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Numerical Modelling of Deformation and Fluid Flow in Hydrothermal Systems

Thesis submitted by

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for the degree of Doctor of Philosophy in

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James Cook University, North Queensland

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STATEMENT OF CONTRIBUTIONS

General contributions towards this study have included:

- Australian Post Graduate Award (APA) scholarship
- pmd*CRC top-up scholarship
- pmd*CRC educational and training fund
- ARC large grant to Oliver & Dickens, financial support towards Chapter 3

Contributions from others towards this thesis have been clearly stated at the forefront of each chapter where applicable, and these people and their contributions to this study include the following:

Chapter 3: P.M. Schaubs – assistance with computer codes relating to the FISH functions for FLAC

Chapter 4: L.Feltrin – 3D Modelling of the Century Deposit and text including the following contribution: 20% (p. 88-103), 50% (p. 67-77, 103-106), and 80% (p. 88-103)

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And normal supervisory conditions throughout the course of this study by

N.H.S. Oliver

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Abstract

Geomechanical processes involved in mineralisation of several Australian deposits were tested using both continuous and discontinuous modelling techniques. Numerical modelling using both the finite difference method and discrete element method, were carried out by firstly devising conceptual models. This also allowed rigorous sensitivity testing of many input parameters throughout the modelling procedure. Fully coupled deformation and fluid flow modelling was applied to investigate and establish the influence of topography, structure and extension on porous media fluid flow. Iron ore genesis in the Hamersley Province, W.A., has been a contentious genetic issue for many years, with several ore genesis models proposed. Modelling results from this study confirm the mechanical feasibility of focusing both surface and basinal derived fluids towards sites of iron ore genesis during Proterozoic orogenic collapse, providing upward and downward migration of (reduced and oxidised) fluids during deformation, and allowing infiltration of banded iron formations and consequent silica loss during permeability increase, resulting in favourable conditions for ore genesis.

Extension and contractional models of potential scenarios of ore emplacement at the Century Zn-Pb-Ag deposit in northwest Queensland were tested by a combination of 3-D structural modelling and fully coupled fluid flow models. Three conceptual models were devised, and two of these were fully tested by numerical simulations (diagenetic and epigenetic), the other (syngenetic) by Geological Computer Aided Design (GoCad). Reconstruction of the 3-D structural model displayed thickness and grade relationships to NE trending growth faults, providing evidence that supports a syngenetic model of

emplacement. Numerical models provide clear evidence that stratiform Zn-Pb mineralisation is difficult to achieve in subsurface conditions, due to the low permeability of shale units. During contractional deformation, modelling results suggest that it would most probably result in fault or vein style mineralisation at the Century deposit, due to the proximal nature of fluid focussing relative to the faults.

The Eastern Succession of the Mt Isa Inlier is a mineral rich region, with many large deposits such as Cannington Pb-Zn-Ag, Osborne Cu-Au, and Slewyn Cu-Au. This area has been the focus of mineral exploration for some years, and evaluating the prospectivity of this region is one of the current goals of the pmd*CRC. Stress partitioning in this region, during the Isan Orogeny, may have played a vital role in determining the locations of mineral deposits as a result of failure and fluid flow. Discrete element modelling of the Eastern Succession provides strong correlations with known ore deposits and prospects, particularly in the Selwyn region, and also provides several testable targets. Comparisons of these results correspond well with other current prospectivity analysis of the region. The results indicate that mineralising fluids were preferentially focussed into zones of anomalous stress in and around fault zone bends and intersections, and intrusive metasediment contacts. Furthermore the optimum far-field stress that provides the best correlation with known deposit distribution was orientated E/SE rather that E/W, suggesting a component of regional transpression late in the 1600 – 1500 Ma Isan Orogeny.

Extension related mineralisation is commonly linked to near surface fluids penetrating into deeper parts of the crust and possible fluid mixing occuring. The general mechanics of extensional faulting are fairly well understood at a

range of scales, and many models have been proposed. Hydrodynamic models, however, are considerably fewer. This study applied fully coupled deformation and fluid flow numerical models to test the role of extensional deformation and its effects on fluid flow, particularly at basement-cover interfaces. Large contrasts in the permeability of the basement and cover restrict fluid exchange between these two units, unless permeable faults or shear zones are present. Downward migration of fluids is a natural consequence of the extension of dilatant materials where strain rates are high. Rapid decreases in pore pressure, as a result of dilation and failure, may provide mechanisms for mass transfer across basement cover interfaces.

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LIST OF SYMBOLS

A	cross sectional area (m)
b	aperture (m)
c	cohesion (Pa)
e	void ratio
E	youngs modulus (Pa)
F	yield function for plasticity models
F_c	horizontal force in the crust (N m^{-1})
g	gravitational acceleration (9.81m s^{-2})
G	shear modulus (Pa)
h	height (m)
H	hydraulic head (m)
k	permeability (m^{2})
$\boldsymbol{k_{ij}}$	permeability tensor (m^{2})
k_n	normal stiffness of joints (Pa)
K	hydraulic conductivity (m s^{-1})
K	elastic bulk modulus (Pa)
K_f	Bulk modulus of fluid
K_s	Bulk modulus of solid
L	length (m)
M	slope of critical state line
$\boldsymbol{M_f}$	Biot modulus for fluid
$\boldsymbol{M_s}$	Biot modulus for solid
n	porosity
N	number of joints per unit distance
p_c	yield surface intercept (strain hardening/softening)
pf	pore fluid pressure (Pa)
Pf	fluid pressure (Pa)
P	pressure (Pa)
PF_f	fluid pressure required for failure (Pa)
q	specific discharge
Q	flow potential function for plasticity models
Q	volumetric fluid flow rate (m^{3} s^{-1})
Re	Reynolds number for porous media
Rk	Stiffness ratio

T	tensile strength (Pa)
ν	poissons ratio
ν	specific volume (m^3 kg^{-1})
ν	kinematic viscosity (m^2 s^{-1})
$\boldsymbol{V_i}$	Darcy fluid velocity (m s^{-1})
V_v	void volume (m^3)
V_t	total volume (m^3)
V_s	volume of the solid (m^3)
w	fracture width (m)
z	elevation (m)
α	angle of shear (°)
β	yield surface parameter for modified Cam-Clay plasticity
ε_a	axial strain
ε_n	normal strain
$\underline{\varepsilon}^{pl}$	plastic strain
ε_v^p	plastic volumetric strain
ε_r	radial strain
ε_s	shear strain
ε_{xx}	normal strain in the x plane
ε_{yy}	normal strain in the y plane
ε_{xy}	shear strain on x plane in y direction
ε_{yx}	shear strain on y plane in x direction
ϕ	friction angle (°)
γ	shear strain
γf	specific weight (kg m^{-2} s^{-2})
γ_p	rate of plastic shear strain
μ	viscosity (kg m^{-1} s^{-1}), (Pa s)
μ	friction coefficient
ρ	density (kg m^{-3})
ρ_c	density of the crust (kg m^{-3})
ρ_m	density of the mantle (kg m^{-3})
ρ_w	density of fluid (kg m^{-3})
η	dynamic viscosity (Pa s)
ηf	viscosity (kg m^{-1} s^{-1}), (Pa s)
σ_c	critical stress (Pa)
σ_{eff}	effective stress (Pa)
σ_m	mean stress (Pa)
σ_n	normal stress (Pa)

σ_o	yield stress (Pa)
σ_s	shear stress (Pa)
$\sigma_{x,y,z}$	normal stress components (Pa)
σ_{xx}	normal stress in the x plane (Pa)
σ_{yy}	normal stress in the y plane (Pa)
σ_{xy}	shear on the x plane in the y direction (Pa)
σ_{yx}	shear on the y plane in the x direction (Pa)
σ_1	maximum principal stress (Pa)
σ_2	intermediate principal stress (Pa)
σ_3	minimum principal stress (Pa)
σ^*	mean stress (Pa)
$\underline{\sigma}$	stress tensor
$\overline{\sigma}$	effective stress (Pa)
τ	shear stress (Pa)
τ_s	shear stress (Pa)
τ^*	maximum shear stress (Pa)
$\boldsymbol{t}$	deviatoric stress measure (Pa)
$\Delta\sigma$	differential stress (Pa)
$\Delta\sigma_n$	effective normal stress increment (Pa)
$\Delta\mu_n$	normal displacement increment (Pa)
π	pi
ψ	dilation angle (°)
Ψ	hardening parameter