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Research paper

Thermal impact of igneous sill-complexes on organic-rich formations and implications for petroleum systems: A case study in the northern Neuquén Basin, Argentina

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ABSTRACT

Numerous sedimentary basins in the world host voluminous igneous sill-complexes, i.e. stacking of sills that are emplaced in different levels of the sedimentary sequence. When sills are emplaced in organic-rich sedimentary formations, they can considerably affect the thermal and maturation history of the hydrocarbon source rock and can be highly relevant elements of the petroleum system. Most models of the thermal impacts of igneous sills on source rock consider one or few intrusions. However, the parameters that govern host rock maturation related to full sill-complexes remain unclear. In this contribution, we integrate borehole data and thermal 2D-modelling to quantify the temperature and maturation effects of a sill-complex in a 2D section on the sedimentary formations of the Neuquén basin, Argentina. In this basin, extensive magmatic activity took place during Oligocene-Miocene and upper Miocene age. There are numerous magmatic intrusions, dominantly sills, emplaced in organic-rich shale formations in the study area. Our modelling results show that (1) the source rock maturation in the study area was dominantly triggered by the sills, so that the area would be immature without the sills, (2) multiple sills have more pronounced thermal impact than a single, thick sill, (3) volumes of host rock between intrusions can have different degree of maturation depending on intrusion spacing, and (4) the temperature of the host rock at the time of sill emplacement controls to a great extent the thermal and maturation impact of the sills. Our work provides valuable insights into how the sills affected hydrocarbon generation during Oligocene-Miocene and Upper Miocene magmatic activity in the Neuquén basin. In addition, our study suggests that most of the kerogen has been transformed to hydrocarbon in areas where the sills are located.

1. Introduction

Numerous sedimentary basins worldwide host voluminous igneous intrusive complexes made of dikes, sills and laccoliths (e.g., Magee et al., 2016), which can affect the thermal state of sedimentary host rocks (Aarnes et al., 2010, and references therein). Local intrusion-induced maturation of sedimentary formations has been documented in, e.g. the Neuquén Basin in Argentina (Orchuela et al., 2003; Monreal et al., 2009), and in the Paraná Basin in Brazil (Thomaz Filho et al., 2008; Santos et al., 2009). When intrusive complexes are voluminous, basin-scale effects can be observed, i.e., in the Vøring Basin in the Norwegian margin (Fjeldskaar et al., 2008; Aarnes et al., 2015), the Karoo Basin in South Africa (Aarnes et al., 2011b) and the Tunguska Basin in Siberia (Svensen et al., 2009).

In many basins, numerous intrusions were preferentially emplaced in organic-rich formations (Monreal et al., 2009; Jackson et al., 2013). The interactions between igneous intrusions and their organic-rich host rocks can have major implications for the petroleum system: (1) the heating of organic-rich rocks can lead to the maturation, and even over-maturation, of organic matter and generation of hydrocarbons (Othman et al., 2001; Jones et al., 2007; Fjeldskaar et al., 2008; Delpino and Bermúdez, 2009; Monreal et al., 2009; Aarnes et al., 2015; Karvelas et al., 2015); (2) large volumes of hydrocarbons can be catastrophically released to the atmosphere and impact global climate (Svensen et al.,

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2004; Aarnes et al., 2015); (3) structures induced by sill emplacement can generate fluid flow pathways or fluid traps (Cartwright et al., 2007; Rateau et al., 2013; Haug et al., 2017; Schmiedel et al., 2017) and (4) intrusions can be fractured hydrocarbon reservoirs (Bermúdez and Delpino, 2008; Monreal et al., 2009; Witte et al., 2012; Gudmundsson and Løtveit, 2014). This study will focus on how intrusions locally heat source rocks.

There is an extensive literature dealing with the thermal impact of igneous intrusions on their organic-rich host rocks, with particular focus on the extent of the thermal aureole, ranging mainly from 30% to 200% intrusion thickness (Simonet et al., 1981; Gilbert et al., 1985; Galushkin, 1997; Othman et al., 2001; Cooper et al., 2007; Thomaz Filho et al., 2008; Santos et al., 2009; Annen, 2011; Agirrezabala et al., 2014). However, they showed that sill intrusions can cause larger aureoles due to elevated background host rock temperatures, and a non-linear response 1:1 of aureole thickness to sill thickness can be expected. Most studies only take into account the thermal effect of one intrusion (see Aarnes et al., 2011a). Aarnes et al. (2011b) quantified how the thermal interactions between two sills can enhance maturation between the sills, depending on the vertical distance between them, affecting the thermal aureole extension. In addition, Fjeldskaar et al. (2008) considered the effects of more than 20 intrusions in the Vøring Basin, offshore Norway, and their implications in terms of host rock maturation. They modelled the thermal impact of multiple intrusions, and suggest that the sill-complex can trigger significant increase of kerogen cracking to hydrocarbon. All of these studies show that the thermal and maturation impacts of sill-complexes on petroleum systems are not trivial and depend on the sill-complex architecture and geological setting.

In this study, we aim to quantify the thermal and maturation impacts of a sill-complex on organic-rich host rocks, located in the Río Grande Valley, northern Neuquén Basin, Argentina (Fig. 1 A). Here, the host rocks of the sills are the main source rocks of the basin, i.e. the Vaca Muerta and Agrio Fms. Host rock maturation and hydrocarbon generation triggered by intrusions in the Neuquén Basin has been demonstrated by several authors (Uliana and Legarreta, 1993; Schiuma, 1994; Rossello et al., 2002; Orchuela et al., 2003; Delpino and Bermúdez, 2009; Monreal et al., 2009; Alberdi-Genolet et al., 2013). Also some authors documented sills as fractured reservoirs (Uliana and Legarreta, 1993; Schiuma, 1994; Rossello et al., 2002; Orchuela et al., 2003). However, a quantification of the thermal and maturation impacts of a whole sill-complex is currently lacking. Thus, the aims of our study are to (1) quantify the thermal impact of a sill-complex on the organic-rich formations, and (2) identify which parameters of the sill-complex influence the degree and distribution of host rock maturation and hydrocarbon generation.

2. Geological setting

The study area is located in the southern Mendoza province, west central Argentina, and belongs to the northern part of the Neuquén Basin (Fig. 1 A). This is a retroarc basin (Ramos, 1978), which extends between 32° and 40° S latitude, from the south of Mendoza province to the extra-andean region of Neuquén (Herrero Ducloux, 1946) covering an area of over 120.000 km^2 (Uliana and Biddle, 1988; Legarreta et al., 1993). The basin comprises a record of up to 7000 m of Late Triassic – Early Cenozoic deposits, the deposition of which was controlled by sea level changes and local tectonics of western Gondwana (Legarreta and Gulisano, 1989). The result was a discontinuous succession of continental and marine deposits that were accumulated in different cycles (Groeber, 1937), separated by several key unconformities (Leanza, 2009) (Fig. 1 B).

The Neuquén Basin was originated during Late Triassic-Early Jurassic as isolated rift depocenters, half-graben types, which were delimited by basement normal faults (Gulisano, 1981; Vergani et al., 1995; Franzese and Spalletti, 2001). They formed as a result of extensional tectonics associated with the break up of Pangea and of the negative subduction velocities in the western margin of Gondwana (Franzese and Spalletti, 2001).

During Middle Jurassic to Early Cretaceous, the isolated depocenters started to coalesce, forming a broad basin, due to a change to neutral subduction regime and the evolution of a volcanic arc. The basin sedimentation was dominated by thermal subsidence (sag stage) and eustatic sea-level changes, forming what is considered the classical filling of Mesozoic marine, evaporitic and continental rocks in northern Neuquén Basin (Gulisano and Pleimling, 1995). In southern Mendoza province, the sag stage resulted in the deposition of the Mendoza Group, which consists of: (1) the Tithonian - Early Valanginian Vaca Muerta Fm. (*ca.* 125–140 m thick), composed of bituminous shales, deposited under anoxic conditions of shelf and slope marine settings, characterized by a high organic matter content (TOC) from 3 to 8%, with peak values of 12% and dominant Type II kerogen (Sylwan, 2014); (2) the Middle Valanginian Chachao Fm. (ca 35–50 m thick), deposited above the Vaca Muerta Fm., consisting of a carbonate ramp full of biogenic material (Kozlowski et al., 1993; Brissón and Veiga, 1998); (3) the Late Valanginian - Early Barremian Agrio Fm. (*ca* 250–300 m thick)

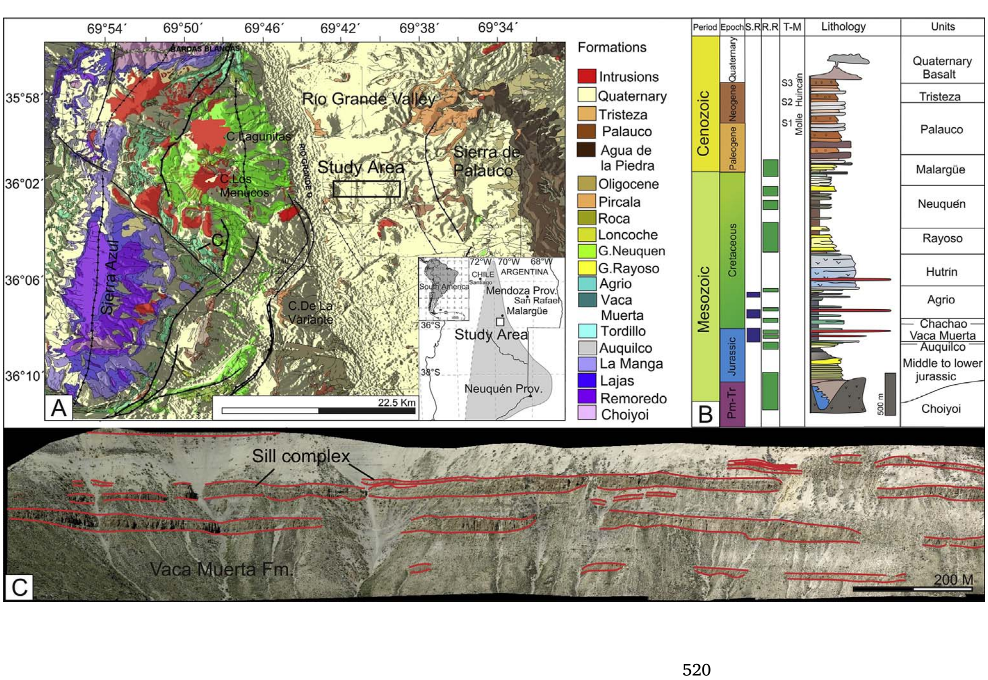

Fig. 1. A. Geological map of the Río Grande Valley area. Letter C accounts for outcrop picture from the next image. **B**. Sedimentary column for the Río Grande Valley. The main sills are hosted in the Agrio and Vaca Muerta organic-rich formations. S.R: source rock. R.R: reservoir rock. T–M: Tectono-magmatic events for southern Mendoza. S1, S2, and S3 are deformation events from Silvestro and Atencio (2009). Molle and Huincán are the eruptive cycles described by Combina and Nullo (2011). **C**. Ortho-rectified photograph of sill intrusions (outlined red) emplaced in the Vaca Muerta Fm., west of the study area. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)