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Inside the volcano: Three-dimensional magmatic architecture of a buried shield volcano

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ABSTRACT

The nature and growth of magmatic plumbing systems are of fundamental importance to igneous geology. Traditionally, magma chambers have been viewed as rapidly emplaced bodies of molten rock or partially crystallized "magma mush" connected to the surface by a narrow cylindrical conduit (referred to as the "balloon-and-straw" model). Recent data suggest, however, that magma chambers beneath volcanoes are formed incrementally through amalgamation of smaller intrusions. Here we present the first high-resolution three-dimensional reconstruction of an ancient volcanic plumbing system as a large laccolithic complex. By integrating seismic reflection and gravity data, we show that the ~200 km^3 laccolith appears to have formed through partial amalgamation of smaller intrusions. The complex appears to have fed both surface volcanism and an extensive sill network beneath the volcanic edifice. Numerous sills are imaged within the volcanic conduit, indicating that magma stalled at various levels during its ascent. Our results reveal for the first time the entire multicomponent plumbing system within a large ancient shield volcano.

INTRODUCTION

Extensive study of modern shield volcanoes, e.g., in Hawaii and Iceland, has provided detailed understanding of surface processes associated with basaltic volcanism (Moore and Clague, 1992; Valentine and Gregg, 2008; Cashman and Sparks, 2013). However, knowledge of the internal three-dimensional (3-D) structure of volcanic edifices and how this influences the storage and transport of magma within plumbing systems is comparatively poor. This is because these systems cannot be observed directly and are generally studied through incomplete eroded outcrops (e.g., Chambers and Pringle, 2001; Westerman et al., 2004; Emeleus and Bell, 2005; Galland et al., 2018). Such exposures commonly provide a limited view of the inner workings of the volcanic system, with most of the structure remaining buried and inaccessible, and key features, such as the conduit and chamber contacts, commonly missing. Although careful reconstruction of eroded plutons based on detailed field mapping (e.g., Mattsson et al., 2018) has proven useful, the fundamental limits of surface exposure cannot be circumvented by fieldwork alone. Previous studies have attempted to image magma chambers using seismic tomography (e.g., Bushenkova et al., 2019), and while such data can indicate locations and approximate volumes of large magma bodies, the low spatial resolution (typically several kilometers) means that detailed geometries and melt distributions remain poorly constrained (Sparks et al., 2019). Seismic reflection data (with typical vertical and lateral resolutions of tens of meters) enable visualization of this detail (e.g., Bischoff et al., 2017). However, although intrusive complexes within sedimentary basins (Cartwright and Hansen, 2006; Schofield et al., 2015) and melt lenses beneath active seafloor spreading centers (e.g., Arnulf et al., 2014) have previously been imaged using seismic data, the fossilized plumbing system associated with a large volcanic center and its magma chamber have never been imaged in detail before.

Magma chambers have traditionally been viewed as large, long-lived, geometrically simple bodies of molten rock, which are emplaced rapidly and slowly crystallize to form plutons (Glazner et al., 2004; Annen et al., 2015; Jerram and Bryan, 2018; Sparks et al., 2019). These chambers are typically depicted as being connected to the surface by a vertical cylindrical conduit allowing for movement and eruption of magma, commonly known as the "balloon-and-straw" model (i.e., a large balloon-like magma chamber and a narrow straw-like conduit; Jerram and Bryan, 2018). There is little geophysical evidence for large melt-dominated magma chambers in active volcanic areas, however, causing researchers to propose that large magma bodies are transient and that magmatic systems are instead dominated by partially crystalline "magma mush" with small melt fractions (Glazner et al., 2004; Annen et al., 2015; Sparks et al., 2019). An emerging view is that magma chambers are emplaced incrementally via amalgamation of numerous smaller intrusions into a single body, so that at any one time, only a small fraction of the chamber is molten (Glazner et al., 2004; Menand, 2011; Michaut and Jaupart, 2011; Annen et al., 2015; Morgan, 2018).

The focus of this study is the Erlend volcano, a polygenetic shield volcano in the northeastern Faroe-Shetland Basin (Fig. 1), which is now buried by ~1100 m of sedimentary strata. This is one of numerous volcanoes that erupted along the pre-rift northeastern Atlantic margin (Ritchie et al., 2011, p. 222–228) between ca. 62 and 55 Ma. Unlike many ancient volcanoes, it has been drilled at three locations (hydrocarbon

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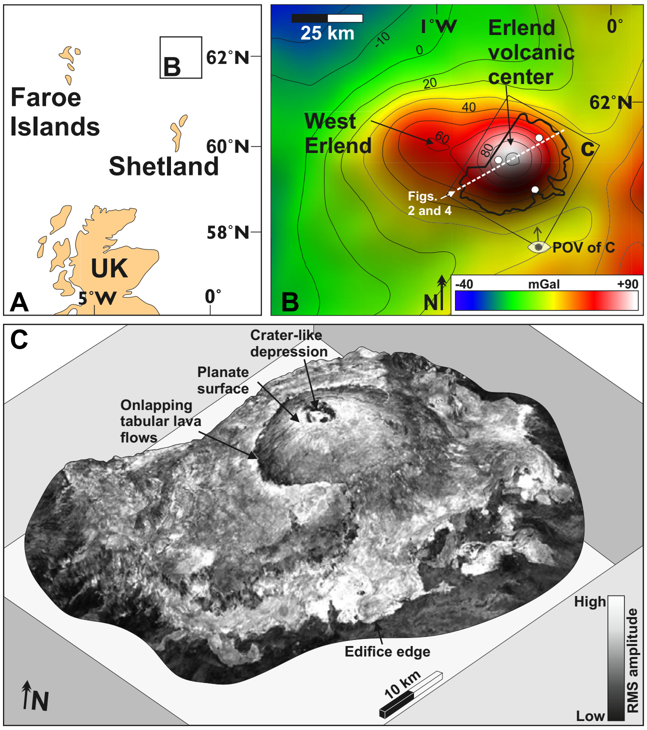

Figure 1. (A) Map of the Faroe-Shetland Basin, showing location of study area in B. (B) Free-air gravity anomaly over Erlend volcano. Black line shows edifice outline; white line shows locations of Figures 2 and 4; box shows location of C (POV—point of view). White dots represent wells penetrating the edifice: 209/04-1A (top), 209/03-1 (left), and 209/09-1 (bottom). (C) Oblique view of the Erlend edifice, showing root mean square (RMS) amplitude of the top of the basalt surface.

exploration wells 209/03-1 (drilled in 1980 by Mobil North Sea Ltd.), 209/04-1a (drilled in 1985 by North Sea Sun Oil Company Ltd.), and 209/09-1 (drilled in 1979–1980 by the British National Oil Corporation; Fig. 1B), providing good subsurface constraints for seismic interpretation. The wells reveal varying thicknesses of basaltic lava and hyaloclastite interbedded with siltstones and mudstones, underlain by Paleocene and Cretaceous sedimentary rocks containing abundant mafic and felsic intrusions (Kanaris-Sotiriou et al., 1993; Ridd, 1983; Jolley and Bell, 2002).

In this study, we present the first high-resolution 3-D seismic images of a subsurface shield volcano (Erlend; Fig. 1C; Fig. S1 in the Supplemental Material[1]) and its magmatic plumbing system, revealed by careful seismic mapping. The plumbing system comprises a large laccolithic complex that appears to feed hundreds of seismically resolvable, radially distributed sills (similar to examples in the Henry Mountains, Utah, USA; Johnson and Pollard, 1973) and a conduit structure containing numerous stacked sills.

METHODS

The first part of this study consisted of detailed seismic interpretation of the Erlend edifice and its plumbing system using a 3-D seismic volume covering an area of ~2000 km^2. The second part of the study used 2-D gravity modeling to determine the nature and geometry of the laccolithic complex. The gravity response was modeled for three different scenarios and compared to the observed free-air gravity anomaly over the volcano. For further details and explanation, see the Supplemental Material.

STRUCTURE OF THE ERLEND EDIFICE

The Erlend volcano is an elliptical dome with a diameter of 30–50 km (Fig. 1C). The volcano flanks comprise numerous subaerially erupted compound lava flows that dip radially away from the crest (Fig. 2). The edifice is onlapped on all sides except the eastern side by a package of tabular lava flows originating from a fissure to the west of the volcano. Packages of clinoforms build radially outward at the edifice margins, interpreted as subaqueous hyaloclastite deltas formed due to lava flowing into a body of water.

The volcanic sequence is as much as ~1 km thick at the crest of the volcano and thins toward its edges (Fig. 2), with an estimated volume of ~400 km^3. The crest has been extensively eroded, resulting in a planate surface ~100 km^2 in area (Figs. 1C and 2). Extending the preserved flanks of the volcanic edifice upward suggests that the thickness of material removed by erosion may be as much as ~600–700 m (Fig. 2).

MAGMATIC PLUMBING SYSTEM

Sedimentary strata beneath the Erlend volcano are heavily intruded, containing >300 seismically resolvable igneous intrusions (Figs. 2

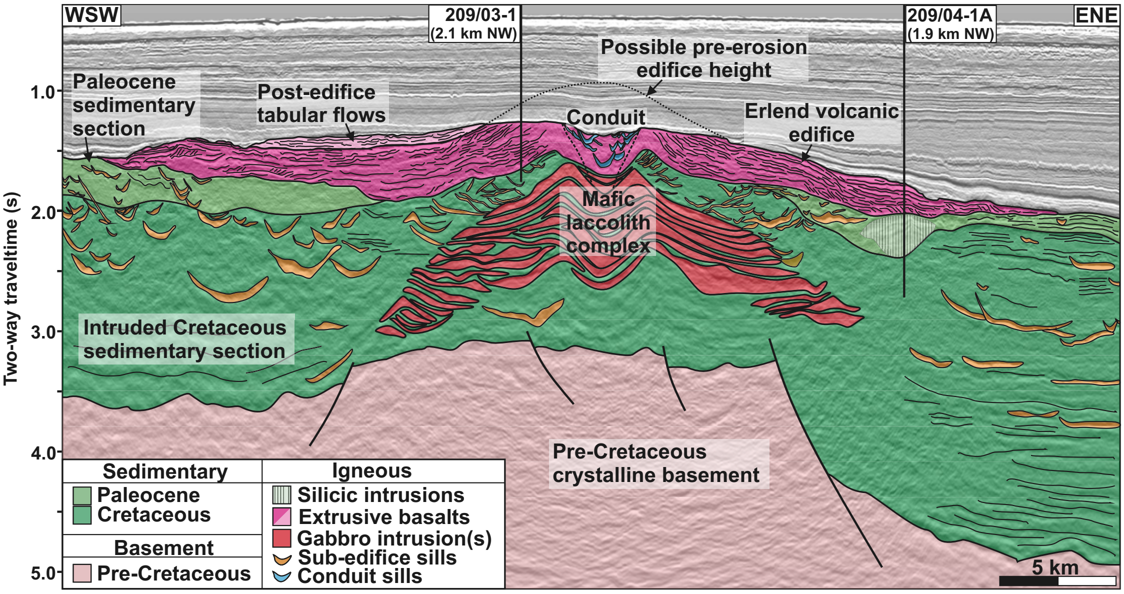

Figure 2. Arbitrary seismic line across the Erlend volcano (Faroe-Shetland Basin) showing extrusive lava flows, volcanic conduit, laccolith complex, and associated sills. Dotted line shows possible edifice height before erosion. Note that wells are offset (distance from line is indicated). Line location is shown in Figure 1B. Uninterpreted line is shown in Figure S2 (see footnote 1).

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[1] Supplemental Material. Detailed methodology, Video S1 (volcanic edifice and plumbing system in 3-D), and Figures S2–S6. Please visit https://doi.org/10.1130/GEOL.S.12990923 to access the supplemental material, and contact editing@geosociety.org with any questions.

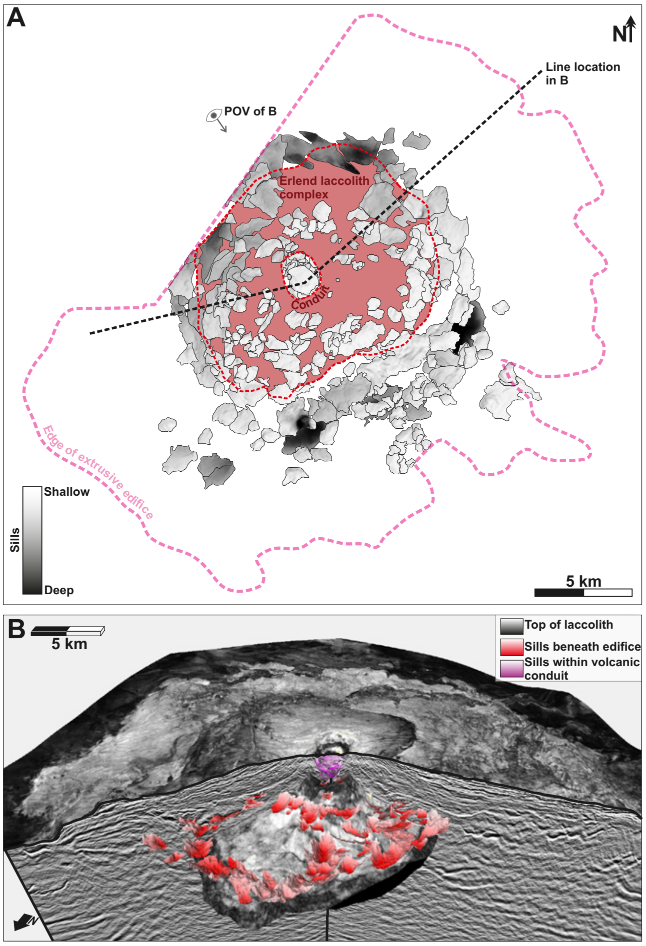

Figure 3. (A) Top-down view of Erlend volcano (Faroe-Shetland Basin) plumbing system, showing all sill intrusions mapped from 3-D seismic reflection data, plus edifice edge, laccolith and conduit. Sills are radially distributed around the conduit and laccolith. POV—point of view. (B) Oblique three-dimensional (3-D) view of Erlend volcano created from 3-D seismic reflection data, showing seismic line combined with the top surface of the edifice to the southeast and plumbing system to the northwest. Tops of the edifice and laccolithic complex are displayed using root mean square (RMS) amplitude to improve contrast with colored sills. Red sills are beneath the edifice, many connected to the top of the laccolith. Purple sills are within the conduit. For a complete 3-D view of the plumbing system, see Figure S3 (see footnote 1).

and 3). Intrusions are commonly saucer shaped in 3-D, with diameters ranging from ~150 m to >2 km (Fig. 3A).

Importantly, when mapped out in 3-D, the sills are distributed in a circular fashion around and away from the center of the edifice. Many of these intrusions appear to originate from an inclined (~10°) high-amplitude positive reflection (Fig. 2) that forms a broad domal feature ~15 km in diameter and ~3 km high with a volume of ~200 km^3, located directly beneath the volcano's crest (Fig. 3B). A second positive high-amplitude reflection occurs ~500–600 ms two-way traveltime (TWT; ~2 km) deeper, which is generally subhorizontal to shallowly dipping (as much as ~6°) away from the center of the edifice. Numerous low- to moderate-amplitude reflections, which are commonly subhorizontal, are observed between these two reflectors (Fig. 2).

IS THE SUB-EDIFICE DOME A FOSSILIZED MAGMA CHAMBER?

Although the nature of the domal feature cannot be determined using seismic data alone, its circular geometry combined with regional seismic interpretation (Fig. S4) precludes it being a subvolcanic crustal basement high. High-pass-filtered gravity data and the short wavelength of the Erlend gravity anomaly (Fig. S3) suggest that the edifice is underlain by a shallow high-density body (Lowrie, 2007). Combined with the observation that sills appear to have been fed in a radial distribution away from the dome (Fig. 3A), this suggests that the feature may form part of the volcano's preserved magmatic plumbing system. To narrow potential interpretations of the nature of the dome, a series of 2-D gravity models was produced to test various geological scenarios constrained by the seismic data.

In model A, the high-amplitude sub-edifice reflections are modeled as mafic ring dikes (e.g., Chambers and Pringle, 2001; Johnson et al., 2002) intruded into a thick sedimentary section (Fig. 4A). The modeled gravity signal is much lower than the observed signal at the edifice crest, indicating that ring dikes alone cannot account for the Erlend gravity anomaly.

Model B shows a solid mafic pluton representing a crystallized magma chamber (Fig. 4B). The upper high-amplitude reflection represents the top of the pluton, and the lower reflection is assumed to be close to the base. Although this produces a better match between the modeled and observed anomalies than model A, the modeled gravity is slightly too high, suggesting that the modeled pluton is too dense. It may therefore not be wholly gabbroic, likely incorporating lower-density material (e.g., lenses of country rock). This interpretation is supported by the observation of reflectivity within the plutonic body, indicative of compositional and/or structural heterogeneity.

In Model C, the dome is modeled as a series of stacked partially amalgamated mafic sheet intrusions, separated by fragments of country rock which comprise up to 20% of the total volume (Fig. 4C). This results in an extremely close match to the observed gravity data, and is our preferred solution.

VOLCANIC CONDUIT FEEDER SYSTEM

A circular depression ~2 km in diameter and ~500 m deep, previously interpreted as a volcanic vent (Gatliff et al., 1984), occurs at the peak of the Erlend volcano (Fig. 1C). Given ~600–700 m of erosion from the volcano crest, such a vent would have been >1 km deep, which seems unlikely given that the edifice itself would have been no more than ~1700 m thick at its highest point. The observation that the depression does not have a flattened base (Fig. 2) suggests that it may represent part of the volcanic conduit, allowing for movement of magma from the deeper plumbing system to the surface, rather than the remnant of a surficial vent. The formation and geometry of volcanic conduits is poorly understood, but it is typically assumed that magma rises vertically through a system of dikes (Bagnardi et al., 2013; Cashman and Sparks, 2013; Burchardt et al., 2018) that branch out and widen upward at very shallow depths (<100 m) to form eruptive vents (Keating et al., 2008).

The Erlend conduit fill is seismically chaotic and contains numerous high-amplitude saucer-shaped reflections (Figs. 2 and 3). These are interpreted as sills intruded into a poorly consolidated volcaniclastic unit and appear to form a stacked network, with clear examples of vertical connectivity between individual intrusions (Fig. 2). This geometry is similar to that of sill complexes identified within crater walls on the volcanic island of Ambrym, Vanuatu (Németh and Cronin, 2008). The sills within the Erlend conduit probably represent the upper part of the volcanic plumbing system, similar to intrusive complexes observed in the cores of exposed eroded volcanoes (e.g., Walker, 1992; Emeleus and Bell, 2005), supporting the interpretation of the circular depression as a volcanic conduit.

DISCUSSION

Our seismic interpretation and gravity modeling suggest that the intrusive complex situated beneath the Erlend volcano is laccolithic in shape with a volume of ~200 km^3, comprising a series of interconnected amalgamated intrusions, similar to a "Christmas tree" laccolith

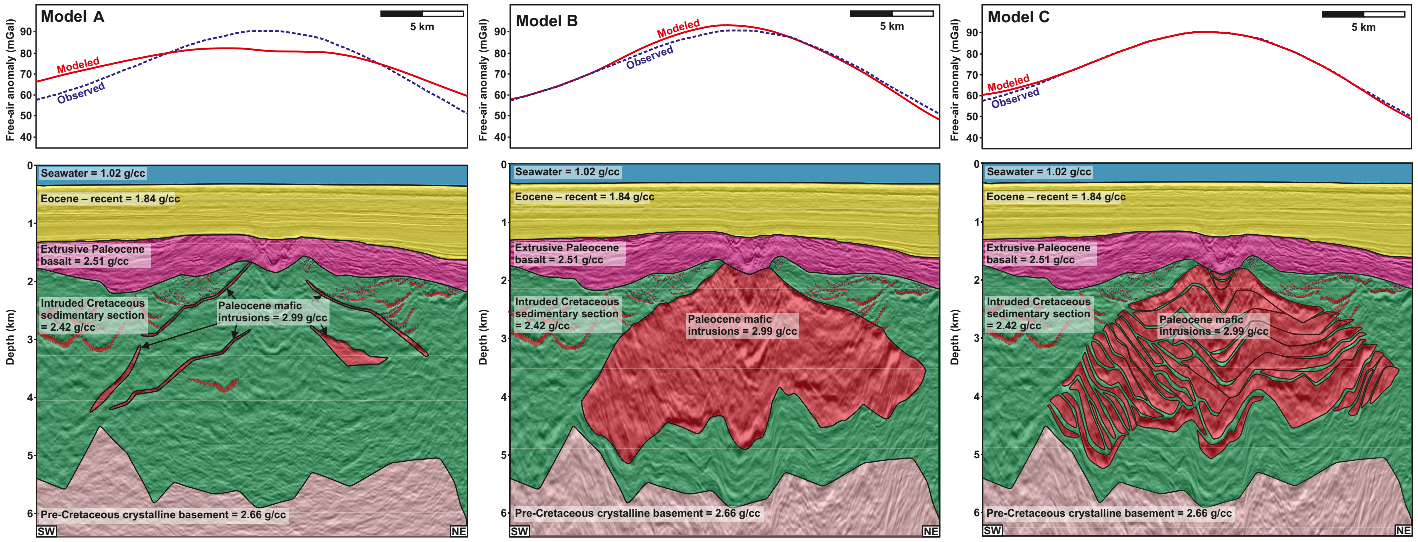

Figure 4. Comparison of modeled gravity with observed free-air anomaly at Erlend volcano (Faroe-Shetland Basin). Lower panels show model parameters overlaid on depth-converted seismic line. (A) Plumbing system is modeled as a series of ring dikes. Modeled gravity anomaly is much lower than the observed anomaly. (B) The plumbing system is modeled as a solid gabbro body. Modeled anomaly is too high over the southwestern part of the system, but otherwise shows a close match to the observed anomaly. (C) The plumbing system is modeled as numerous partially amalgamated intrusions. Modeled and observed gravity anomalies are closely matched. Note: Different geometry of pre-Cretaceous basement between Figures 2 and 4 is due to time-depth conversion.

complex (e.g., Elba Island, Italy; Westerman et al., 2004). Gravity model C (Fig. 4C) plus seismic reflectivity throughout the laccolith suggest that in much of the complex, individual intrusions did not fully coalesce, leaving them separated by lenses of country rock. This interpretation is supported by recent petrological and geochronological data and theoretical modeling pertaining to the formation of crustal plutons, which imply that many large igneous bodies are emplaced incrementally (Glazner et al., 2004; Menand, 2011; Michaut and Jaupart, 2011).

The presence of numerous interconnected sills within the volcanic conduit indicates that sills may play a key role in the ascent and eruption of magma, in addition to dikes as observed in the field (e.g., Keating et al., 2008). It is clear that the common assumption when modeling volcanic eruptions that magma rises up a vertical cylindrical conduit to the surface (Gonnermann and Manga, 2012; Cashman and Sparks, 2013) is likely an extreme oversimplification, and that magma pathways can be far more complex, incorporating both sills and dikes (e.g., Bagnardi et al., 2013).

An overriding observation from our seismic data is that the subvolcanic plumbing system of Erlend is complex and contrasts markedly with the classic "balloon-and-straw" model. Instead, Erlend consists of three distinct magmatic domains: a laccolithic central complex, radiating sills fed away from that complex, and a separate sill network within the volcanic conduit. Although these systems are interconnected, it is likely that there was significant variability in magma properties between the domains due to changes in, e.g., temperature, flow rate, and fractionation. The radiating sill network appears to have been fed from various levels of the laccolithic complex and may therefore have tapped into different magma batches within the evolving magma bodies (Jackson et al., 2018), which may explain the coexistence of mafic and felsic intrusions within the Erlend wells. Similarly, the intra-conduit sills and much of the extrusive lava appear to have been fed from the uppermost part of the laccolithic complex, again sampling another distinct part of the magmatic system. Outcrop- or drilling-based petrological and geochemical studies of similar plumbing systems, which commonly sample only a tiny part of one of these domains, are therefore unlikely to be representative of the entire system. Therefore, while it is important to note that detailed geochronological and geochemical work has given substantial insights into magmatic plumbing systems (e.g., Glazner et al., 2004; Michaut and Jaupart, 2011), such methods are commonly indirect and commonly spatially poorly representative. Our work highlights the substantial challenges in using such methods in isolation to characterize the spatial and temporal evolution of an entire volcanic system when they may have only sampled one subset of a complex subsurface magmatic system.

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