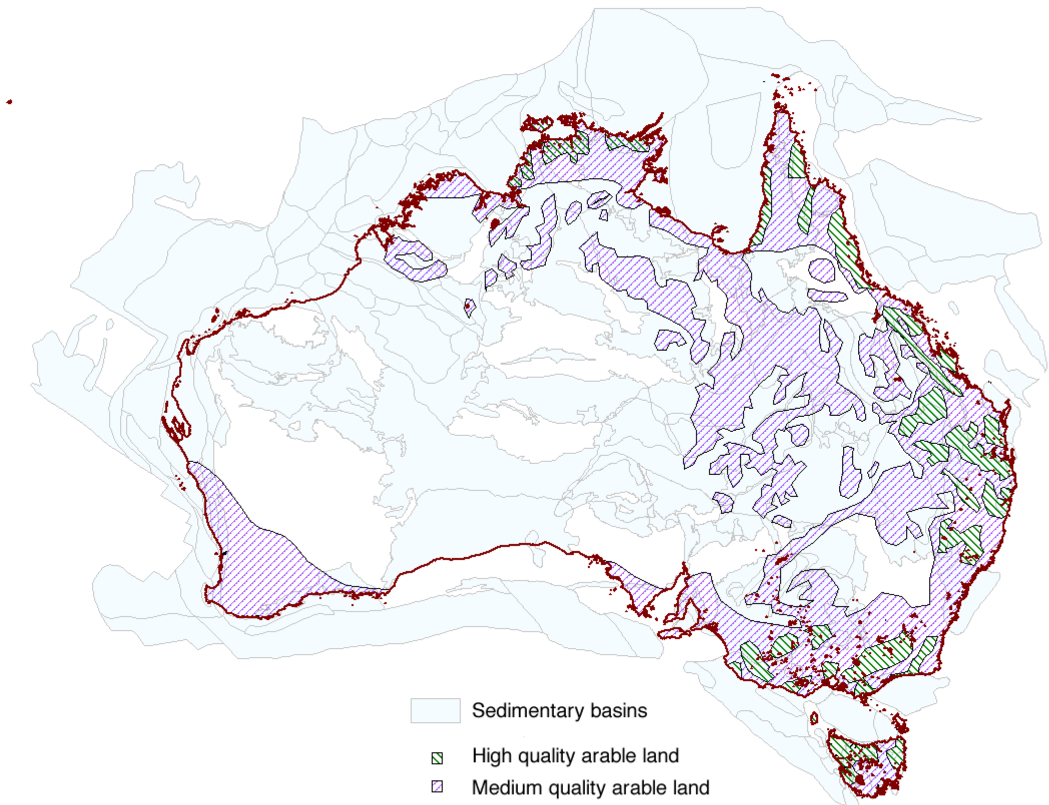

Figure 2. Australia’s arable lands (hatched) overlayed on sedimentary basins (light blue). Distribution of arable land types from Dr Chris Watson, CSIRO (personal communication).

3. Australian sedimentary basins and their usage

Sedimentary basins cover over 50% of the onshore and the majority of the offshore portions of continental Australia (Figure 3). Whilst not all Australian basins contain significant hydrocarbon resources, either due to their absence of good source rocks or because they have exceeded thermal history[14], the vast majority do contain resources critical to Australia's economy and prosperity.

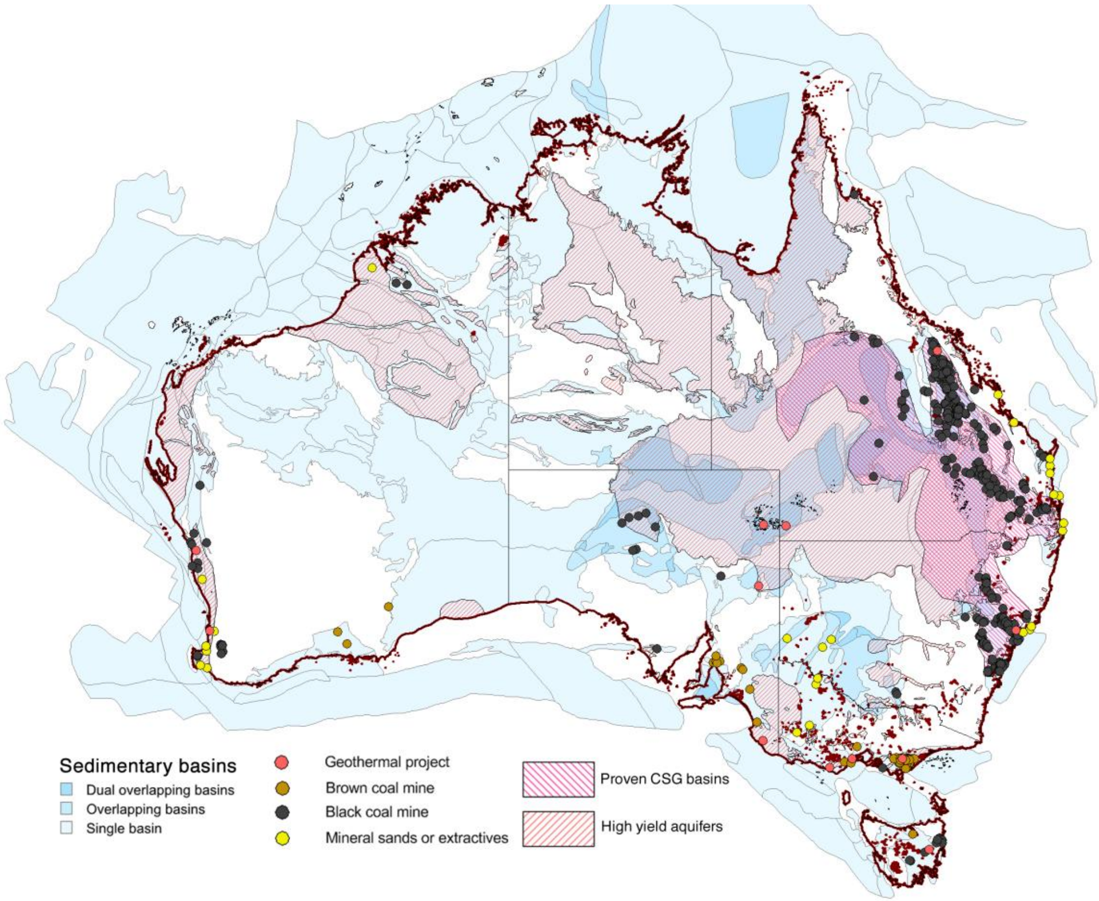

Figure 3. Australia's landmass and coastal waters are dominated resource rich by sedimentary basins shown in blue. High-yield aquifer systems - green, coal seam gas basins - purple, black coal mines- back, brown coal mines - brown, geothermal wells - red, mineral sands and extractive industries - yellow.

Australia's sedimentary basins are complex geological environments containing a variety of resource systems, some of which have a long history of development and have underpinned much of Australia's economic growth while others have

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[14] Hydrocarbon productive basins require deposition of very organic rich source rock strata. The most productive source rock strata tend to be younger than about 500 million years. To preserve hydrocarbon accumulations, the basin must not have experienced temperatures in excess of about 150°C. Many of Australia's interior sedimentary basins being older than 500 million years and thermal histories that make large parts of them over-mature, thermally.

only been recently recognised. Each of these groups is discussed in more detail below. Sedimentary basins also service a range of important functions that are not directly related to their resource endowments, including tourism and biodiversity.

Fossil fuels

The resource systems that are most commonly associated with Australian sedimentary basins are hydrocarbons and coals. Australia is a significant net exporter of hydrocarbons exporting approximately two thirds of its total production by energy content. It is the second largest exporter of coal in the world, exporting a little over 300 million tonnes each year[15] and the fourth largest exporter of liquefied natural gas[16] . Current reserves are estimated at over 1250 million barrels of crude oil, 2700 million barrels of condensate, 1350 million barrels of LPG and 160 TCF (trillion cubic feet) of gas[17]. Currently local production services about 41% of our domestic oil requirements and almost all our natural gas needs. Fossil fuel energy production is critical to the national economy. APPEA (2013) reports fossil fuel production comprises about a third of all planned business investment over the next five years with over A$200 billion committed to new projects.

Oil and gas

Oil and gas deposits (or accumulations) form as a result of the heating under pressure of organic material such as algae, plankton and other plant waste during and after sedimentation in the basin. The hydrocarbons that are formed during this thermal maturation then migrate down pressure gradients (towards the earths surface). In many places this migration results in the oil and gas "seeping" at the surface and being lost. In some places however the hydrocarbons are trapped beneath impermeable layers known as seals. When large volumes of hydrocarbons pool beneath the seal it is known as a reservoir.

Oil and gas within these reservoirs is extracted via wells from the surface. Reservoirs are typically found at depths from several hundred meters to several kilometres with some wells total length in excess of 10,000m. In offshore environments the wells can be drilled from moored or attached platforms or from deviated wells from the coast. Multiple wells branch off from a single wellhead allowing the surface impact of developing a large geological reservoir to be minimised.

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[15] BP2013 statistical review of energy, http://www.bp.com/en/global/corporate/about-bp/statistical-review-of-world-energy-2013.html, see also http://www.worldcoal.org/resources/coal-statistics - Viewed July 2013

[16] Lecarpentier, A., World Natural Gas Outlook - Cedigaz (January 2010)

[17] Gesocience Australia Petroleum Reserve Estimation 2011.

Coal and lignite

Coal forms when organic material, such as plant material trapped in swamps and bogs, is buried and heated under pressure. The maturation of the organic material under these conditions results in the formation of various grades of coal depending of the amount of heat and duration of the heating. Australian coal resources include low rank lignite (or brown coal – e.g. Latrobe Valley, Victoria), sub-bituminous coal (South Australia and Western Australia) or high rank bituminous coal (or black coal – Queensland and New South Wales). Coal fired power stations currently supply about one third of Australia's primary energy production and over 80% of the electricity[18]. Black coal is also an important export commodity with very large markets for Australian coal throughout Asia.

Black coal can either be mined in underground longwall or room and pillar (board and pillar) operations or where the seam is close to the surface and there is little overburden in an open cut mine. Brown coal is typically only mined in open pits as the material is softer and the seams often very thick. Due to the huge volume of some coal deposits open cut mines can become very large and have the potential to leave significant impacts on the landscape and also dewatering of these mines can have significant impact on local groundwater systems.

Unconventional hydrocarbons

Increasingly new technology is unlocking hydrocarbon resources that previously were deemed too difficult and/or costly to develop. These "unconventional hydrocarbons" include tight gas, shale gas, coal seam gas (or CSG) and tar and oil sands. The unconventional technologies associated with horizontal drilling and hydro-fracturing (or fracking) are best developed in the shale gas boom in the US. In the last decade U.S. production from shale gas has increased from <1% of U.S. gas production to over 20%. This increase, due largely to extraction technology developments, has driven a mini-gas boom and the potential that the US may be a net energy exporter at some point in the future (Birol, 2012) which has led to substantial restructure of the U.S. energy markets along the eastern sea board.

In Australia the unconventional gas developments mainly related to coal seam gas in Queensland and New South Wales and tight gas in the Cooper Basins in South Australia.

Tight gas and shale gas

Tight gas and shale gas are natural gas formed by essentially the same mechanisms as traditional gas. However the low permeability, or "tight", nature of the source rock precludes gas migration that typifies the more conventional natural gas reservoir accumulations that have historically provided for almost all gas production. The development of tight gas deposits requires permeability enhancement, typically via fracturing of the host rocks, in order to liberate gas

[18] http://www.ret.gov.au/energy/Documents/facts-stats-pubs/Energy-in-Australia-2011.pdf - August 2013

from the isolated pore spaces and allow it to flow into the extraction well. Artificial fracturing of the rock is typically accomplished by "hydro-fracking" where water and sand (or proppant) is pumped into the formations at pressures that exceed the local tensile strength of the rocks thus stimulating fracturing. The proppant helps keep induced fractures open once the fracking is complete and fluid pressure is released, so contained gas can flow back to the production borehole(s). Tight gas deposits can exist typically occur at similar depths to traditional oil and gas accumulations (i.e. 500m to >2000m).

Coal seam gas

Coal seam gas (or coal-bed methane) deposits form in regions where natural gas (usually methane) has formed and been trapped within deeply buried coal seams. Unlike shale gas, gas adsorbed within coal seam reservoirs is secured in part due to the confining pressure provided by natural groundwater. When the coal seam is depressurized by dewatering, the adsorbed gas begins to diffuse and enter the natural cleat/fracture system. Consequently gas production can be induced by depressurisation through dewatering. In some instances permeability enhancement through fracking is used to increase flow rates. Coal seam gas deposits exist at a variety of depths but typically are developed at significantly shallower depths than tight gas. At depths less than a few hundred meters, CSG production has the potential to compete with groundwater extraction and impact groundwater resources (King, 2012). Large Coal seam gas deposits exist in the Sydney, Gunnedah, Surat, Bowen and Cooper basins in Australia.

Oil sands

Oil (or tar) sand deposits are typically weakly or unconsolidated sands that are saturated with heavy crude oil or bituminous tars. Oil sand deposits are developed either via surface mining (effectively huge shallow open cut mines that are subsequently backfilled) or by a number of *in situ* extraction techniques that use heat (steam) or chemicals to reduce the viscosity of the oil and tars and allow them to be pumped out of wells. The best-known deposits in the world are the Athabasca deposits in Alberta, Canada. There is no current significant production from oil sands in Australia.

Other basin contained and basin related resources

In addition to these traditional and unconventional hydrocarbon resources, Australia's sedimentary basins are host to a number of other real and potential resource systems and uses. A key emerging use is the potential for geological carbon storage (or GCS). GCS involves the permanent storage carbon dioxide captured from large industrial emitters, such as coal-fired power stations, and then injected as a super-critical fluid into the pore space of a basin. This pore space could once have contained hydrocarbon accumulations that have been fully extracted or it could be in a region that never developed hydrocarbons in which case the existing pore-fluid, often a saline brine, is displaced by the injected CO_2.

GCS injection targets can include geological reservoirs of the type described earlier where the injected fluid accumulates in a structural trap such as an anticlinal dome or tilt block (see Figure 4). The long-term trapping of CO_2 occurs via a variety of processes including carbonate mineralisation, through residual trapping in small pore spaces due to surface tension and dissolution in formation waters. Traditional GCS targets need to be at depths greater than 800m to ensure that the injected CO_2 remains in a supercritical state. Ideal targets are in tectonically stable environments. GCS projects have been proposed in a number of Australian basins including the Gippsland and Perth basins.

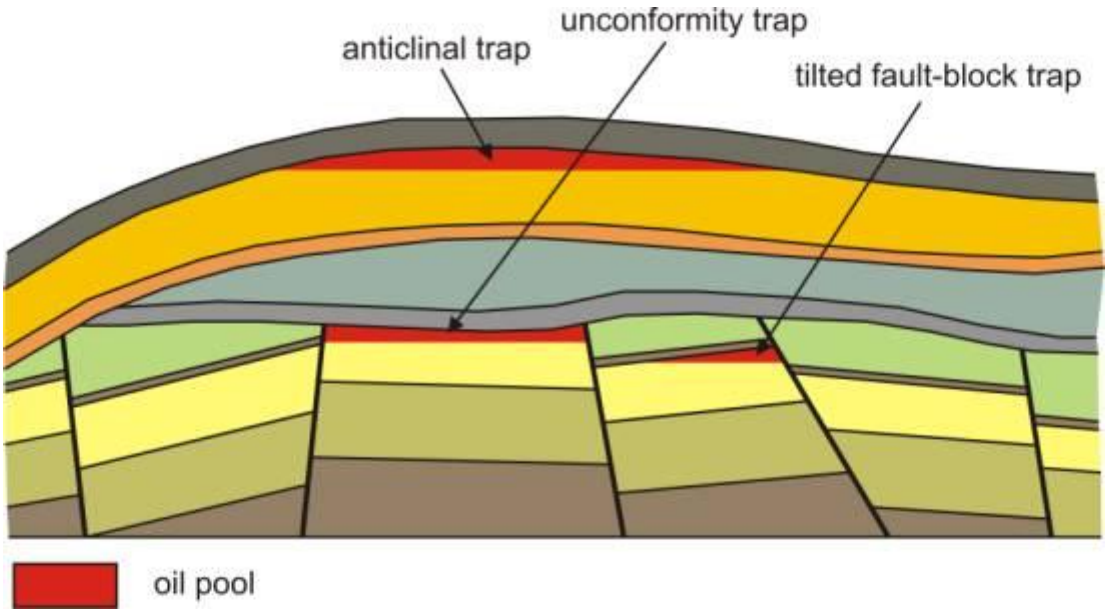

Figure 4. Example of various kinds of 'traps' appropriate to accumulations of bouyany fluids such as oil, gas, or injected CO2[19].

Other in practise or potential uses of basin pore space include the storage of natural gas and compressed air. Geological storage of natural gas is a common practise to provide an easily accessible source of refined gas that is rapidly available to meet increased demand. The natural gas can be stored either in depleted gas reservoirs, in groundwater aquifers or in salt domes. Geological storage of compressed air in very high permeability reservoirs is currently being investigated as a possible energy storage mechanism that could be used in concert with a number of renewable energy technologies with fluctuating output profiles such as wind and solar[20]. Several compressed air energy storage sites have recently been identified in a study by McGrail et al. (2013) where, in combination with a natural gas power plant, the reservoir has the capacity to store 231MW and generate as much as 207MW at a levelised energy cost (LEC – total cost of power production at the point of connection to the grid) of 6.4

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[19] image from http://www.geosci.usyd.edu.au/users/prey/ACSGT/EReports/eR.2003/GroupD/Report2/web%20pages/hydrocarbon_deposits.html

[20] http://news.stanford.edu/news/2013/march/store-electric-grid-030513.html

c/KWh. A similar site where excess wind turbine generated energy is stored as compressed air is combined with a geothermal heat plant to generate 83MW at under 12c/KWh with no greenhouse emissions (McGrail et al, 2013).

Mineral deposits

Sedimentary basins can also host a number of types of mineral deposits. The most critical of these from the perspective of resource conflict within Australian basins are mineral sands and diagenetic or unconformity related uranium deposits.

Mineral sands deposits form when heavy minerals such as rutile, ilmenite, monazite and zircon (sources of titanium, zirconium, rare earth elements and thorium) are concentrated due to the action of rivers, wind and waves over long periods of time. The deposits typically form linear bands in between ancient dune systems that may have subsequently been removed by erosion. Whilst the sorting action of waves is critical to the formation of many mineral sand deposits this does not mean that the deposits must now be located along the present coastline. Indeed some of the largest mineral sand deposits in Australia occur several hundred kilometres from the sea in western NSW and northern Victoria (Murray Darling Basin) and in the Perth Basin of southwestern WA.

Mineral sand deposits are usually mined using strip mining techniques where the top soil is removed, the shallow deposit is removed and processed and then the waste material backfilled as the active mine front works along the deposit. The topsoil is then replaced and re-vegetated.

Groundwater

Groundwater is a key resource in almost all sedimentary basins. In Australia, groundwater has been utilised for over 100 years for drinking water, industrial processes and most importantly, agriculture. Perth depends on the groundwater extracted from the Yaragadee Formation for drinking water, industrial use and irrigation whilst the development of vast regions central Australia for grazing was only made possible by the tapping of the groundwater of the Great Artesian basin, within the Eromanga Basin. In Alice Springs, town water supply is derived from aquifers form the Mereenie sandstone[21] in the Amadeus Basin; from within the same formation that hosts the local town supply gas field, and which also hosts potentially significant Uranium deposits[22].

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21 http://lrm.nt.gov.au/__data/assets/pdf_file/0013/20533/alicesprings_groundwater.pdf Note that the gas fields (Mereenie and Palm valley gas fields)and water bore fields (Roe Creek and Rocky Hill borefields are in the Mereenie Aquifer System) are physically separated from each other

22 http://www.martinferguson.com.au/page15346/Alice-springs-groundwater-study.aspx

Most of the permeable portions of a sedimentary basin will contain water of some kind, however much of it is often salty, particularly in deeper isolated or offshore portions of the basins not recharged by rainfall. As a consequence development of fresh groundwater resources, or other pore-space contained resources connected to groundwater systems can have significant implications throughout the basin and can result in drawdown or saltwater infiltration of once fresh aquifers (Varma & Michael, 2012). Some fresh aquifer systems contain water that is 10s of thousands of years old indicating that recharge rates in some parts of our onshore basins are very low (Cartwright et al 2012, Leblanc et al, 2012).

Geothermal

Another significant future utilisation of the basins will be in the development of geothermal power generation projects. Geothermal energy is effectively mined heat where hot water contained within deep geological reservoirs is extracted and used to turn turbines and generate electricity. Sedimentary basins are critical to the development of a variety of types of geothermal resources as they can contain thick sequences of low thermal conductivity material such as coals that act is insulating blankets that trap the heat. They also can contain deep high permeability aquifers which contain huge amounts of hot fluid that can relatively easily be extracted and re-injected in a closed loop system.

4. Multiuse scenarios and the affected stake-holders

Almost all Australian sedimentary basins are currently either being used for, or in the process of being developed for, multiple resources. Groundwater is accessed in all our onshore basins. Open cut and subsurface mining, especially coal mining, is significant in many of our onshore basins. While subsurface hydrocarbons (oil and gas) production is currently dominated by offshore basins[23], it is increasingly important in the onshore realm largely due to the development of unconventional resources. At a much more local scale, some of our basins are used locally for temporary storage of natural gas[24], and for injection of contaminated wastewaters. Our basins also host a variety of surface and subsurface mining and quarrying activities, including a sub-surface in situ leaching operation[25].

In addition to current uses, our basins are being explored for potential sites for the long-term geological storage of CO_2 and for geothermal resources[26]. Within individual basins, current or proposed different uses may overlap in space and time, or maybe separated in space and/or time. For example, depleted oil and gas reservoirs potentially make for reservoirs for containment of CO_2, provided that former exploration and production boreholes do not compromise containment integrity (see discussion below). In the future, there is potential for use of our subsurface basins for compressed air energy storage where surplus

[23] While conventional hydrocarbon production in offshore basins might not formally be considered under a multi-use scenarios, in several of these basins, offshore production is impacting contiguous onshore parts of basin through coupled pressure changes, most notably in the Gippsland basin. Further, a number of offshore basins are under active consideration for future geological carbon storage in depleted or near depleted hydrocarbon reservoirs.

[24] Such as the Iona Plant in southwest Victoria, operated by Energy Australia. Iona's gas storage fields consist of three open system, porous sandstone reservoirs, with a capacity to supply up to 500 terajoules (TJ) of gas per day. At Iona, depending on demand, compressed gas from offshore production is injected into the South West Pipeline to supply Melbourne, the SEA Gas Pipeline to supply Adelaide, or into the storage reservoirs for later withdrawal. See http://www.energyaustralia.com.au/about-us/what-we-do/power-generation/gas-plants/iona-gas-plant

[25] For example, at the Beverley mine in South Australia, in the Frome Basin, operated by Heathgate Resources, Uranium is extracted by in-situ leaching involving the injection of an acidic fluid containing sulphuric acid into the permeable ore-bearing horizon - http://en.wikipedia.org/wiki/Beverley_Uranium_Mine

[26] Sedimentary basin geothermal waters are being used for power production at Birdsville, Queensland, and have been used for district heating at Portland, Victoria.

energy generated in wind-farms or solar systems can be stored as compressed air and used to address peak loads or when the renewable systems are unable to generate.

Since so much of the use of our sedimentary basins relates either directly or indirectly[27] to the pore space and its contained fluids, the impacts of local subsurface activities can be communicated within the basin, potentially at large-scales, via physical (e.g., pressure) and chemical (e.g., contamination) changes in connected aquifers. Examples of such communication include the offshore petroleum production in the Gippsland Basin which has impacted the onshore parts of the basins through reductions in pore pressure in ground water systems (Underschultz et al., 2007, Varma & Michael, 2012). In the offshore, reductions in pore pressure induced by excessive extraction in reservoir horizons can lead to resource loss from fill-to-spill reservoirs (ie reservoirs that are full to the point of spilling to the next reservoir up sequence)[28]. Currently, there are few legislative requirements for operators to maintain pressure control across the full extent of such basin wide connected aquifers, raising potential to impact on resource recovery and complex management issues (Varma & Michael, 2012).

With so much of sedimentary basin resource use focused on accessing the fluids contain with in the subsurface pore space, potential for conflict arises through connections primarily mediated through impact on the pore space. These can be attributed to both physical and chemical processes that operate within the pore space.

Physical processes

High permeability creates pressure coupling within individual basins since fluids (and gasses) can transmit pressure changes rapidly along permeable pathways. Within aquifers, the pressure coupling can extend over significant scales, such that local changes in pore pressure due to fluid extraction and/or injection can have far reaching consequences (e.g. Underschultz et al., 2007). Permeability barriers between aquifers lead to compartmentalisation of fluid reservoirs. Pressure compartments are characterised by seals[29] that prevents pressure

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[27] Indirect impacts on pore fluids are associated with mining for example, due to the necessity to dewater mining operations.

[28] With many of our oil fields in effectively single horizon reservoirs systems, such issues are paramount. These include on the northwest-shelf and the Gippsland Basin, as discussed by Underschultz et al (2007) and Varma & Michael (2012).

[29] A pressure seal restricts flow of both hydrocarbon and brine and is formed where the pore throats become effectively closed, i.e., the permeability approaches zero. A leaking pressure seal, called a "rate seal," occurs when the pressure difference caused by subsidence-sedimentation or uplift-erosion or other pressure source is greater than the seal pressure leakage. When the internal fluid pressure in the compartment exceeds the fracture pressure of the

equilibration to normal hydrostatic pressure. In cases of permeability sealing, such compartmentalisation can lead to significant abnormal pressure distributions[30], presenting challenges and risk to individual subsurface operations. Maintaining integrity of seals is crucial to many subsurface activities.

Because of the sensitivity of the natural failure state of the shallow crust to fluid pressures, changes in fluid pressure can led to induced seismicity. Indeed it is this very seismicity that allows for the fracking of subsurface reservoirs. Typically induced seismic event are small in magnitude (< magnitude 3) and local in distribution. However, induced earthquakes can reach significant magnitude, with the largest demonstrable induced earthquake associated with dam filling attaining a M_w6.4 (moment magnitude scale), while the largest event attributed to waste water injection is a M_w5.7 (Keranen et al, 2013).

Chemical processes

Chemical contamination is similar to sterilisation but in this case the contamination of a fluid, gas or the atmosphere by some other substance due unforeseen leakage, plume migration or pollution. Migration of fluids within aquifers allows for dispersal of contained containments within basins, both in the subsurface and potentially to the surface. Currently the most visible example of this is the contamination of groundwater aquifer systems by leakage associated with damage to seals in coal seam gas development (e.g. Pavillion Wyoming[31]). These developments are also potentially linked to other types of contamination such as the generation of large volumes of fugitive emissions of greenhouse gasses such as methane.

Contamination of surface waters can also take place as a result of flooding or uncontained runoff from surface activities. Drill pads are required to have a cellar and embankment around the collar to ensure that any water contaminated with drilling fluids or extracted waste is contained within the site.

Prevention of surface water contamination can however be more difficult when dealing with open cut mines and floodwaters. In Victoria, for example, ongoing

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seal, the seal will fracture and fluids will escape from the compartment. The fracture and resealing may occur repeatedly (Ingram et al, 1997).

[30] Abnormal pressure distributions (i.e. those that differ from a hydrostatic pressure), arise from a number of mechanisms including stress related (due to disequilibrium and tectonic stress compaction, tectonic dilatancy), fluid volume changes (due to temperature changes, mineral transformation , hydrocarbon generation and 'cracking') and fluid movement (via buoyancy) - see Zoback (2007)

[31] http://www2.epa.gov/sites/production/files/documents/EPA_ReportOnPavillion_Dec-8-2011.pdf - Viewed Aug 2013

issues relate to breaches in the engineered Morwell River diversion causing flooding of the Yallourn Brown Coal open cut mine[32].

Potential conflicts

The multiple ways in which we currently use our sedimentary basins, combined with new emerging uses such as unconventional gas, geological carbon storage and geothermal, create for potential conflict around several key issues.

Pore space allocation
Because the same pore space can potentially be used in a number of ways, there is potential conflict in pore space allocation. For example, a saline aquifer at depths below 800m could be used to store captured CO_2 or alternatively, if hot enough, it could be used to as a source of geothermal energy. Similarly, confined reservoirs hosting potentially recoverable hydrocarbon resources, can also be useful geological carbon storage sites.

Resource sterilisation/compromisation
Mismanagement of a resource or development of a resource in a region where there may be undiscovered resources of different types could lead to unplanned resource sterilisation and/or compromisation. For example, injection of waste fluids into a reservoir could result in the contamination or displacement of, as yet undiscovered or presently uneconomic, resources in that same reservoir system. Similarly, allocation of saline aquifers for geological storage could compromise future use of recoverable thermal energy or deep groundwater. Likewise reservoir integrity of a potential storage site can be compromised by the existence of poorly completed hydrocarbon exploration or production holes

Impacts of pore pressure
Both the extraction and injection of fluids can have far reaching effects on the pore pressure throughout connected aquifers, particularly in confined aquifers capped regionally with impermeable seals. An example of this would be the drawdown of onshore groundwater aquifers and migration of the freshwater/saltwater interface due to exploitation of offshore oil and gas reservoirs or the dewatering of onshore open cut mines or dewatering of CSG systems.

Water table draw down and surface impacts
The development of deep open cut mines in sedimentary basins frequently requires large volumes of groundwater be removed to prevent flooding of the mine. Similarly, groundwater depressurisation of coal seam gas can involve very

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[32] In cases of flooding, the operator typically seeks permission to pump these floodwaters into adjacent river systems, producing potential downstream contamination. http://www.dpi.vic.gov.au/earth-resources/exploration-and-mining/issues/yallourn-coal.

significant water production[33]. Dealing with such waste water is a significant issue with potential impacts on surrounding shallow groundwater systems and riverine environments and associated ecosystems, either through direct contamination or via indirect consequences, such as surface water drawn down along with the deeper groundwater (Hofmann & Cartwright, 2013). This can result in the degradation of river systems such as the Murray Darling due to increased salinity in the river associated with damage to the freshwater lens that envelops and protects the quality of river water where they flow through regions containing largely saline aquifers (Leblanc et al., 2012). Similarly subsurface mining operations, particularly long-wall coal mining, can impact the surface-groundwater recharge rates, and hence natural surface flows, through changes in near surface fracture dilatancy associated with mining induced subsidence (Kay et al., 2006).

Stake holder groups

The growing demand for access to sedimentary basin resources, and especially energy and ground water resources, make the way we make use of our sedimentary basins increasingly relevant to a wide range of interests. Key amongst the interested stakeholders are:

- The general public, who increasingly require a framework that insures future sustainable development within Australia's sedimentary basins, without adverse consequences.
- Regulators and high level decision makers, and especially those in government departments and agencies that produce and manage policy on energy resources and agriculture.
- The resource sector including large and small companies operating in the energy space including oil and gas explorers and developers, coal miners and electricity generators, coal seam gas and shale gas developers, and geothermal explorers and major groundwater users.
- The electricity and gas production industries and related industries that have interest in long-term subsurface CO_2 storage.

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[33] For example, in its position statement on "Coal Seam Gas and Water" the National Water Commission estimated the Australian CSG industry could extract as much as 7,500 gigalitres of co-produced water from groundwater systems over the next 25 years, at a rate of up to ~300 gigalitres per year. In comparison, the current total extraction from the Great Artesian Basin is approximately 540 gigalitres per year. http://nwc.gov.au/nwi/position-statements/coal-seam-gas. See also "Onshore co-produced water: extent and management Waterlines 54 - September 2011", Waterlines Report Series No 54, September 2011, National Water Commission.
http://archive.nwc.gov.au/__data/assets/pdf_file/0007/18619/Onshore-co-produced-water-extent-and-management_final-for-web.pdf

- The agricultural sector and related groups where dependence on groundwater and shallow aquifers is crucial to ongoing viability.
- The insurance/reinsurance sector who require access to high quality hazard and risk assessment data associated with a variety of engineered systems that have the potential to cause environmental damage via induced seismicity or contamination.
- Community groups, rural communities and affiliated NGO's, that may be directly impacted by new and ongoing sedimentary basin usage, especially new technologies are proposed to access sub-surface resources, and where those activities have direct or indirect effects on surface environments.

6. Potential benefits of multi-basin usage

Whist developing different types of resources in complex sedimentary basin systems presents a number of challenges (see section 6) there are also a number of logistical, regulatory and efficiency benefits that should be noted.

The primary financial benefit of developing multiple resources, particularly if they are all in the energy space is associated with maximising value of existing infrastructure. For example, coal-bearing basins that are currently utilised for generating electricity will likely contain significant generating capacity as well as the high voltage transmission line infrastructure required to get that energy to market. Many of these coal basins also have significant geothermal potential (due largely to the insulating properties of the coal and the relatively high temperatures that can be "trapped" beneath it). Whist the temperatures in these insulation dominated geothermal systems may not be as high as those found in other geothermal systems, like the "hot granites" of the northern South Australia, the colocation of the resource with the existing transmission infrastructure can be enough to make the lower entropy resource economic (savings of <$800million compared to cost of building power lines from the Cooper Basin to east coast markets – Worley Parsons 2010 & Geodynamics Investor Roadshow June 2010).

Additional efficiencies can be found where the heat extracted from the geothermal resource is utilised in a hybrid generator with either coal or gas. The geothermal heat could be used to pre-heat water stock before feeding into the boiler or to dry or condition coal before burning thus increasing the efficiency of the system and reducing emissions.

Finally CO_2 emissions captured from the burning of fossil fuels in these generators can be captured and stored in the same basin as the coal or gas is extracted from. The oil and gas industry has been utilising Enhanced Oil Recovery (EOR) techniques for many years in order to maximise production for low yield reservoirs. Thus typically involves the injection of some gas (usually CO_2) into the reservoir in order to pressurise the system and simplify the extraction of hydrocarbons. More recently some companies, particularly overseas, are claiming carbon credits against this "sequestered" CO_2. Capturing of the emitted CO_2 from a collocated gas fired power station and using this CO_2 to manage pressures in the reservoir from which the gas is being extracted has benefits in the sense that the produced CO_2 is being sequestered (reducing emissions) but is also being used efficiently to manage the system, thus reducing costs associated with acquisition of other fluids for this purpose. Similarly using CO_2 as a working fluid in EGS Geothermal systems has some efficiency advantages over using water and again the "lost gas" is effectively being sequestered.

Recent research in the United States at the Lawrence Berkley National Laboratories has taken this concept of Stacked Basin Systems one step further (Buscheck et al, 2011). In this conceptual development captured CO_2 from a collocated traditional power station is injected into a deep saline aquifer and sequestered. The displaced hot saline fluids are extracted and used to generate geothermal energy. Rather than being reinjected back into the aquifer the displaced working fluid is then desalinated onsite (adding some additional parasitic energy load) and then used to provide potable water for agriculture or industry.

7. The challenge in managing multi-basin usage - risks and likely impacts

Whist there are clearly benefits to applying an integrated approach to developing basin contained resources there are also a number of significant challenges. Many of these relate to direct resource conflict, where the same portion of the pore-space is required by more than one usage, as outlined in a number of examples given above. However, with the increasing realisation that the subsurface pore-space can be multipurposed - for example, by using depleted hydrocarbon reservoirs for future storage of CO_2 - new challenges emerge in ensuring that such future potentials are not unduly compromised by current activities. Multipurpose usage scenarios raise challenging issues around cumulative impacts, in which risk profiles continue to evolve over time, potentially after individual operations have ceased.

As a result the challenge faced by policy makers and regulators when it comes to managing multiple use scenarios within our sedimentary basin are multifaceted:

Pore space conflict

A key challenge is in the allocation of the pore space. Whist in some cases the choices in this regard may be clear (i.e., gas extraction from a defined gas filled reservoir), in others the implications may be less clear, such as in the injection of CO_2 into a sequence of rocks that contain known hydrocarbon accumulations, or contain resources that are not currently economic with existing technologies/prices. The choices around managing these decisions should be informed by the consideration full range of basin-contained resources (see *Societal Value* below).

Plume migration

The injection and or withdrawal of significant volumes of gasses or fluids into or from basins can induce migration of chemically distinct subsurface fluid 'plumes' through time. In well understood reservoirs, the rate of movement and extent of plume migration can be accurately modelled (Nordbotten et al., 2005). However, even in reservoirs that are apparently well understood the rate of migration has proved hard to predict, with observed plume migrations more rapid and of larger extent than expected (Chadwick et al, 2005). Particularly in cases of storage injections (e.g., CO_2, waste water), such uncertainty necessarily requires that contingency must be built into reservoir assessments.

Pressure modification

The extraction (oil and gas, groundwater, geothermal fluids) or injection (CO_2, gas or air storage, geothermal working fluids, proppant, waste water) of material into sedimentary basins will affect the pressure distribution within connected portions of the basin. Even where plume migration is slow (on the order of hundreds or thousands of years) pressure changes associated with injection will be communicated more widely and more rapidly than the fluid migrates, especially in regions where aquifers are contained or sealed. The same is true of depressurising processes such as oil or gas extraction. As a result the effect of changing the pore pressure in one part of the basin can be far reaching, causing subsidence and productivity reduction in groundwater or petroleum wells, or alternatively, where waste water or fluids are being injected and stored in the subsurface, a rise in the water table and associated salinity problems 10's or 100's of km from the injection/extraction site. While managing pore pressure is a crucial and complicated issue for many single-use scenarios, it becomes even more complicated and more uncertain in multiuse scenarios.

Societal value

One of the most difficult aspects of managing multiple basin uses is placing a value on each of the potentially competing resources. In coal seam gas developments, for example, the value of the extracted methane needs to be balanced by the value of any groundwater resources that may have been impacted by the development as well as potential loss of farmland productivity due for example to well placement.

Similarly, the value of a hot permeable geological reservoir as a potential store captured CO_2 in an abatement strategy for an existing coal fired power station, should be assessed against its potential as a source of geothermal energy.

Such assessments are often challenging because of the different timelines needed to realise potential resources, as is the case for example with CO_2 storage and geothermal energy. How is a policy maker to value the access to the pore-space for the competing potential industry for maximum long-term benefit? Given that the timescale associated with plume migration and dispersal are on the order of hundreds or thousands of years what other potential future uses of that portion of the pore-space might be sterilised by decisions made today?

Risk and cumulative impact

All operations in the subsurface carry a degree of risk and, in recognition of such risk, all such operations are subject to significant regulation[34]. In typical single-use scenarios, regulated risks relate to safety issues surrounding drilling and mining operations, to both unintended and/or planned environmental impacts and to the integrity of long-term remediation following operations such as

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[34] For example exploration for and development of petroleum resources may require compliance with numerous international treaties and federal and state acts such as The Environment Protection and Biodiversity Conservation Act 1999 (Com), NOPSEMA legislation, Coastal Waters Legislation, Onshore Petroleum Legislation, AMSA Oil Spill Contingency Planning, Native Title acts, Coastal Management Act 1995, Historic Shipwrecks Act 1976, National Parks Act 1975, United Nations Framework Convention on Climate Change and numerous others. In terms of regulation of well drilling activities most aspects of the drilling and well completion process are regulated including use of drilling fluids, cuttings and disposal, fuel handling, ballast water management, construction, drainage and runoff (onshore sites), design and disturbance. Spill contingencies also need to be established that consider trajectory modelling, containment response and sensitive area identification. Decommissioning of wells is also thoroughly regulated.

plugging abandoned well bores[35]. Individual regimes are subject to significant regulation of subsurface activities, with well established codes of practise particularly around construction and abandonment of well bores to minimum acceptable standard ensuring long term well integrity, containment of gas and the protection of groundwater resources[36]. Operations within the subsurface that impact on fluid pressures, or change permeability (such as fracking), can have impact via a variety of mechanisms, including through induced seismicity, through impacting fluid pressures in connected operations, or by reducing the viability of future operations due to local modifications in the state of the basin (for example the temperature or the capacity of a rock to hold waste or contain a gas).

A relevant example is highlighted by the risk to CO_2 storage integrity in depleted hydrocarbon reservoirs provided by existing well bores. Such well bores may compromise reservoir integrity for CO_2 storage (Figure 5), where the long time-scales (>10^3 years) are a key issue. Typically such well bores are plugged with cement. While such cements may be appropriate to existing fluid chemistries associated with natural *in situ* reservoir fluids, they can be compromised by more acidic conditions that will prevail following CO_2 injections. This is a specific example of a more general issue concerning the necessary activities of drilling that are needed to explore, demonstrate and develop subsurface activities, that have the potential to lead to long-term changes in basin functioning. By virtue of a number of leakage pathways (Figure 5) old abandoned well bore provide particular risks to ongoing and future basin usage scenarios that necessitate changes in the physical and or chemical state of the basin (Gasda et al., 2004).

In multi-use scenarios, in which the cumulative effects of subsurface pore pressure modification manifest over long-times scales, complicated interactions may arise between different usage regimes. In turn that raises important and challenging issues of attribution in relation to issues of cumulative impact. For example, in the case of induced seismicity, where many different usage regimes contribute to changes in subsurface fluid pressures[37], a key question will be whether it is possible to attribute responsibility appropriately amongst the various present and past contributing sources.

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[35] Typically in well bore abandonment, much of the casing is removed and sections of well bore are filled with cement to isolate any potential flow path between gas and water zones, as well as the surface. Completely filling the well bore with cement is normally unnecessary. The surface around the wellhead is then excavated, and the wellhead casing cut off and capped and buried.

[36] For example, the mandated code of practise for CSG well-bore construction and abandonment in Queensland is detailed at http://mines.industry.qld.gov.au/assets/petroleum-pdf/csg_code_of_practice.pdf

[37] including surface loading by dams and reservoirs.

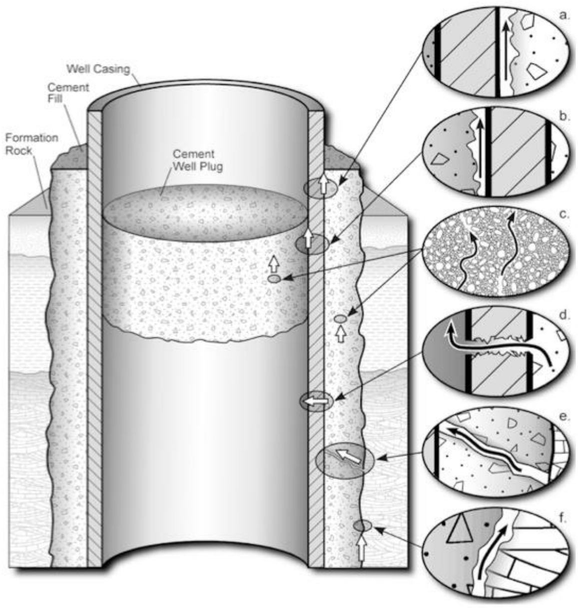

Figure 5. Diagrammatic representation of possible leakage pathways through an abandoned well. a) Between casing and cement; b) between cement plug and casing; c) through the cement pore space as a result of cement degradation; d) through casing as a result of corrosion; e) through fractures in cement; and f) between cement and rock. After Gasda et al. (2004)

9. Key knowledge gaps, unknowns and other issues

The informed management of complex subsurface multiuse operations in sedimentary basins requires confidence in how our basins respond to human activities at a variety of length and time scales. For this two critical data sets must be acquired. These are a comprehensive suite of monitoring data (including, but not limited to stress state, seismicity, fugitive emissions, plume migration, groundwater flow, thermal state) and a detailed geological model that describes the geometry of the basin and which provides a framework for assessing the nature of interactions between various geological reservoirs and aquifer systems within it. These models provide a detailed and robust starting model for any additional mechanical, thermal or flow simulation modelling that may then be required to address individual issues. In order to establish baselines monitoring data acquisition ideally should commence prior to any development activities, and continue during (and beyond) operations.

Monitoring

Monitoring is critical in any subsurface basin operation, and individual monitoring of individual operations is typically regulated. However, we are not aware of any jurisdictions (nationally or internationally) where regulatory requirements for monitoring are sufficient for integrated management of multi-use scenarios. A key issue is the establishment of baselines, ideally requiring monitoring systems in place prior to development. Only with good quality baseline data can the effects of the operations be quantified in a robust way. However, the reality for many producing basins is that baselines are inadequate and/or missing. For such scenarios there is an important need for new protocols concerning methodologies for recovering "best estimate baselines" from available data using sophisticated mathematical reverse modelling techniques. Such estimates are particularly important when changing societal expectations require new forms of accounting be introduced after initial operations are planned.

A key example concerns carbon liabilities associated with the potential for fugitive emissions from subsurface operations. Fluxes of methane and other greenhouse gases do occur naturally in coal and gas bearing basins. The flux rate may change as a result of subsurface operations (such as CSG deposits). If the natural background emissions are not quantified and understood prior to development then it becomes difficult to assess how much of any post development flux is due to anthropogenic fugitive emissions and how much is natural. Such uncertainty yields both financial and societal risk.

With the introduction of new technologies such as fracking, it is similarly critical to deploy dense and high sensitivity seismic monitoring networks within and adjacent to basins prior to their development in quantify the natural levels of seismicity. As discussed above there is potential associated with the development of a number of basin-contained resources to stimulate small earthquakes (fracking, geothermal, CO_2 storage, surface dams). Due to the long recurrence intervals of earthquakes in intraplate tectonic settings such as Australia, without high quality baseline seismic data in a region, collected over timeframes of years to decades, it can be difficult to discriminate human induced activity from naturally occurring events. This is illustrated by the recent debate over the rise in earthquake activity in US basins and the associated discussion about whether these are natural or induced anthropogenic events[38].

The routine application of monitoring should be designed to give confidence that subsurface operations are conducted within a well-understood and regulated risk framework. The types of monitoring needed for long-term[39] sedimentary basin management should include:

- *Stress state* – Geodetic markers and high precision GPS, seismometers, borehole and mine site deployed stress monitoring.
- *Seismicity* – Seismometer networks both regional and local including permanent stations, rapidly deployable aftershock kits, borehole seismometers and ocean bottom seismometers (offshore basins).
- *Fugitive emissions* – various types of spectral gas flux monitoring depending on the type of basin.
- *Plume migration* – geophysical and borehole based monitoring of plume migrations using 4D reflection seismic imaging, electrical methods,

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[38] For example, a remarkable increase in the rate of magnitude 3 and greater earthquakes is evident in the US midcontinent. Starting in 2001, there has been a six-fold increase over 20th century levels in 2011. Is this increase natural or manmade? Ellsworth et al. (2012) addressed this question in terms of catalogue completeness levels, showing that from 1970 through 2000, the rate of M > 3 events averaged 21 events per year in the entire region. This rate increased to 29 from 2001 through 2008. In 2009, 2010 and 2011, 50, 87 and 134 events occurred, respectively. The modest increase beginning 2001 is due to increased seismicity in the coal bed methane field of the Raton Basin along the Colorado-New Mexico border west of Trinidad, CO. The acceleration in activity that began in 2009 appears to involve a combination of source regions of oil and gas production, including the Guy, Arkansas region, and in central and southern Oklahoma. Horton (2012) provided strong evidence linking the Guy, AR activity to deep waste water injection wells. In Oklahoma, the rate of M > 3 events abruptly increased in 2009 from 1.2 per year in the previous half-century to over 25 per year exclusive of the November 2011 M 5.6 earthquake and its aftershocks. A naturally-occurring rate change of this magnitude is unprecedented outside of volcanic settings or in the absence of a main shock, of which there were neither in this region. While the seismicity rate changes described here are almost certainly human induced, it is not clear how they are relate specifically to either changes in extraction methodologies or the rate of oil and gas production.

[39] Long-term in this context implies planning basin activities over tens to hundreds of years but many of these activities may have impacts that will last for thousands of years or longer.

microseismic monitoring, geochemical monitoring, borehole gravity gradiometry, etc.

- *Groundwater pressures* – borehole based groundwater level monitoring and pressures in regional connected confined aquifers, flow meters and chemical monitoring.
- *Thermal state* – borehole deployed temperature gauges to monitor cooling associated with development of geothermal systems or injection of large volumes of waste-water.

Well-designed monitoring deployments are important to mitigating operational risk in several ways. In allowing the effects of human activity on the basins systems to be assessed, changes in system state that have the potential to be damaging (either to the environment or to other developments in the region) they allow for timely remediation. Most existing subsurface basin operations are regulated to some extent to meet such needs however monitoring is still designed with a commodity or industry specific mindset.

Secondly, solid baseline data should reduce the risk that developments face issues around "social license to operate" (i.e., ongoing community and stakeholder approval), due to apparent and/or inferred links to natural events, such as earthquakes. This is clearly an issue of contemporary relevance to fracking activity where there is significant potential for a public backlash, if operations coincide with natural earthquake activity. Quality baseline data is essential to more certain discrimination between induced and natural phenomenon. In the case of induced phenomena, baseline data is critical to providing context and allowing critical assessment of any associated risk.

Geological models

The second critical data component that is required for robust informed management of multi-use basin systems is a dynamic and fully attributed 3D geological model of the basin and its surrounds.

A geological model of this type allows complex management scenarios to be modelled and the outcomes of activities and interactions between different developments and basin systems to be predicted. The model must be fully attributed (that is rock properties such as permeability, porosity, thermal conductivity and density to be contained within the model) in order to allow sophisticated predictive modelling. For multipurpose use, models need to be basin-wide and be commodity independent thus allowing multi-use scenarios to be analysed effectively.

Multipurpose basin models need to be adaptable, and allow updating over time as new data is acquired, for example, through the new datasets such as 3D reflection seismic surveys. Developing a 3D geological model of a basin prior to development, and in the absence of much of this geophysical data, can also highlight critical data gaps that should be addressed as part of ongoing programs.

Few detailed geological models of this type exist anywhere in the world however a good example of an excellent starting point is the modelling that has been done in the Gippsland Basin recently by the Geological Survey of Victoria under their VicGCS and 3DVictoria initiatives (see McLean & Blackburn, 2013 and Rawling *et al*, 2011).

Informed basin management environments

The broader framework for informed sedimentary basin management requires input from scientific, technical, regulatory, finance, market design and social science perspectives. This is currently not being done in a fully integrated way anywhere in the world and represents a significant innovation opportunity in Australia.

- Predictive geoscience/geotechnical understanding incorporates developments in various fields such as coal seam gas, shale gas, geothermal power, geological carbon storage and groundwater that explicitly include consideration and assessment of uncertainties and risks at a range of temporal and spatial scales.
- Comprehensive, independent monitoring of both the subsurface (e.g., induced and natural seismicity, including from fracking and related activities, and groundwater systems) and surface (e.g., tracking natural and fugitive greenhouse gas emissions and land subsidence) is required to provide baselines against which to detect and measure resource-related impacts.
- Legal and regulatory issues surrounding multipurpose interactive basins systems have the potential to be mired in complex intergovernmental regimes and regulatory duplication. Regulatory systems will need to take account of the fact that some of the future broad-scale development, such as unconventional gas developments will need to be regulated on a regional rather than on a site specific basis, especially where there is coupling via connected aquifers or reservoirs (connected pore-space) across usage regimes.
- Robust, independent, assessment of benefits and costs of basin resource usage plans (including economic benefits, environmental impacts and potential impact of development of one resource on another). Market structures and auctioning regimes to pore-space usage need to be reconsidered in terms of multipurpose usage scenarios.
- Sophisticated modelling constrained by large, rich datasets to allow the physical state (pressure, temperature, pore fluid chemistry) of the basin to be predicted and the effects of various activities simulated with enough fidelity to facilitate analysis at both the basin and resource scale.
- Social science analysis that acknowledges the many ways our usage of sedimentary basin resources has impacted on community aspirations, and can be adapted to meet future aspirations, as well as ensuring that social license as an issue is fully integrated into basin management decision systems.

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11. Appendix 1. Terms of reference

To deliver a background paper to the Office of the NSW Chief Scientist and Engineer (OCSE) providing information and a discussion about the multiple uses of sedimentary basins (e.g. agriculture, communities, energy resources) including potential environmental impacts and synergistic opportunities.

The background paper will be an input into an independent review of CSG activities in NSW being undertaken by the NSW Chief Scientist and Engineer in accordance with a request made by the Premier of NSW on 21 February 2013 (The Review). The Terms of Reference (TOR) for the Review are at Schedule 5.

The background paper will be used to inform the review, and will also provide background to the set of information papers referred to in TOR 6. The background paper will likely be made available on the Chief Scientist and Engineer's website.

The purpose of this background paper is to provide an overview of the multiple uses of sedimentary basins for community, agriculture and energy and mineral resources. The paper will also look at strategies and opportunities associated with the multiple usages of sedimentary basins.

The report should include a discussion of the following:

- What is a sedimentary basin?
- What is the importance of sedimentary basins?
- What resources and usages are there in sedimentary basins?
- What are the potential for conflicts over sedimentary basin resources/usage?
- What are the potential economic benefits or disadvantages of multi sedimentary basin usage?
- What are the other benefits or disadvantages of multi sedimentary basin usage?
- What are the issues/challenges associated with managing multiple sedimentary basin usage? Discuss the potential for synergistic opportunities.