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Abstract

Coupled heat and fluid flow modeling of the Carboniferous Kuna Basin, Alaska: implications for the genesis of the Red Dog Pb–Zn–Ag–Ba ore district

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Abstract

The Red Dog deposit is a giant 175 Mton (16% Zn, 5% Pb), shale-hosted Pb–Zn–Ag–Ba ore district situated in the Carboniferous Kuna Basin, Western Brooks Range, Alaska. These SEDEX-type ores are thought to have formed in calcareous turbidites and black mudstone at elevated sub-seafloor temperatures (120–150 °C) within a hydrogeologic framework of submarine convection that was structurally organized by large normal faults. The theory for modeling brine migration and heat transport in the Kuna Basin is discussed with application to evaluating flow patterns and heat transport in faulted rift basins and the effects of buoyancy-driven free convection on reactive flow and ore genesis. Finite element simulations show that hydrothermal fluid was discharged into the Red Dog subbasin during a period of basin-wide crustal heat flow of 150–160 mW/m^2. Basinal brines circulated to depths as great as 1–3 km along multiple normal faults flowed laterally through thick clastic aquifers acquiring metals and heat, and then rapidly ascended a single discharge fault zone at rates ~ 5 m/year to mix with seafloor sulfur and precipitate massive sulfide ores.

Keywords: Basin hydrogeology; Stratiform ores; Free convection; Normal faults

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1. Introduction

Numerical methods in hydrogeology and geochemistry have seen widespread use in the study of hydrothermal ore deposits, particularly since computer processor speeds have advanced and numerical codes have been improved for hydrodynamics and geochemical thermodynamics. In recent years, a number of studies have documented the application of fully coupled reactive flow models to problems of sediment-hosted ore genesis, for sandstone-hosted unconformity-type uranium ores of the Athabasca Basin, Canada (Raffensperger and Garven, 1995), and for carbonate-hosted lead–zinc ores of southeast Missouri and Ireland (Garven and Raffensperger,

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1997; Garven et al., 1999; Appold and Garven, 2000), and for synsedimentary shale-hosted ores of the McArthur Basin, Australia (Garven et al., 2001). These authors have used reactive flow modeling as a tool to test hydrologic and geochemical theories for ore genesis and explore the effects of model parameters such as permeability, porosity, and metal concentration on patterns of rock alteration and ore mineralization.

Many rift-hosted deposits of lead, zinc, and barite ore appear to have formed at or near the seafloor by focused venting of hot basinal fluids and modified seawater (Sangster, 1990), although the hydrogeologic nature of these systems is not understood. For example, the upper Kuna Formation, a finely laminated black, organic-rich siliceous mudstone and shale in the Western Brooks Range of northwest Alaska, is host to the largest resources of zinc yet discovered in the Earth's crust, containing ore reserves of about 175 Mton, with grades averaging about 16% Zn and 5% Pb (Jennings and King, 2002). Although situated today in a highly deformed series of structural allochthonous plates thrusted during the Jurassic to Cretaceous Brookian Orogeny, the stratiform ores are thought to have formed much earlier in the anoxic, mud-rich, Carboniferous-age Kuna Basin when adjacent carbonate platforms were drowned by rifting and tectonic subsidence (Dumoulin et al., 2001). Fluid inclusion studies of ore-stage sphalerite and gangue minerals indicate sub-seafloor mineralization temperatures less than 200 °C, and most likely, between 120 and 150 °C, during a period of sediment diagenesis and extensional faulting. The ore-stage mineralizing fluids were both hot and salty: preliminary fluid inclusion analyses indicate brines with up to 15 wt.% NaCl equivalent.

2. Theory and methods of numerical analysis

In the present work, we are applying the numerical techniques of Garven and Freeze (1984) and Raffensperger and Garven (1995) to extensional basins where large normal faults have had a major control on brine migration driven by thermal gradients. As we shall discuss below, the presence of normal faults has a major impact on controlling the geometry of free convection cells, allowing for deep circulation of fluids to great depths in the basin and underlying crystalline basement, and allowing for relatively rapid discharge, which creates hydrothermal environments near seafloor vents.

Submarine fluid flow and heat transport in saturated geologic media can be mathematically modeled by solving continuum-based partial differential equations representing conservation of fluid mass, flow vorticity, and thermal energy. Numerical solutions to the flow equations are required for geologically interesting basins and to accommodate the nonlinearity in fluid properties, effects of convective flow on heat transport, and multidimensional effects of heterogeneity in permeability and thermal conductivity. We first solve for the Darcy flow field for variable-density flow in porous media, cast in terms of a stream function-based vorticity equation for steady-state models and in terms of a pressure- or hydraulic head-based equation for transient flow models, using the theory, model parameters, and finite element methods described in Raffensperger (1996). The result is a coupled mathematical model for steady-state and/or transient fluid flow and heat transport in a nondeforming, two-dimensional crustal profile. Fluid density and viscosity are assumed to depend on pressure, temperature, and salinity according to the equations of state for NaCl-type fluids programmed in Raffensperger and Garven (1995). For the present application, we assume a uniform salinity everywhere in the flow field and focus on the issues of steady-state fluid and heat flow in an extensional basin with normal faults. Issues of brine geochemistry and the transient evolution of fluid salinity require development of a transient solute transport calculations, such as the type described in Appold and Garven (1999, 2000) and Wilson et al. (1999), and these issues will be explored in a later publication, as will the effects of sediment overpressuring and deformation.

3. Application to the Kuna Basin

To evaluate the role of faults and free convection on Pb–Zn–Ag–Ba ore formation in the Kuna Basin, we have constructed fully coupled numerical models of heat and fluid flow, which are partially constrained by paleoheat flow estimates and petrologic observations. A finite element grid containing 41 element rows and 68 element columns was designed and adapted for a geologic cross section of the Kuna Basin, structurally and stratigraphically restored to latest Mississippian–Pennsylvanian time (Fig. 1). Hydrologically, the Kuna Basin was a rifted asym-

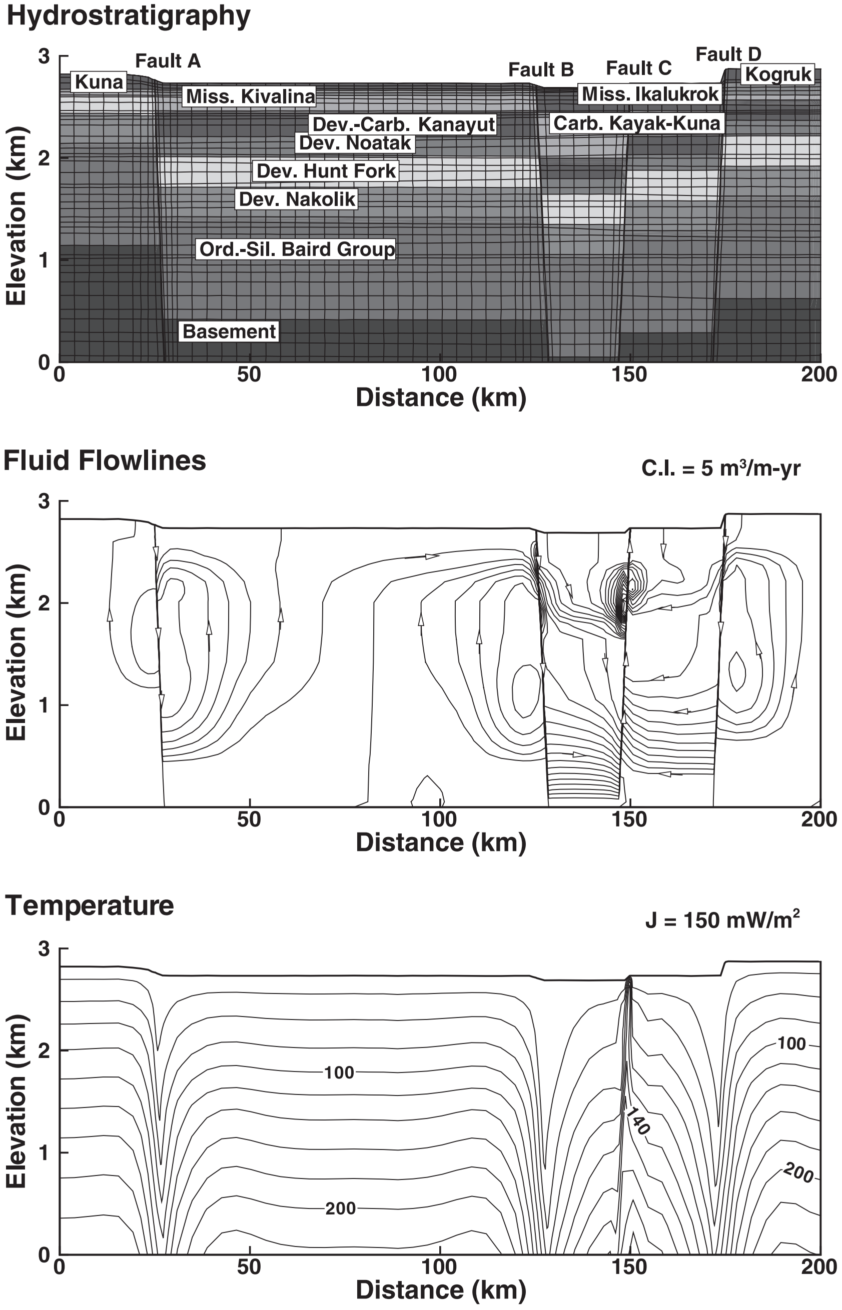

Fig. 1. Hydrogeologic cross-section model of coupled fluid flow and heat transport in the Carboniferous Kuna Basin, Alaska, showing numerical mesh, fluid flowlines, and isotherms.

metric basin layered with calcareous turbidites and mudstones overlying a thick conglomerate and sandstone aquifer, which was likely thickest and more faulted near Red Dog (Ikalukrok graben). The profile model extends southwest to northeast over a lateral distance of 200 km and includes undifferentiated crystalline basement, Ordovician–Devonian carbonates and shale of the Baird Group, Devonian–Carboniferous shale, sandstone, and conglomerates of the Hunt Fork Formation through Kanayut Formation, and up through the shale, mudstones, and calcareous turbidites of the Carboniferous Kuna Formation, which includes the stratigraphic footwall Kivalina shale–turbidite unit and the overlying host unit for ore, the black Ikalukrok mudstone (Moore et al., 1986). The combined thickness of the sedimentary section and underlying crystalline basement represented in the hydrogeologic model is about 3 km, and the normal faults extend from top to bottom across the profile. Numerical boundary conditions for the grid are assigned as follows: the bottom is assigned a constant basal heat flow and assumed to be impermeable, the lateral sides are thermally insulated and impermeable, and the top is open to the seafloor, which has variable bathymetry and prescribed to be isothermal (20 °C). We assumed that basinal brines with a salinity of 15 wt.% NaCl equivalent completely saturate the profile, as we seek only the steady-state flow field driven by thermal gradients. Processes of basin subsidence, sedimentation, and rift deformation are not considered here, and so we do not consider the effects of overpressuring.

Buoyancy-driven free convection cells drive fluid migration up to 3-km-depths in the submarine basin and underlying crystalline basement, at rates of about 5 m/year within four major normal faults, which are assumed to be “vertical conduits” and of similar permeability to the clastic aquifer. Mostly, lateral flow is predicted to occur in the deep Devonian–Carboniferous clastic formations. The clastic aquifers appear to be the principal reservoir for metal-bearing brines that ultimately discharged near the seafloor within slightly permeable, highly porous, and organic-rich muds, where sulfate was likely reduced to form massive sphalerite and galena ores. Although four major normal faults were assigned to the hydrogeologic model, the free convection system self-organized itself such that only one fault zone developed as part of a focused upward flow vent near Red Dog; all the others serve as recharge conduits for circulating fluids back into the deep clastic aquifers. This two-dimensional convective flow pattern appear to be consistently self-organized and similar over a range of crustal heat flow values assigned to the base of the model and over a range of permeabilities assigned to the aquifer and faults.

Based on a model sensitivity study, both basin-wide paleoheat flows of 150–160 mW/m^2 and focused fluid discharge (along normal faults) are required to explain the hot thermal venting recorded within these ore fields, as inferred from fluid inclusion studies of ore and gangue mineralization. This Carboniferous hydrothermal system provides a remarkable geochemical model for the role of faults, free convection, and extensional basin heat flow in ore genesis. Future modeling studies need to consider the effects of transient and reactive flows, as geochemical and petrologic observations suggest multiple stages of hydrothermal flow and/or variable local geochemical fluxes in the ore district (Kelley et al., 2001).

4. Conclusions

Crustal heat flow can provide a strong mechanism for driving groundwater flow, particularly in submarine basins where other mechanisms for driving pore fluid flow such as topography, compaction, and crustal deformation are too weak or too slow to have a significant effect on disturbing conductive heat flow. Furthermore, fault zones appear to play a crucial role in focusing fluid migration in basins, as inferred in ancient rocks by many examples of hydrothermal deposits of sediment-hosted ores worldwide, but in particular, for giant lead–zinc deposits like Red Dog of northwestern Alaska. Hydrogeologic modeling of the Carboniferous-age Kuna Basin suggests that elevated temperatures and sulfide ore formation near Red Dog resulted from a large-scale free convection in a submarine extensional basin where normal faults and a clastic aquifer served to focus deep fluids from depths of about 1 km to discharge and precipitate Zn–Pb–Ag–Ba ore within sub-seafloor muds and turbidites.

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