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Fracturing of doleritic intrusions and associated contact zones: Implications for fluid flow in volcanic basins

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A B S T R A C T

Igneous intrusions act as both carriers and barriers to subsurface fluid flow and are therefore expected to significantly influence the distribution and migration of groundwater and hydrocarbons in volcanic basins. Given the low matrix permeability of igneous rocks, the effective permeability in- and around intrusions is intimately linked to the characteristics of their associated fracture networks. Natural fracturing is caused by numerous processes including magma cooling, thermal contraction, magma emplacement and mechanical disturbance of the host rock. Fracturing may be locally enhanced along intrusion–host rock interfaces, at dyke–sill junctions, or at the base of curving sills, thereby potentially enhancing permeability associated with these features. In order to improve our understanding of fractures associated with intrusive bodies emplaced in sedimentary host rocks, we have investigated a series of outcrops from the Karoo Basin of the Eastern Cape province of South Africa, where the siliciclastic Burgersdorp Formation has been intruded by various intrusions (thin dykes, mid-sized sheet intrusions and thick sills) belonging to the Karoo dolerite. We present a quantified analysis of fracturing in- and around these igneous intrusions based on five outcrops at three individual study sites, utilizing a combination of field data, high-resolution lidar virtual outcrop models and image processing. Our results show a significant difference between the three sites in terms of fracture orientation. The observed differences can be attributed to contrasting intrusion geometries, outcrop geometry (for lidar data) and tectonic setting. Two main fracture sets were identified in the dolerite at two of the sites, oriented parallel and perpendicular to the contact respectively. Fracture spacing was consistent between the three sites, and exhibits a higher degree of variation in the dolerites compared to the host rock. At one of the study sites, fracture frequency in the surrounding host rock increases slightly toward the intrusion at approximately 3 m from the contact. We conclude by presenting a conceptual fluid flow model, showing permeability enhancement and a high potential for fluid flow-channeling along the intrusion–host rock interfaces.

1. Introduction

The matrix of crystalline igneous rocks is typically tight, with sub-milliDarcy permeability (e.g., Sruoga et al., 2004) and primary porosity commonly less than 0.5–1% (e.g., Petford, 2003; van Wyk, 1963). Fractured igneous aquifers may nonetheless be considered as potential groundwater reservoirs (e.g., Gustafson and Krásný, 1994; Woodford and Chevallier, 2002) due to the presence of fracture networks, a characteristic feature of virtually all igneous

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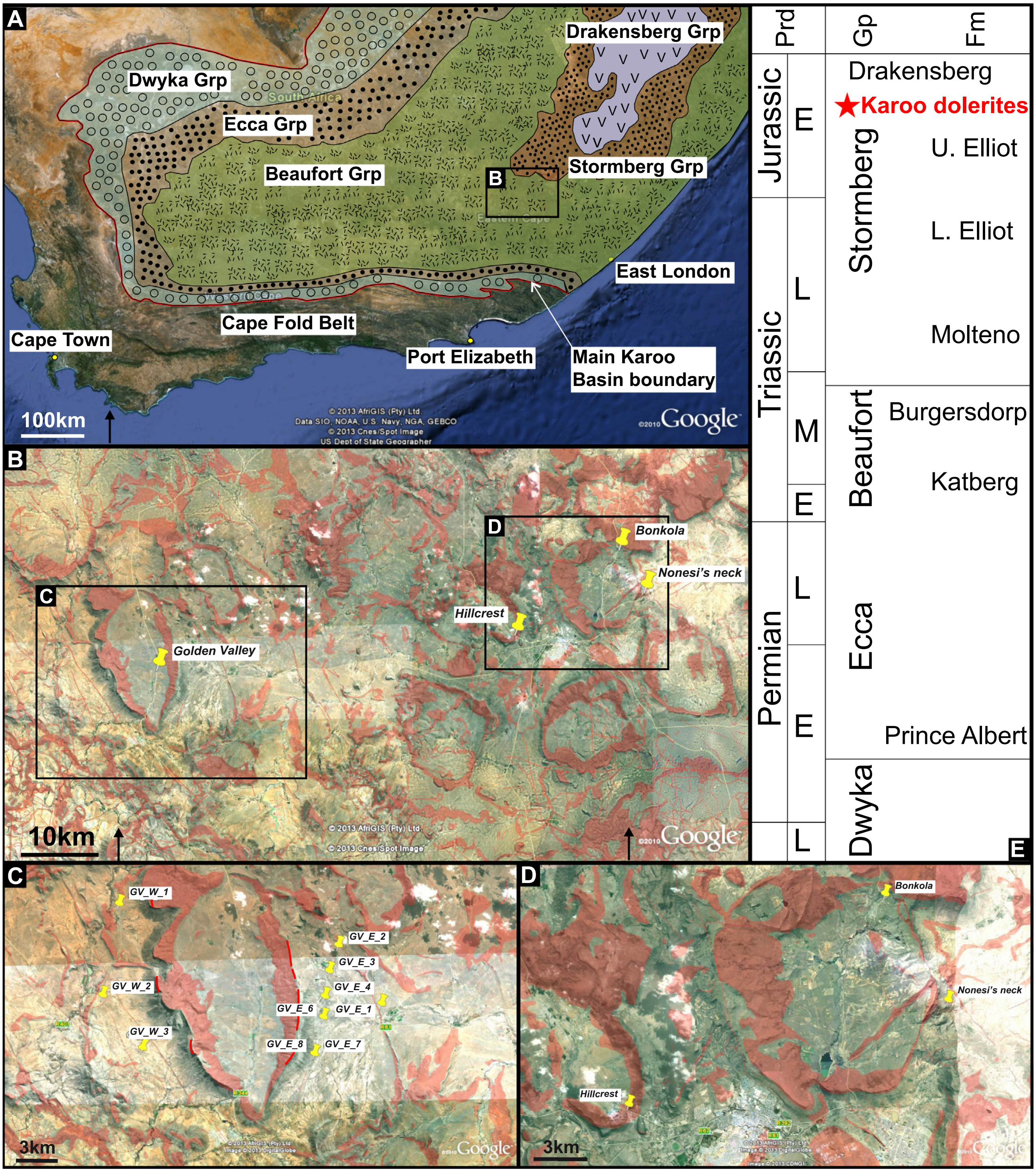

Fig. 1. Location and geological setting of the study area. (A) Location of study area (black rectangle) superimposed on a simplified geological map of southern Africa, after Smith (1990) and Svensen et al. (2012). (B) Satellite image of the study area, illustrating the sills (dark red polygons) and dykes (bright red lines). Note the evident exposure of the saucer-shaped intrusions and the study area locations (yellow pins). (C) Close-up of the Golden Valley saucer-shaped sill, and the locations of the photo-mosaics (photographed rim segments and photograph location) presented in this study. (D) Close-up of the Queenstown area, with the three lidar scan sites marked. Refer to Table 1 for details. (E) Simplified stratigraphic column of the Karoo Supergroup, after Tankard et al. (2009). The star at 183 Ma indicates the timing of the Karoo dolerite emplacement (Svensen et al., 2012). All satellite images from Google Earth. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

rocks. This dual nature of the permeability of igneous intrusions causes them to influence reservoir fluid flow in an apparently non-predictable manner, sometimes forming fully sealing, impermeable barriers (e.g., Gurba and Weber, 2001; Thomaz Filho et al., 2008), at other times high-permeability pathways (e.g., Mège and Rango, 2010; Sankaran et al., 2005), and sometimes both (e.g., Rateau et al., 2013; Stearns, 1942).

The economic and societal consequences of improved understanding of fractured igneous aquifers is significant, with underexplored fractured igneous reservoirs, such as in the Argentinian