Computers & Geosciences 38 (2012) 99–106

Contents lists available at ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo

The influence of igneous intrusions on the peak temperatures of host rocks: Finite-time emplacement, evaporation, dehydration, and decarbonation

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ARTICLE INFO

Article history:
Received 20 July 2010
Received in revised form
12 March 2011
Accepted 22 May 2011
Available online 12 June 2011

Keywords:
Igneous intrusions
Peak temperature
Dehydration and decarbonation
Evaporation
Intrusion mechanism

ABSTRACT

Using a 13-m-thick basic sill and its limestone host rocks of the Permian Irati Formation from the Parana Basin, South America, as an example, this paper presents a numerical investigation based on heat conduction models on the effect of the emplacement mechanism of igneous intrusions, pore-water evaporation, and dehydration and decarbonation of host rocks on the peak temperature (T_{peak}) of host rocks. Our results demonstrate that: (1) the finite-time intrusion mechanism of magma can lower the predicted T_{peak} of host rocks by up to 100 °C relative to the instantaneous intrusion mechanism, and although pore-water evaporation together with dehydration and decarbonation reactions can also depress the thermal effect of the sill on its host rocks, the maximum effect of these mechanisms on T_{peak} only reaches approximately 50 °C. (2) The effect of pore-water evaporation on T_{peak} is obviously greater than that of the dehydration and decarbonation reactions: the former can cause a maximum deviation of 40 °C in the predicted T_{peak}, whereas the deviation due to the latter is less than 20 °C. Further, the effect of the dehydration and decarbonation reactions on T_{peak} is less than 10 °C if pore-water evaporation is allowed simultaneously in the models and can hence be ignored in thermal modeling. (3) The finite-time intrusion mechanism of magma probably represents the natural condition of the sill. Pore-water evaporation and dehydration and decarbonation of host rocks are also likely to play important roles in lowering the thermal effect of the sill.

1. Introduction

The thermal effect of igneous intrusions on their host rocks has been extensively investigated in different geological contexts, including in relation to organic geochemistry (Peters et al., 1978; Galushkin, 1997; Othman et al., 2001; Aarnes et al., 2010), contact metamorphism (Jaeger, 1959; Hanson, 1992, 1995; Barker et al., 1998; Wang et al., 2007), coal geology (Stewart et al., 2005; Cooper et al., 2007; Mastalerz et al., 2009), epithermal ore deposits (Hayba and Ingebritsen, 1997; Zhao et al., 2003; Driesner and Geiger, 2007), and petroleum geology (Jones et al., 2007; Fjeldskaar et al., 2008). In order to obtain the thermal evolution of host rocks during cooling of magma intrusions, various heat flow models have been developed and subsequently applied to the exploration and evaluation of petroleum, coal, and other resources (Gvirtzman and Garfunkel, 1996; Galushkin, 1997; Stewart et al., 2005; Jones et al., 2007; Fjeldskaar et al., 2008). Furthermore, heat flow models can also provide useful information on the thermal state of these structures, when studying metamorphic reactions and indicator minerals of host rocks, especially when direct measurements or other geothermometers (e.g., fluid inclusions and vitrinite reflectance) are unavailable or inaccurate (Bishop and Abbott, 1995; Barker et al., 1998; Stewart et al., 2005; Wang et al., 2007; Mastalerz et al., 2009). The reliability of heat flow models is crucial for their successful application in these geological studies and this usually depends strongly on the accuracy of the model parameters used to describe heat sources in intrusive magma and heat sinks in host rocks (Jaeger, 1959; Peters et al., 1978; Galushkin, 1997; Barker et al., 1998; Wang et al., 2007, 2008; Santos et al., 2009).

Heat sinks in host rocks mainly include dehydration and decarbonation reactions of rock matrix and pore-water evaporation. They can reduce the thermal effect of magma intrusions on host rocks (Jaeger, 1959; Peters, et al., 1978; Galushkin, 1997; Wang et al., 2007). Ignoring their roles in thermal modeling will result in the overestimation of the thermal effect of igneous intrusions on host rocks. However, these two types of heat sinks have not always been considered simultaneously in the previous heat flow models. For example, Galushkin (1997) considered the dehydration and decarbonation reactions, but ignored pore-water evaporation, thus disregarding the possibility of pore-water evaporation in the shallow host rocks. By contrast, Jaeger (1959), Peters et al. (1978), and Wang et al. (2007) recognized

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doi:10.1016/j.cageo.2011.05.011

the importance of pore-water evaporation in influencing the thermal evolution of the host rocks in the vicinity of the shallow buried intrusions. However, they ignored dehydration and decarbonation of the host rock in their models. Thus, if both pore-water evaporation and the dehydration and decarbonation reactions occur simultaneously in reality, then these models will be somewhat in error. This source of inaccuracy has not been quantified in previous numerical studies.

Another model error could potentially result from the heat budget of magma intrusion itself (Galushkin, 1997; Barker et al., 1998). Galushkin (1997) assumed that melted magma gradually intruded into the presolidified magmatic shell and termed it as the finite-time intrusion mechanism. This assumption actually leads to a reduction in the total heat amount of intrusive magma as compared to the more commonly used instantaneous intrusion mechanism. The finite-time intrusion mechanism, however, appears to successfully explain why some heat flow models of the instantaneous intrusion mechanism overestimated the thermal effect of magma intrusions on host rocks (Galushkin, 1997). It should be noted that the validation of the finite-time intrusion mechanism depends on the accuracy and reliability of the vitrinite-reflectance (R_o) geothermometer employed by Galushkin (1997). However, such geothermometer information is not generally available and is subject to uncertainty at high pressures or high temperatures (Barker et al., 1998) since pore water in host rocks can reach a supercritical state or boil under such conditions. As a result, R_o can be reduced and even decreases when approaching intrusions (Peters et al., 1978; Bostick and Pawlewicz, 1984; Barker and Pawlewicz, 1994; Barker et al., 1998; Wang et al., 2007). Therefore, the heat flow models of the finite-time intrusion mechanism still need to be extensively verified based on real geological cases by comparing model predictions with other reliable geothermometers, e.g., as derived from fluid inclusions or using the spore coloration index (SCI).

In this study, we take a 13-m-thick basic sill of the Permian Irati Formation from the Parana Basin, South America, as an example to quantitatively evaluate and compare the influence of intrusion mechanism of magma, pore-water evaporation, dehydration, and decarbonation of host rocks on the T_{peak} prediction. Our study allows us to improve our understanding of their relative importance in influencing the thermal evolution of host rocks. Furthermore, we also discuss the possible intrusion mechanism of this sill and the potential heat sinks in its host rocks by comparing the predicted T_{peak} with the measured SCI.

2. Geology of the Parana Basin, South America

The Paraná Basin is a large intracratonic basin and extends over most of the southern part of South America. This basin was filled from the Late Ordovician to the Late Cretaceous by six, second-order, sedimentary-magmatic supersequences (Anjos et al., 2010): Rio Ivaí (Rio Ivaí Group of Ordovician-Silurian age), Paraná (Paraná Group, Devonian), Gondwana I (Tubarão and Passa Dois Groups, Carboniferous-Permian), Gondwana II (Triassic units), Gondwana III (São Bento Group, Jurassic-Cretaceous), and Bauru (Cretaceous) Supersequences.

The Permian Irati Formation is stratigraphically located at the base of the Passa Dois Group, which represents the regressive phase within the major Upper Paleozoic transgressive–regressive cycle (Milani and Zalán, 1999). This unit has an average thickness of 40 m and extends over an area of 4 million km^2. Recent dating of volcanic ash layers has indicated an age of 278 Ma for this unit (Santos et al., 2006). This formation is divided into the lower Taquaral Member and the upper Assistência Member. The Taquaral Member is formed of gray claystones representing the beginning of the deposition of the sedimentary series. The Assistência Member consists of dolostones and limestones alternating with dark-gray to black shales.

The Permian Irati Formation is well-known for its oil-bearing rocks and fossils. The organic-rich rocks are black laminated claystones with a total organic carbon content of 16.3% (Santos et al., 2009). Organic geochemistry indicates that the maximum burial depth of these black shales is about 2–3 km (Santos et al., 2009; Anjos et al., 2010) and the corresponding maximum burial temperature should be 60–80 °C (Araújo et al., 1996). Comparably, the igneous intrusions related to the Serra Geral magmatism event at about 138–127 Ma played a more important role in accelerating the maturation of organic matter in the claystones (Anjos et al., 2010). The heat released from the sills into the organic-rich rocks triggered synchronous processes of hydrocarbon generation and migration, leading to a petroleum system with atypical characteristics.

In particular, a 13-m-thick basic sill and its host rocks in the Irati Formation have been extensively studied (e.g., Santos et al., 2009). The sill has a porphyritic texture with phenocrysts of plagioclase (0.5–1.5 mm) and olivine (0.2–1 mm). The aphanitic matrix is composed mainly of plagioclase and augite. Near the contact, the basic rock displays a glassy texture and a large number of millimeter- to centimeter-sized amygdales that are usually filled with carbonaceous material, carbonate, talc, or smectite. The measured spore coloration index of the host rocks indicates that the sill imprints thermal effects on the host rocks (Santos et al., 2009) and can be used as a geothermometer to reconstruct the peak temperature experienced by host rocks and verify heat transfer models. Thus, this 13-m-thick basic sill and its host rocks constitute a good geological example for the numerical investigation of the influence of igneous intrusions on the peak temperature of host rocks.

The limestone in the host rocks of the sill frequently interbeds with thin layers of low-permeability shale. This can potentially obstruct the vertical migration of the pore fluids. Furthermore, Nd isotopes and trace element geochemistry imply that the mineralogical changes in the host rocks caused by the thermal effect probably occurred under closed system conditions, and hence the flow of pore water in host rocks has been reasonably restricted. The absence of significant mass exchange between the sill and the host rocks also suggests that the heat transfer from the sill to its host rock was mainly controlled by thermal conduction (Santos et al., 2009). Therefore, this study will adopt heat conduction models to simulate the heat transfer in the host rocks.

3. Method

3.1. Heat conduction model

One-dimensional heat conduction models have been proved particularly useful for the thermal-evolution reconstruction of the host rocks composed of shale, mudstone, coal and carbonates, which generally have a relatively low permeability (e.g., $<10^{-16}$ m^2, Hanson, 1995; Hayba and Ingebritsen, 1997) (Peters et al., 1978; Galushkin, 1997; WoldeGabriel et al., 1999; Stewart et al., 2005; Wang et al., 2007, 2008; Santos et al., 2009). Some general assumptions (Jaeger, 1959; Delaney, 1988; Peacock, 1990; Galushkin, 1997; Barker et al., 1998; Stewart et al., 2005; Wang et al., 2007, 2010; Santos et al., 2009) are usually required in establishing a one-dimensional heat conduction model of magma intrusions: (1) The shape of the intrusion is regular, sill-like or dike-like, and both sides of the intrusion are infinitely extended; and (2) convection of magma is not considered and the heat loss due to any volatile escape is also neglected. Thus, the basic heat conduction equation