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MODELLING TWO-PHASE FRACTURE FLOW ABOVE A DIORITE INTRUSION

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SUMMARY – A model is presented of a hydrothermal reservoir containing a reactive fluid dominated by CO_2. A pulse of magmatic vapour is injected into the base of this reservoir, and the changed chemical and physical conditions calculated as the reservoir is allowed to evolve for 15,000 years. The chemistry in the reservoir is described by twelve component species, H_2O, H^+, Cl^-, $SO_4^=$, HCO_3^-, HS^-, SiO_2, Al^{+++}, Ca^{++}, K^+, Fe^{++} and Na^+. Associated with these components are 32 secondary species, nine minerals and two gases.

1. INTRODUCTION

Magmatic intrusions are obvious heat sources for geothermal fields. Perhaps the most thoroughly studied intrusion is that at the Kakkonda reservoir in Japan (Sasada et al 1998). Although less well studied, a diorite intrusion was also intersected during the drilling of geothermal well NM4 in the Ngatamariki field, New Zealand. This is to date the only in situ plutonic rock encountered in the Taupo Volcanic Zone (TVZ). There is extensive hydrothermal alteration both within the intrusion and in a halo surrounding the intrusion that suggests it acted as a heat source for the convective hydrothermal system active at the time (Christenson et al 1997,1998).

White and Christenson (1998,2000) modelled the rock alteration about such an intrusion using the reactive transport simulator CHEM-TOUGH2 (White 1995). Here we extend this work by: 1) including several iron containing minerals, either in the initial rock assemblage or as possible alteration products; and 2) by including the effect of dissolved gases (CO_2 and H_2S) on saturation pressure. HCl and SO_2 gases are included in the source but not included in the gas phase. A MINC (Pruess and Narasimhan 1982) formalism is used to represent a flow that is dominated by fracture flow with transport to the rock matrix primarily by diffusion.

2. MODEL DESCRIPTION

Drilling at Natamariki intersected a 700 ka old diorite intrusion at about two kilometres below the surface (Figure 1). We have adopted a similar shallow-intrusion scenario in our model, and consider the thermal and chemical effects on the hydrothermal system immediately after emplacement.

The model is cylindrically symmetric with a radius of two kilometres, and extends from the surface to two kilometres depth. Surface waters contain no dissolved solids or gases, have a pH of 7, a constant temperature of 20°C and a confining pressure of one bar. On the vertical boundary of the model we assume hydrostatic pressures and temperatures consistent with a temperature gradient of 40°C/km. The boundary fluids are assumed to be in equilibrium with the rocks that make up the unaltered reservoir. At the base of the model fluid and heat flow is possible only over a central circular region of radius 450 metres at the base where various magmatic chemical components enter the modelled region from the degassing intrusion.

The upper 200 metres of the reservoir forms a partial cap and has a permeability of 0.01 milli-Darcy in the fracture network. The rest of the reservoir has a permeability of 1.0 milli-Darcy in the fracture network. Matrix permeability is 0.001milli-Darcy throughout. Fracture and matrix porosities are 0.5 and 0.05 respectively.

We have adopted a simplified subset of reservoir component species, including H_2O, H^+, Cl^-, $SO_4^=$, HCO_3^-, HS^-, SiO_2, Al^{+++}, Ca^{++}, Fe^{++}, K^+ and Na^+. These components allow the modelling of reactions between 'the main magmatic volatiles (CO_2, SO_2, H_2S, HCl) and the most common rock-forming minerals (albite, anorthite, K-feldspar and quartz). Added to this initial mineral assemblage are iron-bearing phases fayalite and hematite which exert an additional redox control on the fluid composition. Simplifying assumptions adopted in the treatment are:

- chemical equilibrium is maintained;
- fracture flow is treated using a MINC representation of the reservoir.

While the assumption of chemical equilibrium is justified in the hot area of the reservoir, the assumption is certainly invalid in the cool areas. For example, the pH in the cool surface waters is much higher than normally found, but is correct for the interaction between pure water and the assumed rock assemblage at 20°C. Fluid flow within a geothermal reservoir is predominantly in (micro)fractures and only a small portion of the rock volume will be in direct contact with fluid flowing in the fractures and available for reaction with the reservoir fluid. We represent the reservoir as a series of interacting continua (Pruess and Narasimhan 1982).

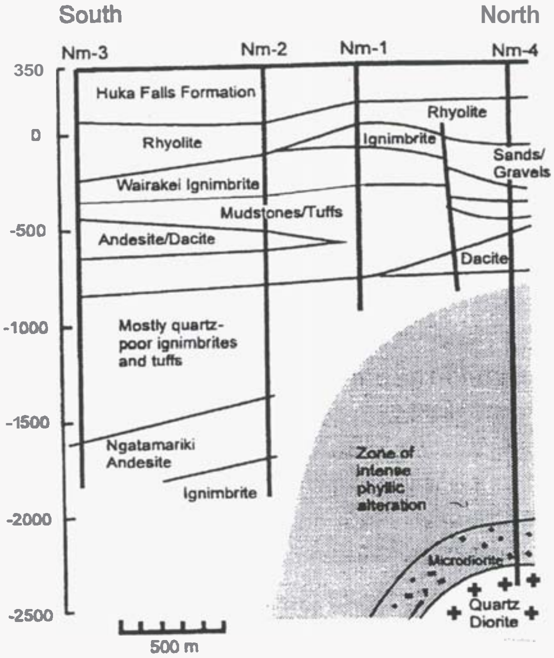


Figure 1: Geologic cross-section through four exploration wells at Ngatamariki (from Christenson et *al.,* 1998).

The **MINC** method is a generalisation of the dual porosity (see, for example Warren and Root, 1963) approach. The basis of this approach is to partition the reservoir porosity into primary porosity associated with the pores of the rock matrix and a secondary porosity associated with fractures and joints. Each of these porosities is treated as a continuous media within which Darcy's law describes fluid flow. Darcy's law also describes fluid flow between these continua. Heat and chemical constituents are transported between the continua either convectively **by** flowing fluid or by diffusion through the fracture network and rock matrix. Figure 2 illustrates the MINC description of the Ngatamariki reservoir used in this work.

3. MAGMATIC INTRUSION

The fluxes of magmatic volatiles injected at the base of the model are based on estimated inter-eruptive fluxes from White Island. The SO_2 flux is set at 350 t/d and the flux of other magmatic volatiles are normalised to this. The values used are given in Table 1 in the row labelled 'full model'. These gases, with an enthalpy of steam at 350°C, are injected into the model over the source area for a period of three years. After this the rate is dropped to 1% of the initial rate and the simulation run to a final time of 15,000 years.

4. CHEMICAL ENVIRONMENT

The hydrothermal environment within or immediately adjacent to shallow (< 4km) cooling diorite plutons is characterised by high temperatures (up to 1100°C), pressures ranging fiom hydrostatic to lithostatic (ca. 200 – 1000 bar), and by the presence of highly reactive fluids. Here we consider only the interaction between the volatile species released from a cooling magma, and the overlying hydrothermal environments. This is in keeping with evidence from Ngatamariki suggesting that release of magmatic volatiles occurred periodically during the cooling history of the diorite intrusion found there.

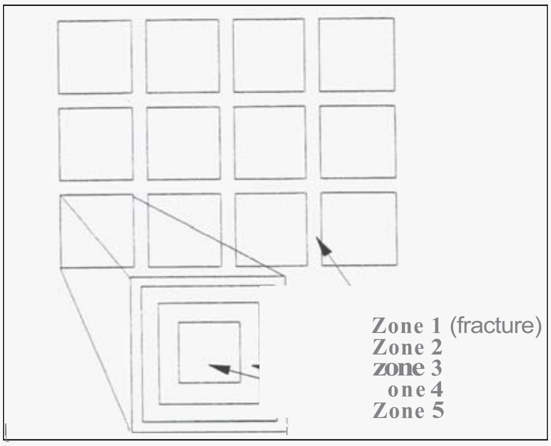


Figure 2: The **MINC** approximation used in this work.

Scenario	H_2O	H^+	HCO_3^-	HS^-	$SO4^{=}$	Cl^-
Initial	0.54	0.0	0.0	0.0	0.0	0.0
CO_2 only	0.54	3.17 e-4	1.94e-2	0.0	0.0	0.0
Full model	152.5	1.33	59.79	2.77	12.87	2.47

Table 1: Mass flows for the three modelled scenarios. All mass flows are in kg/s. In all cases the heat flow above the intrusion is **2** W/m^2

Calculation of the initial state of the reservoir is described in White and Christenson (1998).

Name	Composition	Weight %
Albite	$NaAlSi_3O_8$	39
Anorthite	$CaAl_2Si_2O_8$	39
K-Feldspar	$KAlSi_6O_8$	6
Quartz	SiO_2	14
Fayalite	Fe_2SiO_4	1
Hematite	Fe_2O_3	1

Table **2:** Initial rock composition.

This calculation provided starting temperature and pressure conditions for the second calculation described in this paper. The aim was to estimate chemical conditions and rock alteration products in a liquid-dominated reservoir containing CO_2

and the initial mineral assemblage (Table **2).** The heat and mass flows into the reservoir during this run equate to a source fluid containing ***3.6%*** CO_2 by weight (Table 1). This model was run to simulate the evolution of the reservoir for 100,000 years. The temperatures, pressures aqueous chemical components and mineral assemblage at the end of this simulation provided the initial state of the reservoir prior to intrusion of the diorite. This initial condition was applied to both the rock matrix and fracture domain of the MINC model, the assumption being that over very long timescales diffusion will allow equilibrium to be reached between the fracture network and the rock matrix.

Name	Composition
Alunite	$KAl_3S_2O_{14}$
Anhydrite	$CaSO_4$
Calcite	$CaCO_3$
Kaolinite	$Al_2Si_2O_5(OH)_4$
Muscovite	$KAl_2(AlSi_3O_{10})(OH)_2$
Pyrophyllite	$Al_2Si_4O_{10}(OH)_2$
Pyrite	FeS_2
Sulphur	S

Table **3:** Rock alteration products included in the calculations

5. RESULTS

Results of the modelling are summarised in Figures **4-8.** Selected fluid parameters (i.e. pH, and Cl^-, Figures **4** through 5) depict the shape of the convective upwelling over the intrusion. We present results for two or three MINC zones, these represent parameters at different distances from the fractures. Zone 1 is the fracture zone, zone **2** immediately adjacent to the fracture zone and zone 5 most distant from the fracture zone. Hydrogen ions within the plume are consumed in hydrolysis reactions, and after 15,000 years, the distribution of Cl^- in the system shows that the cell has accomplished about one complete convective cycle. SO_2/H_2S ratios show the fluids near the heat source to be most oxidising. Figure **5** shows the extent of the hydrolysis reactions dissolving albite in two zones of the reservoir after addition of the magmatic volatiles, as does the distribution of some of the reaction products kaolinite and muscovite (Figures 7a-b). Elemental S and alunite form in the low pH and oxidised environment close to the intrusion. Similarly, Ca^{++} released from the increased dissolution of anorthite is taken up in anhydrite in the low pH zone close to the heat source, and calcite further away (Figures 8a-b,9a-b). Diffusion into zones away from the fracture is a slow process on the time scale **of** the modelling presented here and rock alteration is much less intense away from the fiacture zone.

6. DISCUSSION AND CONCLUSIONS

We have demonstrated that it is possible, with the assumptions given earlier, to model the chemical changes that take place in a geothermal reservoir in response to a large pulse of magmatic vapour from the heat source. The chemical modelling includes sufficient detail to represent the processes associated with the neutralisation of the low pH, oxidising fluids that result from the dissolution of magmatic vapour into reservoir fluid.

We feel that the dual porosity model results presented here realistically portray the resulting water-rock interaction processes. The degree to which fluids are acid neutralised and reduced through water-rock interaction is in large part controlled by permeability. Highly permeable fracture channels, with relatively high water/rock ratios, foster rapid transfer of the aggressive fluids through the system resulting in extensively leached and hydrolysed fracture-bound mineralisation (assemblages of alunite, kaolinite, anhydrite and quartz). Within the blocks, the lower permeability (lower water/rock ratios) preserves mineral assemblages more typical of near-neutral pH environments. Similarly, the fracture channel fluids are more oxidising than their mid-block counterparts, as evident from the elevated SO_2/H_2S ratios, and this is reflected in the common occurrence of sulphate minerals in vein assemblages.

The reactive transport approach described here has implications for future geothermal exploration and development. Not only does it provide a predictive capability for "fitting" observed fluid chemistry and alteration products in shallow reservoir environments to unexplored heat source environments at depth, but also it will ultimately allow for testing production scenarios in near heat-source environments.

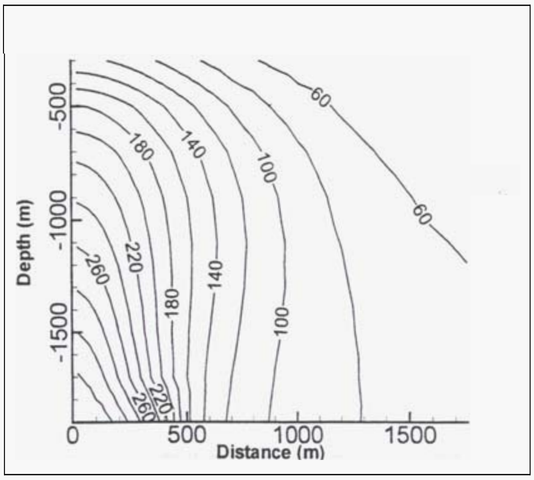


Figure **3:** Temperature contours of the hydrothermal system at 15,000 years.

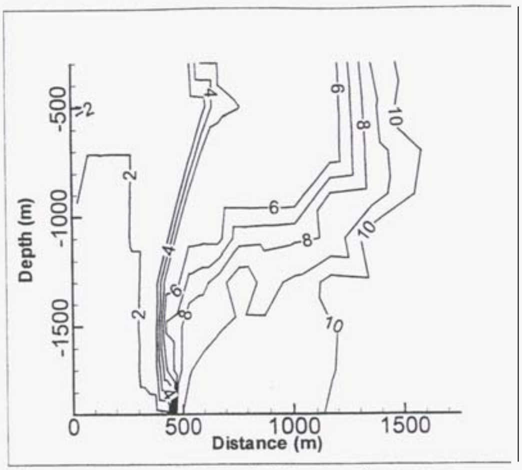


Figure 4 (a): pH Zone 1 (fracture)

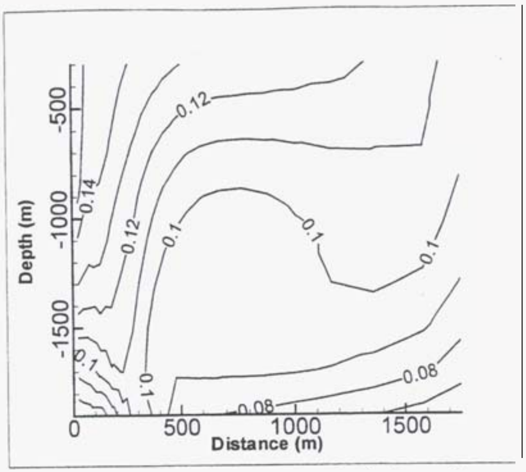


Figure 5(a): Cl^- concentration (M), Zone 1

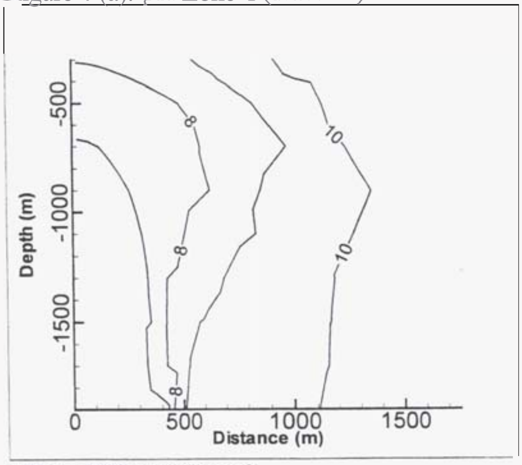


Figure 4(b) :pH Zone 2

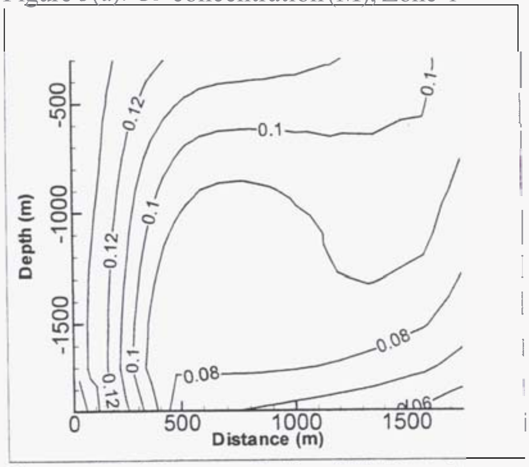


Figure 5(a): Cl^- concentration (M),Zone **2**

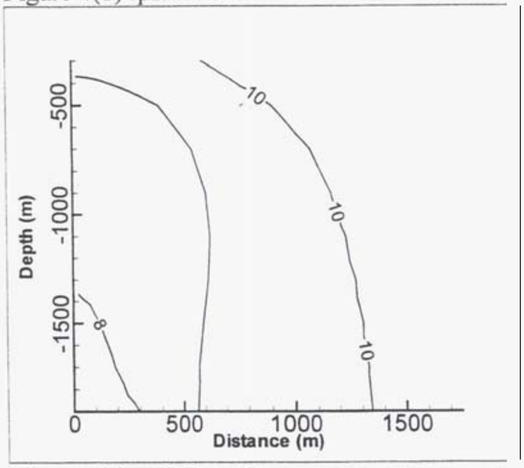
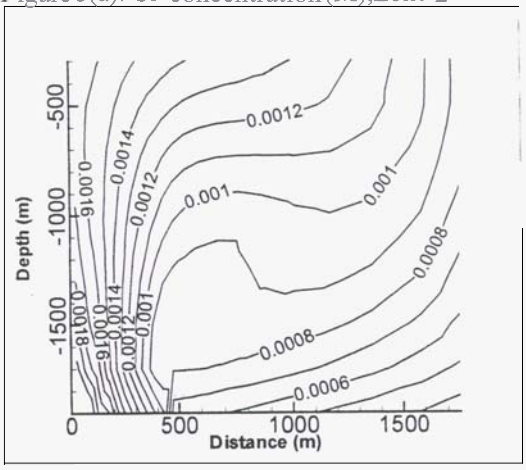


Figure 4(c): pH Zone 5.



igure 5(a): Cl^- concentration (M)Zone **5**

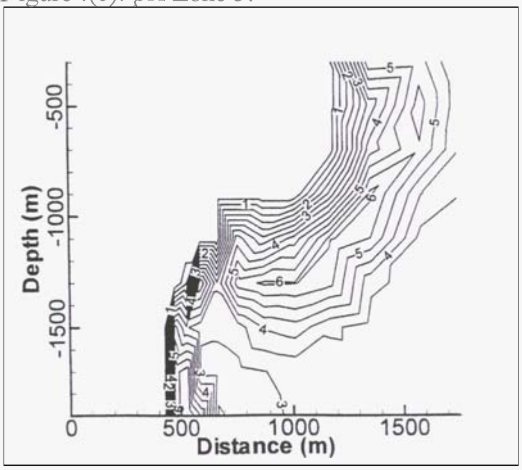


Figure 5(a):Albite distribution in Zone 1

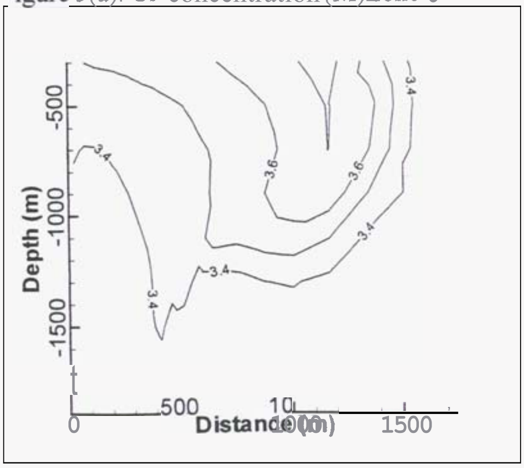


Figure 5(b):Albite distribution **in** Zone **2**

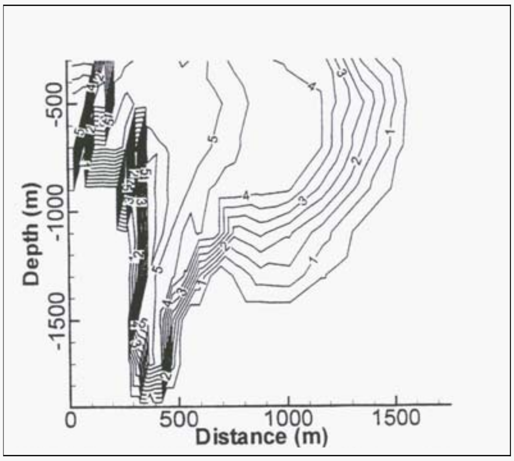


Figure 6(a) :Kaolinite distribution (M/l) Zone

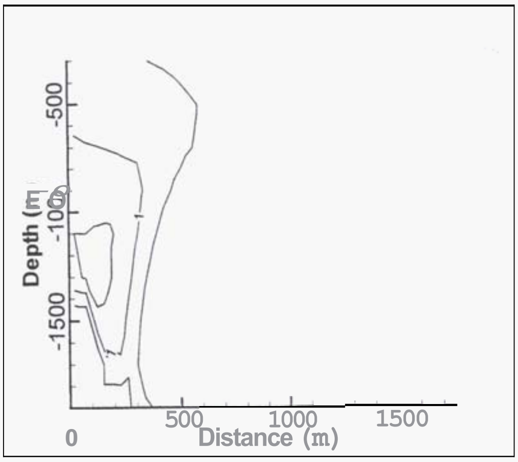


Figure 6(b):Kaolinite distribution (M/l) Zone 2

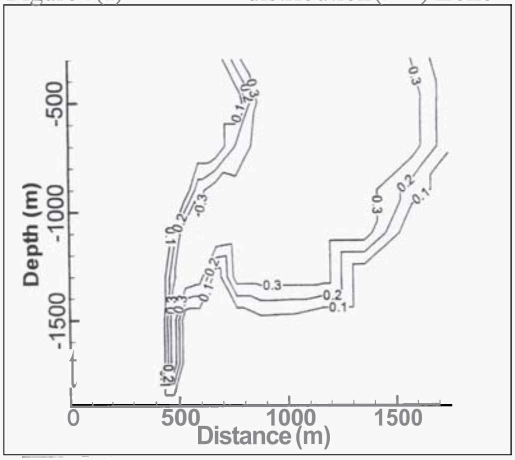


Figure 7(a): Muscovite distribution (M/l) Zone 1 :

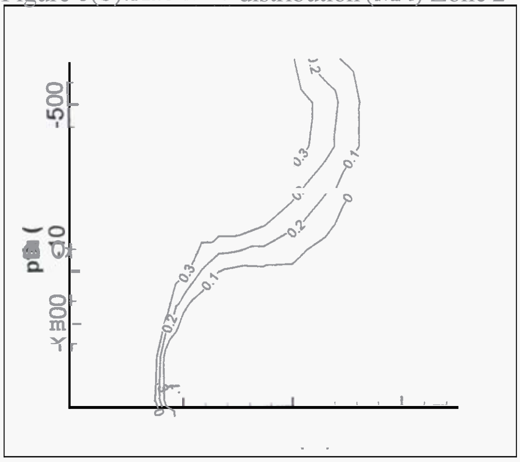


Figure 7(b): Muscovite distribution (M/l) Zone 2

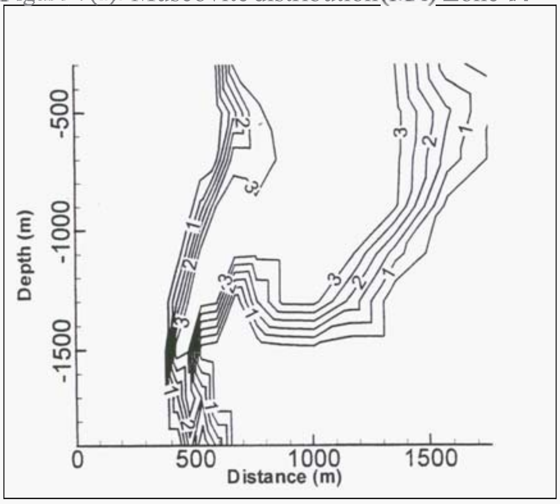


Figure 8(a): Calcite deposition (M/l) Zone 1

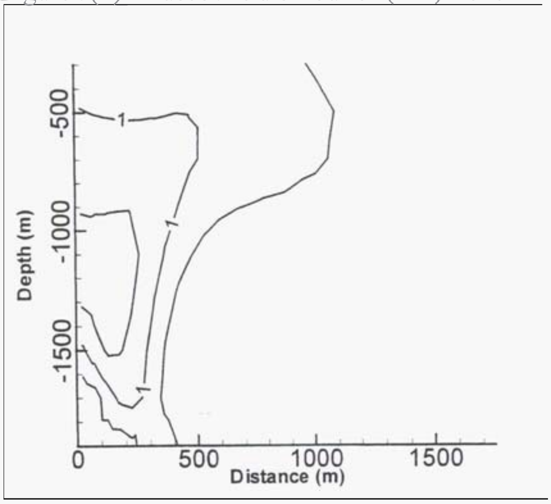


Figure 8(b): Calcite deposition (M/l) Zone 2

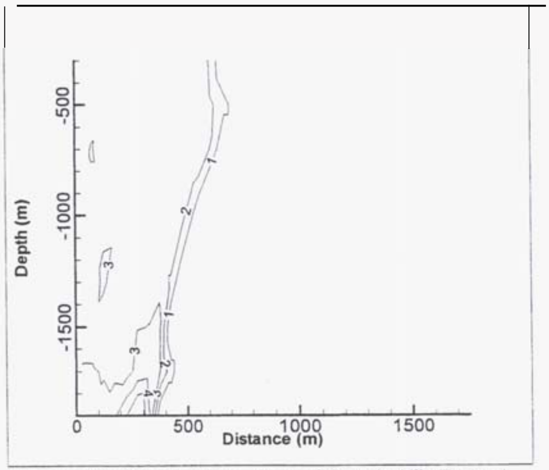


Figure 9(a):Anhydrite deposition (M/l) Zone 1

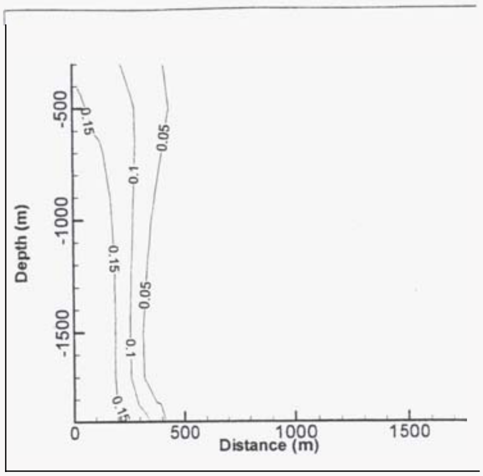


Figure 9(b):Anhydrite deposition (M/l) Zone 2

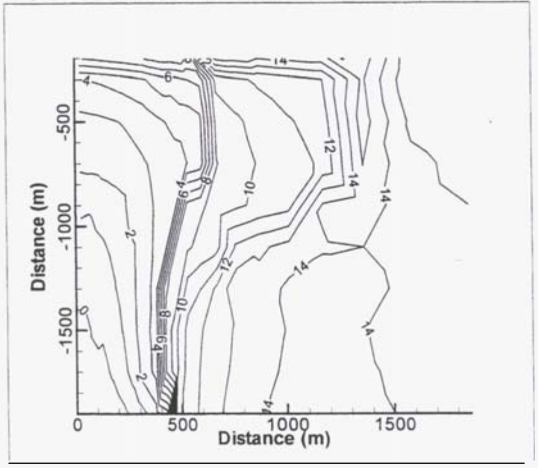


Figure 10(a) Log(P_{H2S}/P_{SO2}) Zone 1

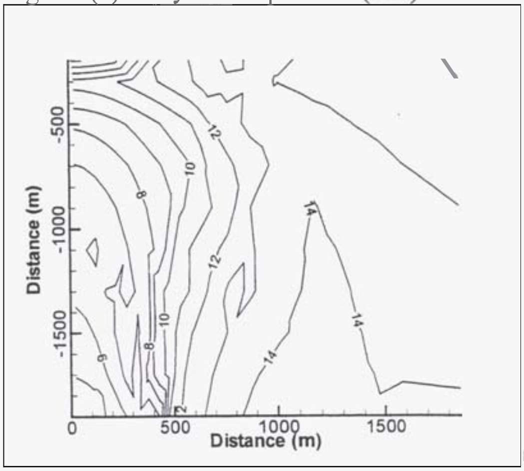


Figure 10(b) Log(P_{H2S}/P_{SO2}) Zone 2

Note that solid concentrations are given as Moles / litre of reservoir fluid.

7. REFERENCES

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