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Sill geometry and emplacement controlled by a major disconformity in the Tarim Basin, China

Zewei Yao [a,b,*], Guangyu He [b,**], Chun-Feng Li [a,c], Chuanwan Dong [b]

[a] *Ocean College, Zhejiang University, Zhoushan 316021, China*
[b] *School of Earth Sciences, Zhejiang University, Hangzhou 310027, China*
[c] *Laboratory of Marine Mineral Resources, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266237, China*

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ABSTRACT

Igneous sills are widely distributed in sedimentary basins worldwide. Sill emplacement has significant impacts on structural and thermal evolutions of sedimentary basins and also provides important insights into volcanic and sub-volcanic processes. Dyke deflection and sill formation are largely controlled by mechanical layering of the host rock, and a number of mechanisms have been proposed. However, most models of sill formation are based much on numerical and analogue modeling. For many natural sills, the key mechanism governing the dyke deflection and sill formation remains to be discussed and, in some cases, controversial. To better understand the control of mechanical layering on sill formation and test the existing models, we study detailed geometries of igneous sills from the central part of the Tarim Basin, China, based on seismic reflection data and borehole data. Nineteen igneous sills which are expressed as packages of high-amplitude reflections are observed, and they were all emplaced in the Upper Ordovician strata at current burial depths of about 5–8 km. The sills can be classified into three geometric types: type 1, saucer-shaped sills; type 2, strata-concordant sills; and type 3, hybrid sills, which have the characteristics of both type 1 and 2. The geometry of the saucer-shaped sills is typical and comprises three distinct parts: a flat inner sill, inclined sheets and, in many cases, flat outer sills. All the bases of the saucer-shaped sills coincide with the disconformity between the Middle and Upper Ordovician strata (the M disconformity), indicating that the disconformity controlled the sill geometry and emplacement depth in the basin. The M disconformity is characterized by a lithological change from underlying limestones to overlying mudstones. We suggest that among the three main mechanisms for the deflection of dykes into sills, namely Cook–Gordon debonding, stress barriers and elastic mismatch, the Cook–Gordon debonding is the dominant mechanism in the study area. This is a mechanism by which a weak contact opens up ahead of a vertically propagating dyke, allowing the dyke to be deflected into a sill when the dyke meets the open contact. This study indicates that the control of mechanical layering of the host rock on sill formation is largely depends on the host-rock lithologies and confirms again that the saucer shape is the fundamental sill geometry under the control of layering.

1. Introduction

Igneous sills have been widely observed in sedimentary basins around the world from out-crops (e.g., Galerne et al., 2011; Muirhead et al., 2012; Eide et al., 2017) and seismic reflection data (e.g., Planke et al., 2005; Cartwright and Huuse, 2005; Hansen and Cartwright, 2006; Magee et al., 2016). These intrusions exhibit various shapes, including horizontal sills, laccoliths and saucer-shaped sills (Planke et al., 2005; Jackson et al., 2013). Sill emplacement can have significant impacts on the structural and thermal evolutions of sedimentary basins. Among others, sill emplacement may cause uplift of the host rock, forming forced folds of the overlying strata (Hansen and Cartwright, 2006; Magee et al., 2014), and affect the maturation of the organic matter in the surrounding host rock as well as the hydrocarbon migration and accumulation (Rateau et al., 2013; Spacapan et al., 2018). Sill complexes are also an important part of sub-volcanic plumbing systems (Galland et al., 2014). Understanding the formation of these intrusions is key to assessing the volcanic and sub-volcanic processes (Wilson et al., 2016).

Sills form when subvertical dykes or inclined sheets become deflected into a sub-horizontal orientation. However, detailed for-

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[*] Corresponding author at: Ocean College, Zhejiang University, Zhoushan 316021, China.
[**] Corresponding author.
E-mail addresses: zealway@zju.edu.cn (Z. Yao), hegy@zju.edu.cn (G. He).

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mation mechanisms can be complicated and have been discussed for decades (Barnett and Gudmundsson, 2014, and references therein). The first mechanism suggests that sill emplacement is largely controlled by the level of neutral buoyancy, which corresponds to depths where the magma pressure equals the lithostatic pressure (Bradley, 1965; Francis, 1982). However, this point of view is questioned in many circumstances because sills often intruded in a wide range of depth in a sedimentary basin and preferably followed rock-rock interfaces (e.g., bedding planes and disconformities) (Planke et al., 2005; Muirhead et al., 2012; Barnett and Gudmundsson, 2014; Eide et al., 2017). Other three mechanisms, namely Cook–Gordon debonding, stress barriers and elastic mismatch, are proposed to focus more on the controls from local stresses and layering of the host rocks (Barnett and Gudmundsson, 2014, and references therein). Cook–Gordon debonding is a mechanism by which a propagating extension fracture, here a dyke, opens up a weak contact ahead of the fracture tip (Cook et al., 1964; Gudmundsson, 2011). These mechanisms, supported by analogue modeling, suggest that mechanical properties of host rock at boundaries can determine the dyke-to-sill deflection process (Pollard and Johnson, 1973; Kavanagh et al., 2006; Menand, 2008). However, the dominant mechanism has yet to be discussed in real cases. Better geological observations are still needed to refine these theories.

Furthermore, under the control of the host rock layering, individual sills are expected to evolve to a saucer shape after their initial horizontal spreading (Pollard and Johnson, 1973; Malthe-Sørenssen et al., 2004; Thomson and Hutton, 2004; Polteau et al., 2008; Galland et al., 2009; Magee et al., 2013; Chen et al., 2017). The saucer-shaped sill consists of a horizontal sill along a planar discontinuity, stretching outward and upward to inclined sheets, and subsequently to flat outer sills, and such a geometry is considered as a fundamental shape for magma intrusions in sedimentary basins (Thomson and Hutton, 2004; Polteau et al., 2008; Galland et al., 2009). Although this viewpoint is widely accepted, many of the saucer-shaped sills, imaged by seismic data, have cup-shaped bodies (Mathieu et al., 2008), such as those in sedimentary basins along the NE Atlantic margin (Hansen, 2004; Hansen and Cartwright, 2006). The bases of these sills, in accordance with recent field observations from a sill in the Faroe Islands (Walker, 2016), appear to be mildly transgressive through the layering of the host rock, implying that layering is not the primary control on sill geometry. These observations question whether mechanical layering is a fundamental control on the formation of saucer-shaped sills.

In this paper, we investigate seismically examples of the igneous sills in the Tarim Basin, northwestern China, to further understand the mechanisms of the deflection of dykes into sills at contacts, and evaluate the control of mechanical layering on the geometry and emplacement depth of saucer-shaped sills. We suggest that the Tarim Basin is a suitable place to undertake the study, because saucer-shaped sills there are typical and are well imaged, their spatial relationships to the dominant layers of the host rock are distinct, geological evolution of the study area is relatively simple and the host sequences are generally flat-lying. We first use high-quality two-dimensional (2-D) seismic data combined with borehole data to document the seismic expression and geometry of igneous sills. We then discuss the main control on sill geometry and growth. For the first time, these intrusions are revealed in seismic data in the Tarim Basin.

2. Geological setting

With an area up to 50 × 10^4 km^2, the Tarim Basin is the largest basin in northwestern China (Fig. 1). The basin is diamond-shaped in plan view and bounded by large mountain belts at its margins, including Tianshan mountains, Kunlun mountains and Altyn mountains. The initial formation of the Tarim Basin is related to the breakup of Rodinia in the Neoproterozoic time (Jiang et al., 2017). Its oldest sequences are Sinian/Ediacaran strata exposed in the northwestern and northeastern margins of the basin, but their distribution within the basin is still under discussion (He et al., 2010). After the initial formation, the Tarim Basin received sedimentary deposition almost continuously from the Cambrian to Quaternary, with a total thickness up to 15000 m. However, as a result of multi-phased tectonic events, current thickness of sedimentary rocks varies within the basin (Lin et al., 2012). The basin can be roughly divided into seven tectonic units, including the Kuqa depression, Tabei uplift belt, Northern depression belt, Central uplift belt, Southwestern depression belt, Southeastern uplift belt and Southeastern depression belt (Fig. 1A). These tectonic units can further be subdivided into sub-units (Fig. 1A).

Our study area is around the Tazhong uplift in the central part of the Tarim Basin (Fig. 1A). The Lower and Middle Cambrian strata are dominantly composed of dolomite (Fig. 2). In the southern part of the study area, they are supposed to contain interbeded gypsum, acting as an important detachment layer (Yao et al., 2017). The Upper Cambrian to Middle Ordovician sequences consist of dolomite and limestone. During the Late Ordovician, the Tazhong uplift bounded by the Tazhong NO.I fault and Well Zhong2 fault was significantly uplifted (Fig. 1B) and the Upper Ordovician depositional facies in the uplifted area was different from those in adjacent area. In the uplifted area, the Upper Ordovician strata consist of the Lianglitage formation (O_{3l}) and Sangtamu formation (O_{3s}) which dominantly contain limestone and mudstone respectively (Fig. 2). Toward the depressed area, the Upper Ordovician sequences gradually turn into the Qiaerbake formation (O_{3qb}) and Queerqueke formation (O_{3qq}) (Fig. 1B). The Qiaerbake formation is about 20 m thick and consists of limestone and marlstone (Cai et al., 2011). The overlying Queerqueke formation which comprises the most part of the Upper Ordovician strata is dominantly mudstone and siltstone.

From the Silurian to Quaternary, the area was covered by marine and terrestrial sequences up to 6000 m thick. Structural deformation was weak in the northern part of the study area. The igneous sills studied in this paper are mostly observed here and they mostly intruded the Upper Ordovician units or generally followed the boundary between Upper and Lower Ordovician strata (the M disconformity) (Fig. 3). In contrast, structure deformation was relatively strong in the Tazhong uplift and southwestern area, which were subject to detachment faulting and transpressive faulting because of the collision between the Altyn block and the Tarim block (He et al., 2011).

Igneous activity within the Tarim Basin is marked by widespread volcanic rocks in the Permian strata. These igneous rocks have been revealed by numerous wells in the basin and field observations in the northwestern corner of the basin (Fig. 2). Among them, the flood basalts are up to 700 m thick and in an area of about 2 × 10^5 km^2 (Yu et al., 2011). They were extruded within a period of 2–3 Ma in the Early Permian, although the absolute age is still controversial (Yu et al., 2011; Zhang et al., 2012). These flood basalts and some other igneous rocks together are named as the Tarim Large Igneous Province (LIP) (Yang et al., 2014). However, the relationship between the igneous sills documented in this study and the Tarim LIP remains to be discussed.

3. Data and methods

This study uses zero-phase, time-migrated 2-D seismic reflection dataset, which has a total length of about 25000 km and covers an area of about 50000 km^2 (Fig. 1A). The grid of 2-D seismic profiles is between 2 × 2 km and 4 × 4 km, permit-