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Conditions of magma crystallization in the Henties Bay-Outjo dyke swarm, Namibia: Implications for the feeder system of continental flood basalts

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ABSTRACT

The Henties Bay-Outjo dyke swarm (HOD) in NW Namibia presents a well-exposed example of the magma feeder system for continental flood basalts. This study uses bulk-rock, mineral and melt inclusion compositions from dyke samples to define pressure–temperature crystallization conditions and thus contributes to the understanding of the magma plumbing and storage beneath the province. The thermobarometry calculations for near-equilibrium mineral–melt pairs (the latter proxied by whole-rock) indicate olivine crystallization at ~1170 to 1350 °C and lower, overlapping, temperatures for clinopyroxene and plagioclase (~1070 to 1210 °C) in keeping with the order of crystallization inferred from petrographic observation. The dykes yielding the highest temperatures (>1300 °C) are in a specific region of the HOD near the litho-tectonic boundary of the Neoproterozoic Kaoko and Damara Belts, where magma permeability of the crust may have been enhanced.

Pressure estimates from clinopyroxene–melt pairs range from 0 to 10 kbar overall (13 dykes) indicating polybaric crystallization. The lowest pressures are recorded by clinopyroxene oikocrysts intergrown with plagioclase, which likely represent the dyke emplacement depths. Clinopyroxene phenocrysts and plagioclase-free oikocryst cores yield a higher range of crystallization pressures at 4–6 kbar, corresponding to mid-crustal depths of 11–17 km. There is no spatial pattern in the pressure variations, suggesting a rather uniform level of magma stagnation and crystallization in all areas of the HOD. Partial crystallization at intermediate depths is consistent with the inference of entrained crystals and with geochemical evidence for crystal accumulation in some of the dykes. Comparison of model magma densities and the crustal density derived from seismic velocity profiles suggest the dyke magmas had positive buoyancy in the lower- and middle crust and near-neutral buoyancy in the upper crust. The depth of magma stagnation or pooling at 11–17 km depth may relate to this or to the brittle–ductile transition in the felsic Damara crust.

1. Introduction

Large Igneous Provinces on continental crust (continental flood basalts or CFB) are important for many reasons. One aspect explored in this study is understanding how the huge and relatively homogenous magma volumes in CFB provinces are transported through the continental crust. Dyke swarms are better suited to address the questions of magma plumbing systems than surface lavas since they tend to survive erosion, are compositionally less evolved and less altered, and are more likely to contain phenocryst assemblages suitable for estimating pressure–temperature conditions. Finally, the location of a dyke is directly related to magma ascent and its orientation reflects the local stress environment, whereas eruptive vents for CFB lavas are rarely known and can be distant from the sampling site.

This paper discusses conditions of magma crystallization, storage and evolution in the Etendeka CFB Province of Namibia based on mineral–melt equilibrium thermobarometry in about 50 dykes from the Henties Bay-Outjo dyke swarm (HOD). Previous work on the HOD has focused on determining the geochemical variations and identifying different magma types, including some near-primitive (picritic) compositions which have attracted special attention (Duncan et al., 1990; Keiding et al., 2011; Thompson et al., 2001; Trumbull et al., 2004a). The most common dyke rocks are chemically evolved tholeiitic dolerites similar in composition to the main (Tafelberg) type of flood basalts in the southern Etendeka. This, and the similar ages of dykes and CFB lavas, suggests a genetic relationship (Trumbull et al., 2007). The only previous study addressing the pressure–temperature conditions of magma evolution in the HOD was by Thompson et al. (2007), who inferred multiple levels of magma evolution in the crust based on geochemical models of fractionation crystallization and assimilation. The approach taken here is more direct. We estimate the pressure–temperature (*P*–*T*) conditions

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of crystallization from mineral–melt equilibria in the dykes, and combine these *P–T* estimates with rock compositions to calculate magma densities and erect scenarios of magma ascent, differentiation and assimilation in the crust.

2. Geological background

The HOD was defined by Trumbull et al. (2004a) from satellite images and high-resolution aeromagnetic data. It is the largest concentration of dykes on the African margin of the South Atlantic, extending some 400 km inland from the present coastline (or 550 km from the continent–ocean boundary of Bauer et al., 2000), and more than 100 km across. The HOD is located mostly within the Neoproterozoic Damara Belt, south of the erosional remnants of Etendeka CFB lavas (Fig. 1). Dolerite dykes of the same apparent age (dating is sparse, see below) occur in coastal exposures north of the HOD up to and beyond the Angola border (Ewart et al., 2004; Marsh et al., 2001; Marzoli et al., 1999), and as far south as Cape Town in South Africa. The dykes described in this study are from the HOD area proper, i.e. within the southern Etendeka Province. See Trumbull et al. (2007) and references therein for descriptions of the dykes farther north and south along the African margin, and the review by Peate (1997) for information on dyke compositions on the conjugate margin of South America.

The HOD dykes are mainly hosted by Neoproterozoic metasediments and granites in the central and northern zones of the NE–SW-striking Damara Belt. The dominant dyke orientation in the HOD is parallel with the Damara structures and a second trend, more prominent in locations near the coast, is NNW–SSE. The Damara central zone also hosts about 20 Early Cretaceous intrusive and subvolcanic igneous complexes which are contemporary with the HOD dykes and lavas of the Etendeka CFB (Trumbull et al., 2004a and references therein). This association of magmatism with the Damara Belt and the coincidence of the dominant dyke orientation with the NE–SW Damara structural grain indicate an important role of basement structures on magma emplacement. Interesting in this respect is the fact that the NW portion of the HOD is at the tectonic boundary between the Damara Belt and the Kaoko Belt (Fig. 1). Both are part of the Neoproterozoic system of "Pan-African" mobile belts but the latter has a coast-parallel structural grain (as do the Etendeka dykes within it, see Trumbull et al., 2007). As discussed later in this paper, the Damara–Kaoko boundary may have played a role in localizing the most primitive, high-temperature dykes.

Typical dyke thicknesses are in the order of 1 to 10 m, but there are an exceptional few intrusions in the central region of the HOD up to 500 m thick which appear from their aeromagnetic signatures to be elongate stocks rather than thick, tabular dykes. The dykes are undeformed and fill dilational structures. Chilled margins are well developed and in some cases allow recognition of dyke-in-dyke intrusion.

2.1. Age constraints

Neoproterozoic rocks of the Damara Belt are exposed at the surface in large parts of the HOD, and only in a few places where Mesozoic rocks are preserved is it possible to more closely constrain the intrusion age from geologic relations. These were reviewed by Miller (2008) and are briefly summarized here. Dolerite dykes and sills in the Huab River region NW of Brandberg intrude aeolian sandstones and basal lavas of the Etendeka Group, the latter of which were dated by Jerram et al. (1999) at 133 ± 0.3 Ma using $^{40}Ar–^{39}Ar$ in plagioclase. The geologic

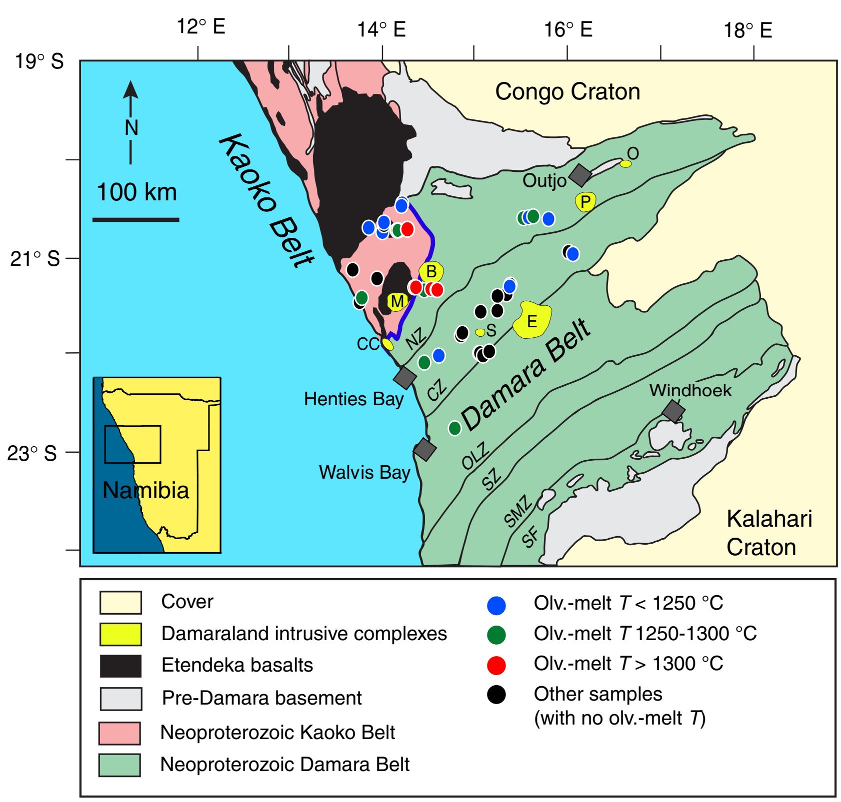

Fig. 1. Structural geological map showing sample locations, the Etendeka lavas and the most prominent anorogenic intrusive complexes in the area. The latter are shown in yellow circles and labeled as follows: Brandberg (B), Cape Cross (CC), Erongo (E), Messum (M), Paresis (P), Spitzkoppe (S) and Okoruso (O). Tectonostratigraphic zones of the Damara Orogen are shown in italics: *CZ*, Central Zone; *NZ*, Northern Zone, *OLZ*, Okahandja Lineament Zone; *SF*, Southern Forland; *SMZ*, Southern Margin Zone; *SZ*, Southern Zone. Geographical locations of olivine-melt obtained crystallization temperatures for individual HOD dykes from this study are indicated in colors. Note that the high-*T* results (>1300 °C) come from a specific region of dyke emplacement coinciding with or close to the boundary zone (indicated by blue line) between the Damara Belt and the Kaoko Belt. The base map is modified from Miller (1983).