DECLARATION

The work contained in this thesis is original, except as acknowledged in the customary manner, and has not been submitted previously for a degree at any university. To the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made.

The author consents to the thesis being made available for photocopying and loan if accepted for the award of the degree.

____

Jonathan Peter Salo
Adelaide, Australia
30 May 2005

EVALUATING SITES FOR SUBSURFACE CO_2 INJECTION/SEQUESTRATION: TANGGUH, BINTUNI BASIN, PAPUA, INDONESIA

(VOLUME 1: Text)

Jonathan P. Salo

Supervisors:
Dr. Simon C. Lang
Dr. John G. Kaldi

Australian School of Petroleum
University of Adelaide
South Australia
S.A. 5005

May 2005

ACKNOWLEDGEMENTS

The author expresses his gratitude to BP for their sponsorship and support. Particular thanks are extended to John A. Marcou (BP Tangguh Subsurface Development Manager 2000-2002); Dr. Neil Davis (BP Acting Tangguh Subsurface Development Manager 2002-2003); Achmadi T. Kasim (BP Tangguh Subsurface Development Manager 2003-2004); Dr. Godofredo Perez (Reservoir Engineer); Frans J. P. Silitonga (Reservoir Engineer); and Pranoto (BP Geophysicist).

The author would also like to thank the University of Adelaide, particularly the Australian School of Petroleum (ASP). The author wishes to express sincere gratitude to Dr. Simon C. Lang and Dr. John G. Kaldi for their time and assistance as supervisors and their keen interest in guiding the research, particularly in sedimentology/sequence stratigraphy and seal capacity/potential.

The author also wishes to thank the following ASP staff for time and assistance in their respective geological specialties, particularly Professor Richard Hillis (geomechanics and fault reactivation); Dr. Jochen Kassan (geologic modelling and geostatistics); Dr. Jerry Meyer (fault reactivation); Dr. Tobi Payenberg (sedimentology); Dr. Richard Daniel (seal evaluation); and Andy Mitchell (geophysics). The author also thanks fellow students Dr. Mark Tingay for FMI/FMS processing, and Dr. Takeshi Nakanishi for advice in probabilistic prospecting.

The author would also like to thank the GEODISC Programme of the APCRC (now the CO2CRC) and their key personnel including Dr. Peter Cook, Dr. Andrew Rigg, Dr. John Bradshaw, Dr. Jonathan Ennis-King, and especially Catherine Gibson-Poole for their kind assistance and helpful insights.

In addition, the author would like to thank Steve Tyson, of GeoVisual Systems, for his assistance with 3D geologic modelling, and numerous customizations to the GeoCARD software program.

Thanks also to Ben Royal, and especially Nathan Ceglar, for assistance with drafting and compilation. Finally, I would like to express thanks to my wife, Nurkayati Salo, and my son, Jason Michael Salo, for being patient and forgiving of the long periods of time spent away from home in the course of this study.

Jonathan Peter Salo

October 2004

ABSTRACT

The venting of anthropogenic CO_2 emissions into the atmosphere at increasing rates is probably influencing global warming and climate change. The Tangguh LNG development project in Papua, Indonesia will produce significant volumes of CO_2, which might be vented into the atmosphere. The LNG process will necessitate the separation of CO_2, estimated at 2.4 trillion cubic feet (TCF sc), from the natural gas reserves prior to liquefaction and shipping. This study screens and assesses the possible alternatives to atmospheric venting, and recommends subsurface CO_2 injection and sequestration/storage in saline aquifers. The study identifies specific subsurface locations for several Environmentally-Sustainable Sites for CO_2 Injection (ESSCI) in Bintuni Basin, where the Tangguh production fields are located.

Alternatives to atmospheric venting of the estimated CO_2 volume at Tangguh include both non-geologic and geologic disposal options. Non-geologic options such as biosphere sinks (enhanced forest or agricultural growth), deep-ocean sinks (subsea dispersal), and direct commercial usage (e.g. use in beverage or fertilizer production, fire-retardant manufacturing) are impractical and of questionable impact in remote Papua, Indonesia.

Several subsurface geological disposal options were investigated, but the most viable geologic disposal option for Tangguh CO_2 is injection into the downdip aquifer leg of the Roabiba Sandstone Formation hydrocarbon reservoir. Injected CO_2, at supercritical phase, is expected to migrate updip into the sealed structural traps at Vorwata or Wiriagar Deep, as the natural gas reserves are produced.

A probabilistic ranking of data quality and quantity for five potential ESSCI reservoirs determined that the Middle Jurassic Roabiba Sandstone Formation has the highest likelihood of viable ESSCI sequestration/storage.

A probabilistic ranking of data quality and quantity for eight ESSCI structural traps within the western flank of Bintuni Basin, determined that Vorwata, followed by Wiriagar Deep, are the most viable ESSCI structural traps at the Middle Jurassic reservoir level.

Five potential ESSCI seals were evaluated and it was determined the best seal potential occurs in the Pre-Ayot Shales, directly overlying the Middle Jurassic reservoir at Vorwata. This unit is capable of holding a 3300 to 4660 foot (1006 to

1420 meter) CO_2 column. Seal integrity of the Pre-Ayot is very good because it is a relatively homogeneous deep-water shale that is composed primarily of ductile illite and kaolinite clays with a minor quartz and feldspar content. Sequence stratigraphy analysis suggests that the zone extends over the entire Vorwata three-way dip closure, with thickness between 17 feet (5 m) and 233 (71 m) feet.

The maximum effective storage capacity of the Middle Jurassic reservoirs for each structure was calculated, taking into account irreducible water, trapped water, and trapped residual gas pore volumes. The Vorwata structure is capable of storing 19.3 TCFsc supercritical CO_2 at reservoir temperature and pressure. The Wiriagar Deep structure has potential storage capacity of 3.5 TCFsc, and Ubadari 2.8 TCFsc, at their respective reservoir temperatures and pressures.

A 'Rating Product Ranking' was developed to quantify the results of the quality and quantity of four factors: Reservoir Data, Structure Data, Seal Data, and Storage Ratio. Each structure, and the respective top and lateral seal overlying the Middle Jurassic reservoirs, was evaluated. The net result was that Vorwata rated a 0.88 on a scale of zero to one, where 1.0 represents 100% confidence in ESSCI potential. Ubadari and Wiriagar Deep scored, respectively, 0.52 and a 0.45.

Finally, the structures were evaluated for relative proximity to the proposed CO_2 source (i.e. the LNG plant location). With a weighted distance factor calculated with the Rating product for each potential injection site, Vorwata rated 0.88 on a scale of zero to one, Wiriagar scored 0.24, and Ubadari scored only 0.09.

The Middle Jurassic 'Roabiba Sandstone Formation reservoir' at the Vorwata structure has the greatest potential as an ESSCI storage site. The Middle Jurassic 'Aalenian Sandstone Formation reservoir' at the Wiriagar Deep is the second-best potential ESSCI storage site. The subsurface ESSCI injection location proposed for the 'Roabiba Sandstone Formation' aquifer, 10 km southeast and down-dip from the known gas-water contact (GWC), is on the southeast Vorwata plunging anticlinal nose. An alternate potential ESSCI injection location proposed for the 'Roabiba Sandstone Formation' aquifer is 6 km south of and down-dip from the known gas-water contact (GWC) on Vorwata structure southern flank.

A key issue was to determine the possible risk of fault re-activation from CO_2 injection. NE-SW striking vertical faults have the highest risk of re-activation requiring an increase of over ~1460 psi (103 kg/cc) over hydrostatic at 14,000 ft TVDss (4267 m), for slippage to occur. The closest fault with a high risk of re-activation is 5 km northwest of the recommended ESSCI site location. Supercritical CO_2 pressure is not expected to exceed the estimated pressure determined to cause fault re-activation.

A 3D geological model of the Mesozoic interval was constructed over a large area of western Bintuni Basin. The model was constructed so as to preserve as much geological heterogeneity as possible yet still have a manageable number of active cells. Faults were incorporated into the model as strike-slip vertical fault surfaces (or indexed fault polygons) as a separate attribute.

The geo-cellular model was built suitable for importation into a reservoir simulator (VIP), and a 25-year simulation run for natural gas production from the Vorwata Middle Jurassic reservoir, with concurrent CO_2 injection downdip into the Vorwata Middle Jurassic aquifer at the primary recommended ESSCI site location. The simulation verified the recommended location with the CO_2 slowly migrating into the Vorwata structural trap within the Middle Jurassic reservoir, and not compromising the hydrocarbon reserves or production.

It is recommended that additional data be acquired such as conventional core, formation water samples, and specific logs such as dipole-sonic, multi-chambered dynamic formation testers (MDT), and mechanical rotary sidewall coring tools (MSCT).

Lastly, several CO_2 monitoring methods and techniques are recommended for Tangguh to monitor CO_2 migration, pressures, and potential leakages. One such method is a vertical monitoring well at the recommended injection site. Other monitoring techniques include smart well completions, detection monitors at production wells with tracers injected prior to CO_2 injection. In addition, crosswell seismic surveys, electromagnetic methods, and electrical-resistance tomography techniques are suggested during the injection phase.

TABLE OF CONTENTS

TABLE OF CONTENTS

VOLUME 2 (FIGURES and APPENDICES)

AGU : American Geophysical Union
ANGP : Australian-New Guinea plate
ARCO : Atlantic Richfield Inc.
ASP : Australian School of Petroleum
bar : equivalent to Atmospheres
BBOE : billion barrels of oil equivalent
BCPD : barrels of condensate per day
BG : British Gas Ltd. Inc.
BHMC : Bird's Head micro-continent
BO : barrels of oil
BOE : barrels of oil equivalent
BP : British Petroleum Ltd. Inc.
C : Celsius
CCC : complete carbon cycle
CCV : CO2 sequestration in cavity or void
CDOGR : CO2 sequestration in depleted oil/gas reservoir
CECMP : CO2 for enhanced coal bed/seam methane production
CEGR : CO2 sequestration with enhanced gas recovery
CEOR : CO2 sequestration with enhanced oil recovery
CO2 : carbon dioxide
CSA : CO2 sequestration in saline aquifer
CUCS : CO2 sequestration in unmineable coal seams/beds
DITF : drilling induced tensile fractures
DOE : Department of Energy (USA)
DST : drill-stem test
EEA : European Environmental Agency (EU)
EO : Earth Observatory (US Agency of NASA)
EOR : enhanced oil recovery
ERT : Electrical Resistance Tomography
ESSCI : Environmentally Sustainable Site for Carbon Dioxide Injection
F : Fahrenheit
FAPS : Fault Analysis Projection System (software program)
FAST : Fault Analysis Seal Technology (software program)
GeoCARD : GeoCARD 3D geo-cellular model (software program)
GEODISC : Geological Disposal of CO2
GHG : greenhouse gases
HST : highstand systems tract
IPCC : Inter-governmental Panel on Climate Change
Ka : Thousands of years before present
KOM : Kumawa-Onin-Misool Ridge (also known as MOK)
LNG : liquefied natural gas
LTFB : Lengguri Thrust/Fold Belt
Ma : Millions of years before present
MFS : maximum flooding surface
MICP : mercury injection capillary pressure
MMBO : million of barrels of oil
MMscf/d : million standard cubic feet per day (gas flowrate)
MPa : megapascals
MSL : mean sea level
NASA : National Aeronautical and Space Administration (USA)
NGLG : New Guinea Limestone Group
NIST : National Institute of Standards & Technology
NNGPM : Nederland Nieuw-Guineese Petroleum Maatschappij
NOAA : National Oceanic and Atmospheric Administration
NTFA : National Tidal Facility of Australia
PMEL : Pacific Marine Environmental Laboratory
PSC : Production Sharing Contract
PSI : pounds per square inch
PSIA : pounds per square inch absolute
RS : Royal Society
RST : regressive systems tract
SB : sequence boundary
SFZ : Sorong Fault-Shear Zone
TCF : trillions of cubic feet (gas)
TST : transgressive systems tract
TVDss : True Vertical Depth subsea
Unc : unconformity
UND : University of North Dakota
UNFCCC : United Nations Framework Convention on Climate Change
WIMC : West Irian micro-continent
XRD : x-ray diffraction
YBP : years before present

CMR : magnetic resonance tool (Schlumberger trade-name)
CNL : compensated neutron porosity log tool (Schlumberger trade-name)
CSAT : wireline seismic geophone tool (Schlumberger trade-name)
DLL : dual laterolog tool (Schlumberger trade-name)
DSI : dipole sonic induction tool (Schlumberger trade-name)
DT : delta T (sonic transit time)
eLOT : extended leak-off test
LOT : leak-off test
FDL : formation density log tool (Schlumberger trade-name)
FMI : 64-button borehole resisitivity imaging tool (Schlumberger trade-name)
FMS : 32-button borehole resisitivity imaging tool (Schlumberger trade-name)
GR : gamma-ray
ILD : induction conductivity tool (Schlumberger trade-name)
LWD : logging while drilling
MDT : formation fluid sampling and pressure testing tool (Schlumberger trade-name)
MRIL : magnetic resonance tool (Western-Atlas and NUMAR trade-name)
MSCT : mechanical sidewall rotary coring tool (Schlumberger trade-name)
MSFL : micro-spherically focussed laterolog tool (Schlumberger trade-name)
MWD : measurement while drilling
OBM : oil-based mud (drilling fluid)
RHOB : density log (Schlumberger trade-name)
RKB : rotary kelly bushing (drill floor datum)
SHmax : stress horizontal (maximum)
SHmin : stress horizontal (minimum)
SV : stress vertical
SGR : spectral gamm-ray (Schlumberger trade-name)
SOBM : synthetic oil-based mud (drilling fluid)
SP : spontaneous potential tool and log
Sw : water saturation
Swir : irriducible water saturation
VSP : vertical seismic profile log (Schlumberger trade-name)
WBM : water-based mud (drilling fluid)

WD-1 : Wiriagar Deep #1
WD-2 : Wiriagar Deep #2
WD-3 : Wiriagar Deep #3
WD-4 : Wiriagar Deep #4
WD-5 : Wiriagar Deep #5
WD-6 : Wiriagar Deep #6
WD-7 : Wiriagar Deep #7
WD-8 : Wiriagar Deep #8
V-1 : Vorwata #1
V-2 : Vorwata #2
V-3 : Vorwata #3
V-4 : Vorwata #4
V-5 : Vorwata #5
V-6 : Vorwata #6
V-7 : Vorwata #7
V-8 : Vorwata #8
V-9 : Vorwata #9
V-10 : Vorwata #10
V-11 : Vorwata #11
N-1 : Nambumbi #1
R-1 : Roabiba #1
O-1 : Ofaweri #1
W-1 : Wos #1
EO-1 : East Onin #1

LIST OF TABLES Volume 1

LIST OF TABLES (Appendices) Volume 2

LIST OF FIGURES Volume 2

LIST OF FIGURES (Appendix 4) Volume 2