Volcanic and Volcaniclastic Lithofacies in a Mesoproterozoic Arc Sequence, Barby Formation, Southwest Namibia

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Abstract

The Barby Formation makes up part of a major Mesoproterozoic arc complex along the Kalahari Craton margin in southern Africa. Previous workers interpreted the Barby Formation, which has a composite stratigraphic sequence of 8.5 km, to consist dominantly of basaltic to andesitic lava flows and minor associated hypabyssal intrusions. Our initial mapping in a representative and well-exposed portion of the unit reveals a more complex lithofacies assemblage. Throughout the study area the volcanic rocks are intercalated with lacustrine deposits ≤ 54 m thick that consist of planar-laminated tuffaceous andesitic sediments and are inferred to have accumulated in distal settings relative to source vents. Lavas are present in minor amounts and consist of compound basaltic flows, in which lava tongues grade on all sides into aa-type flow breccia. Compositionally similar hypabyssal sill packages are also present. Basaltic to andesitic pyroclastic deposits are much more abundant and form successions up to ~ 45 m thick that are intercalated with thinner intervals of lacustrine strata and occur over an area ≥ 20 km^2. The most common deposits consist of moderately agglutinated to densely welded spatter accumulations inferred to have formed along fissure vents erupting Hawaiian-style lava fountains. The spatter accumulations typically grade upward into phreatomagmatic deposits containing minor amounts of spatter and bombs mixed with poorly vesicular lapilli tuff and up to 30% disrupted lacustrine sediment. The change in eruptive style is inferred to record decreasing magma supply to the vents, which allowed external water to mix with magma in the right proportions to trigger violent phreatomagmatic explosions. This in turn has implications for volcanic hazards associated with normally weakly explosive lava fountains from fissure vents.

Geological Background

The 1.35-1.0 Ga Namaqua-Natal Orogenic Belt located in southern Africa (Figure 1) forms exposed and subsurface segments that extend along the southern margin of the Kaapvaal Craton (Hanson, 2003). The belt represents one of the main convergent margins active during the assembly of the Rodinia supercontinent and consists of juvenile and reworked crust (Hanson, 2003; Jacobs et al., 2008). The study area for this project is within the Konkiep Terrane, a major Mesoproterozoic tectonic element of the Namaqua-Natal Belt located in southwest Namibia (Miller, 2008). The terrane is divided into five main volcanic and sedimentary sequences (Figure 2) that mostly show little metamorphism, are separated by major unconformities, and formed partly in arc settings (Watters, 1974; Brown and Wilson, 1986; Hoal, 1990). Volcanic rocks are abundant within the first four sequences and are associated with plutonic rocks (Miller, 2008). The 1.2 Ga Barby Formation is the largest and most extensive volcanic unit within the terrane (Figure 2), is well exposed, and is the focus of this study.

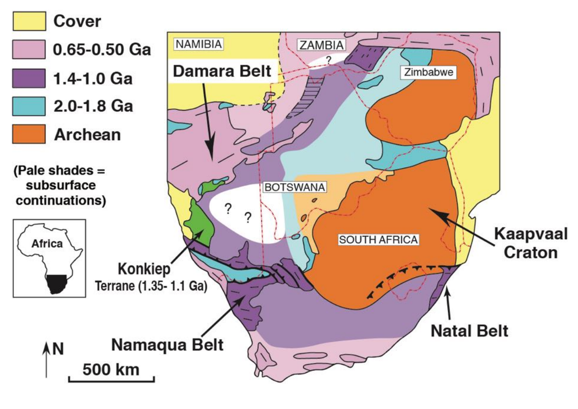


Figure 1: Regional Precambrian tectonic framework of southern Africa, modified from Hanson (2003).

Previous Work and Statement of the Problem

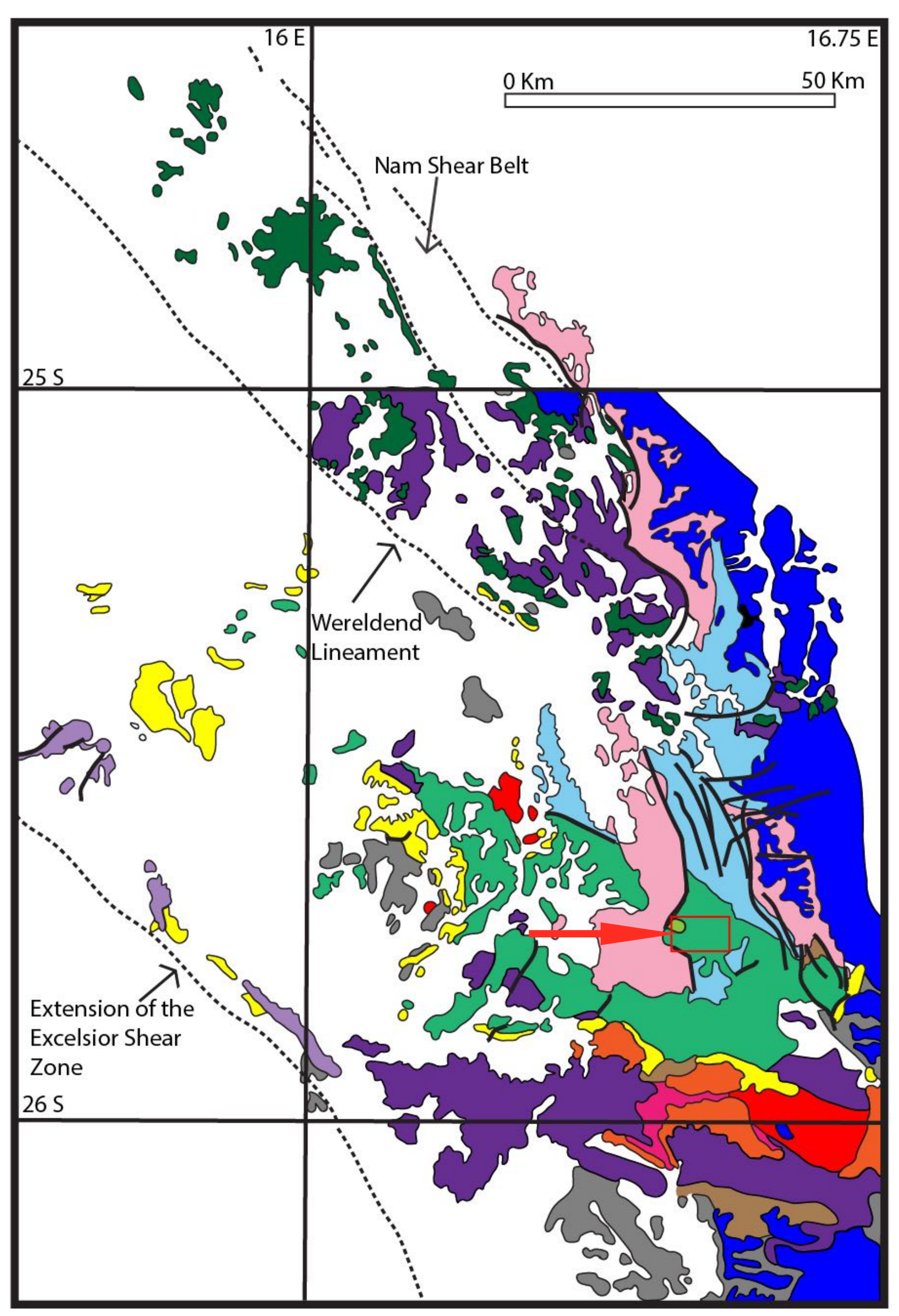
Most workers in the area have interpreted Barby volcanism to have occurred in an active continental arc setting. Watters (1974), Hoal (1990), and Becker et al. (2006) showed that the Barby Formation and the coeval Haiber Flats Formation farther west in the Konkiep Terrane have calc-alkaline to high-K calc-alkaline or shoshonitic compositions. Hoal (1993) has suggested that these rocks accumulated in extensional basins that formed as a result of oblique subduction along the convergent margin.

Watters (1974, 1977) has done the only relatively detailed previous mapping within large parts of the Barby Formation. He estimated the formation to be ~ 8500 m thick, and mapped most of the units within it as lava flows, with limited intrusive units directly associated with the volcanic activity. He described the lava units as laterally interfingering, with a basal rhyolite member being more laterally continuous.

This project represents the first modern detailed field study of the Barby Formation. The goal is to document the volcanic make-up, eruptive styles, lithofacies architecture, and hypabyssal intrusive feeder systems within a representative part of the unit.

New Mapping

One new result of the field work is the recognition of sequences of planar-bedded and laminated, generally fine-grained andesitic tuffaceous sedimentary rocks up to 54 m thick (Figure 3) that are inferred to have been deposited in lakes during pauses in eruption activity and occur throughout the study area. Results of our reconnaissance mapping of the other different lithofacies in the Barby Formation are shown in Figures 4 and 5. Compared to previous work, our mapping has revealed only a limited amount of lava flows in the study area, which represent parts of compound lava flow fields. The lavas are olivine-phyric basalts and in some cases are rich in vesicles. Smaller flows consist of massive lava tongues that grade on all sides into aa-type flow breccia. More extensive flows, in which the sides are not exposed, contain massive interiors which pass above and below into flow breccia. One of the most interesting features that was previously undocumented are abundant basaltic to andesitic pyroclastic fall sequences that were emplaced close to source vents and show variations in eruptive styles.



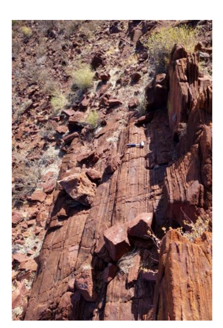


Figure 3: Volcaniclastic siltstone to fine-grained sandstone at the top of measured section 2, showing planar bedding and lamination with some low-angle cross bedding. This outcrop is representative of sediment interbeds within the pyroclastic successions that are inferred to have accumulated in lacustrine settings. Hammer for scale.

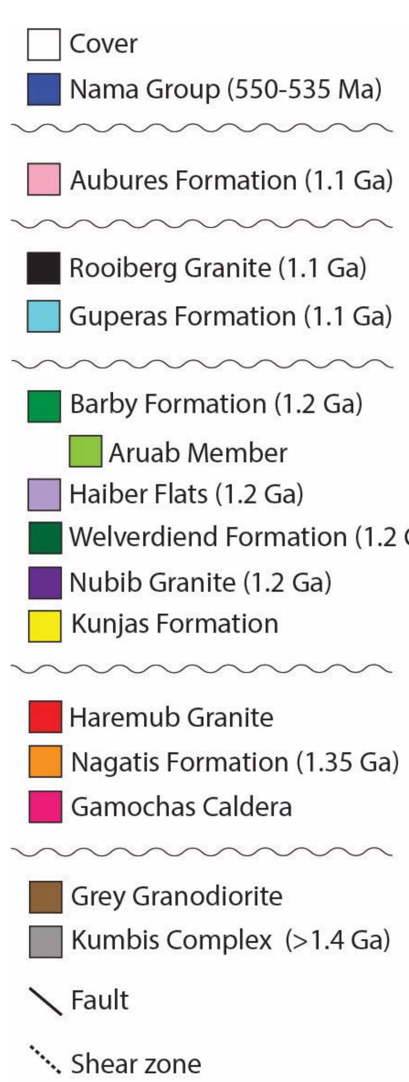


Figure 2. Map of the Konkiep Terane modified from Von Brunn (1969), Waters (1974), and Miller (2008). Location of Figure 4 is outlined in red and arrowed.

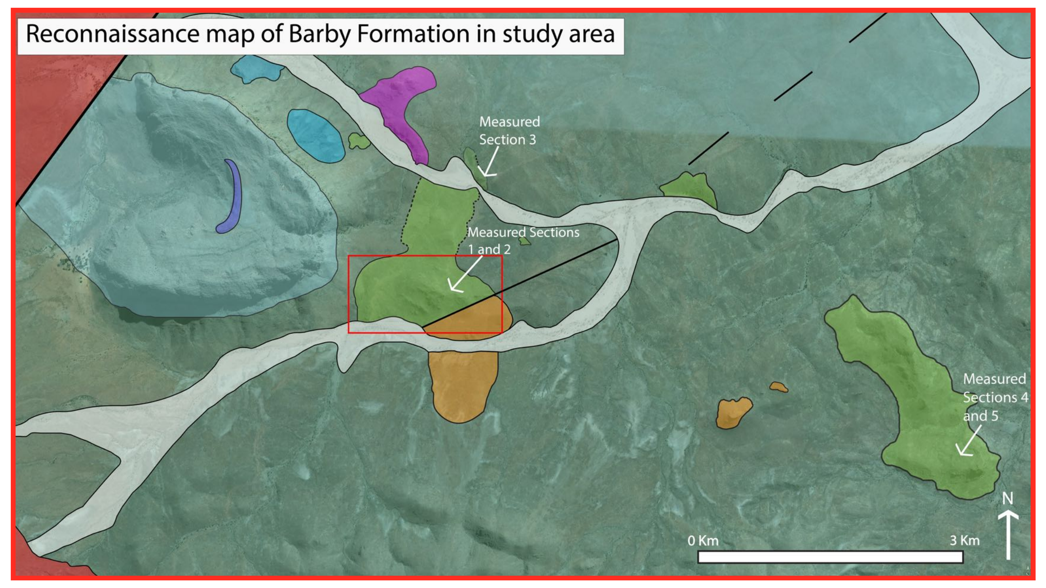


Figure 4: Overview map showing the extent of spatter and phreatomagmatic deposits. Location shown on Figure 2.

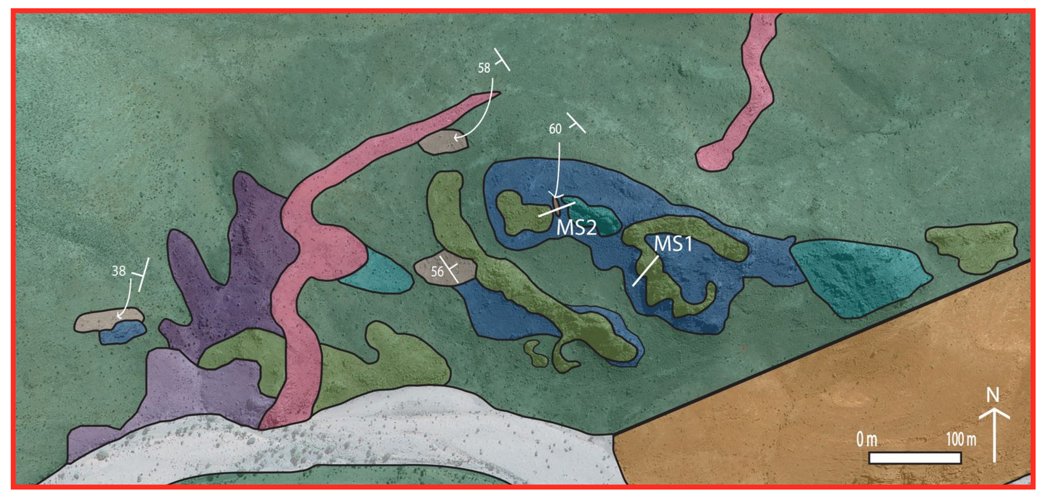
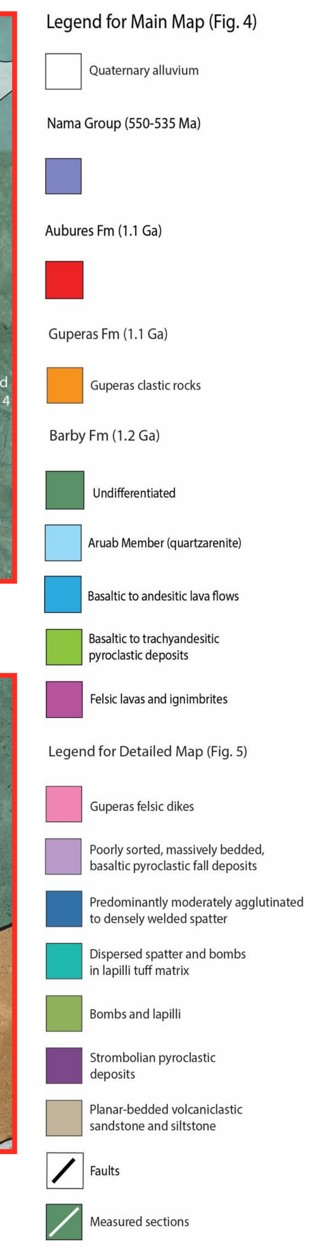


Figure 5: Detailed map showing the Hawaiian-style to phreatomagmatic successions. Location shown in Figure 4.



Magma Ascent Rate as a Control on Eruption Styles

Figure 8 shows our model for the variations in eruptive styles documented in the measured sections. (A) Hawaiian-style eruption with rapid magma ascent rate prevents the magma from mixing with sediment in the right proportions to drive phreatomagmatism. Spatter deposits range from moderately agglutinated to densely welded depending on eruption rate. (B) A decrease in magma ascent rate allows minor amounts of wet sediment to start mixing with the magma, but the ratio of water to magma is not yet high enough for a true phreatomagmatic eruption (Wohletz, 1986). This produces the interval shown in the middle part of measured section 1 where some disrupted sediment is present within spatter deposits. (C) The magma ascent rate has decreased even more, allowing the ratio of magma to water to reach an optimal value for phreatomagmatic explosive behavior. (D) An increase in magma ascent rate causes a return to Hawaiian-style spatter eruptions and the cycle may repeat again.

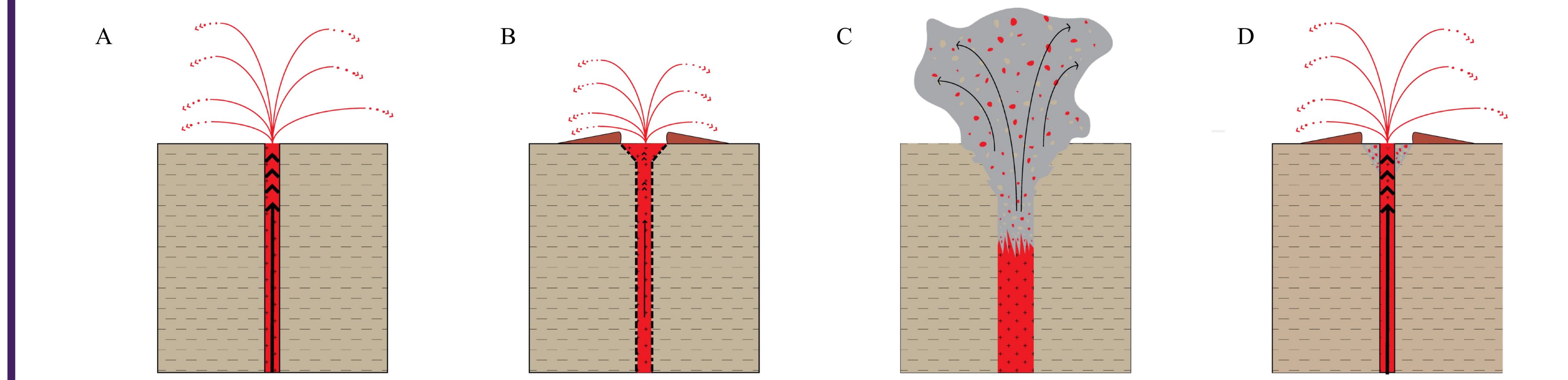


Figure 8. Model showing variations in magma ascent rate.

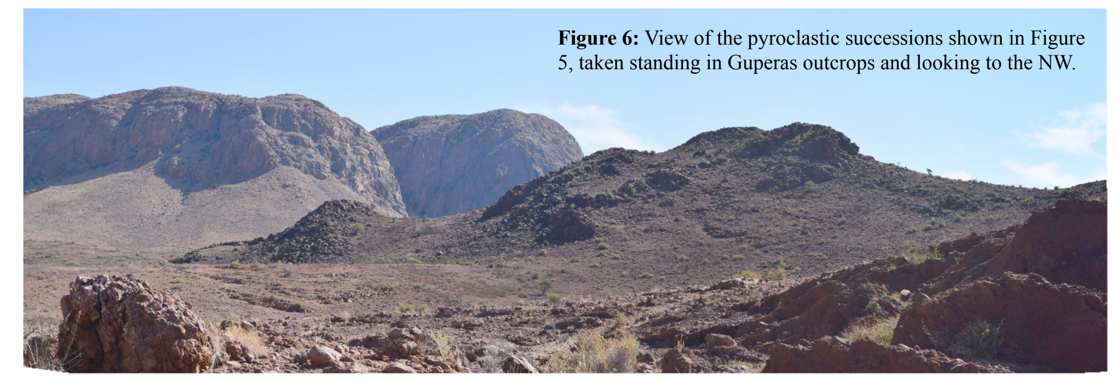


Figure 6: View of the pyroclastic successions shown in Figure 5, taken standing in Guperas outcrops and looking to the NW.

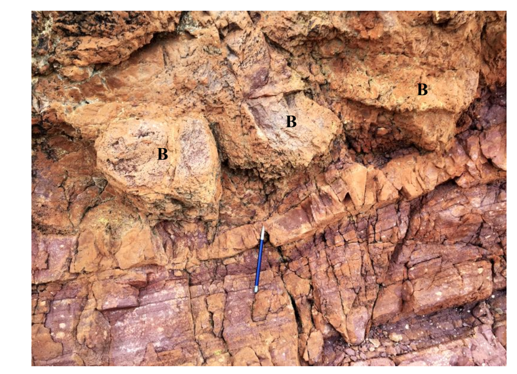


Photo E: Planar-bedded, fine- to coarse-grained sandstone with preserved bomb sags in measured section 5. B = bombs.

Photo F: Vesicular bombs penetrating into sediment in measured section 5.

Photo G: Ribbon bomb near the bottom of measured section 3.

Photo H: Coarse spatter in measured section 3.

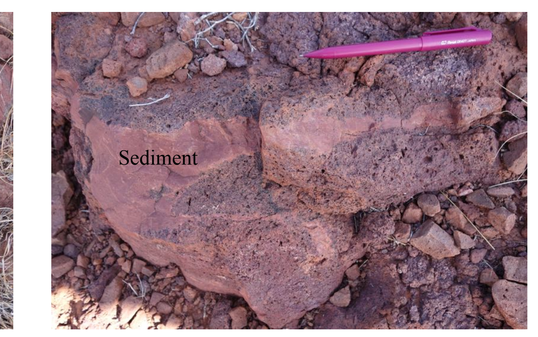


Photo I: Intermixed sediments in phreatomagmatic deposits.

Photo J: Well-preserved, moderately agglutinated spatter in measured section 3.

Photo K: Fluidal bombs and small but abundant disrupted sediment masses in measured section 1 indicating thorough mixing of wet sediment and magma during explosive activity.

Photo L: Fusiform bomb with fluidal tail from measured section 3.

Measured Sections of Proximal Pyroclastic Fall Deposits

Five representative measured sections of the proximal pyroclastic fall deposits are shown in Figure 7. Locations of the sections are given in Figures 4, 5, and 6 and representative views of diagnostic deposits are shown in photos A-L. The sections demonstrate successions from predominately moderately agglutinated or densely welded spatter deposits typical of Hawaiian-style eruptions to phreatomagmatic pyroclastic deposits. Both types of deposits contain cow-dung, ribbon, fusiform, and ellipsoidal volcanic bombs. Phreatomagmatic deposits characteristically also contain angular, variably vesicular pyroclasts and cored lapilli, with finer grained interstitial ash-sized particles and disaggregated sediment. These features point to explosive interactions between magmas and external water and/or wet sediment. Measured sections 1 and 2 show gradual transitions from spatter to phreatomagmatic lapilli and bombs with distinct zones of disaggregated sediment intermixed with juvenile pyroclasts. Measured section 3 exhibits spatter ranging up to 30 cm in length, and a zone of large flattened bombs that are parallel to bedding. Measured section 4 demonstrates repeated variations from Hawaiian-style to phreatomagmatic eruptions. The bottom of measured section 5 shows large bomb sags and bombs penetrating into lacustrine sediment, with lava flows of similar composition stratigraphically above, recording a change from explosive to effusive eruptions.

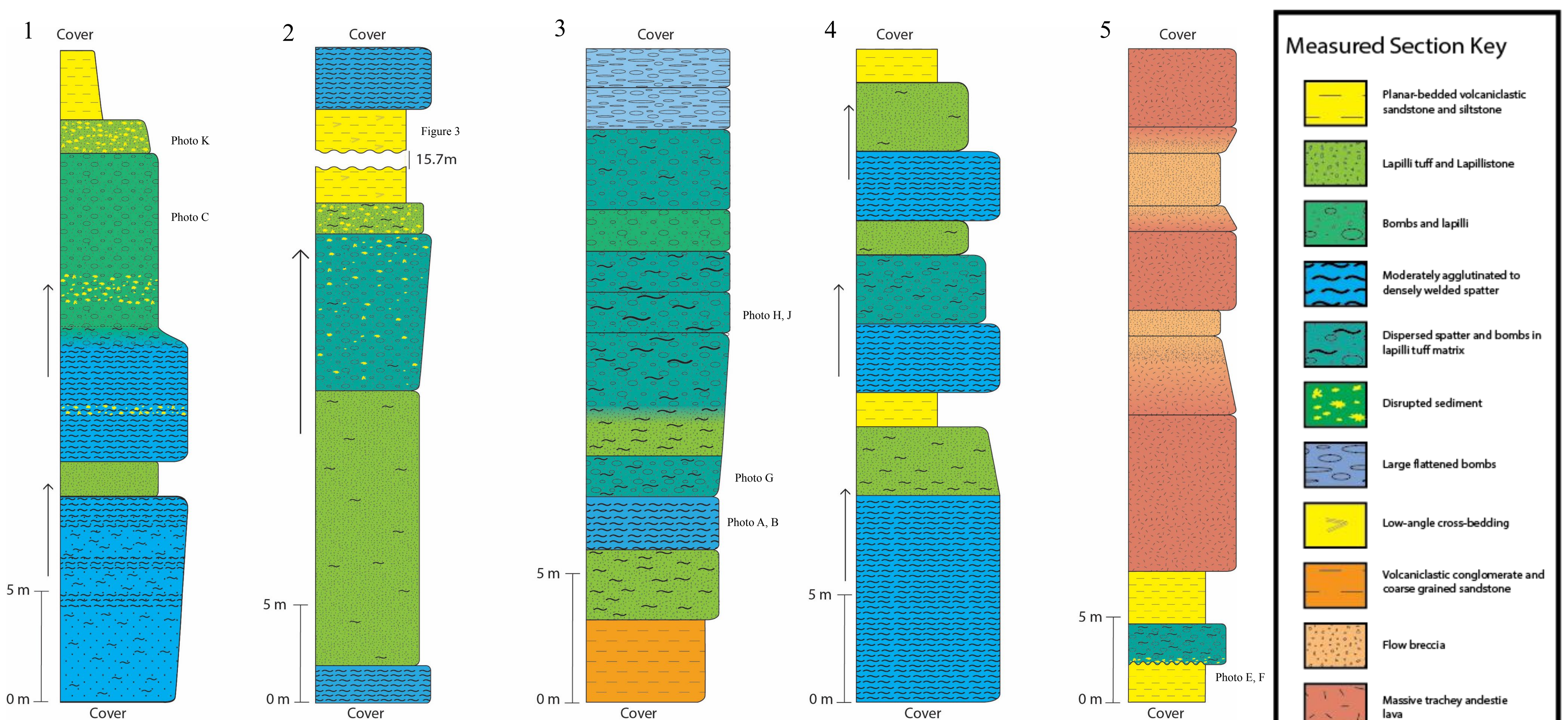


Figure 7: Measured sections of pyroclastic deposits shown at different scales. The arrows indicate an upward increase in phreatomagmatic explosive activity, supporting the model proposed in Figure 8. Terminology from Brown et. al. 2014.

Photo A: Moderately agglutinated coarse spatter in measured section 3. Pencil points to mass of recycled agglutinate.

Photo B: Cored lapillus in agglutinate in measured section 3. The core has fallen out but probably was sediment wrapped by fluidal magma.

Photo C: Ellipsoidal to more irregular bombs, with abundant angular to droplet-shaped lapilli in phreatomagmatic deposits in measured section 1.

Photo D: Lapilli tuff recording fine-scale mixing of sediment and juvenile pyroclasts (see Figure 8 C).

Conclusion

Our new mapping shows that significant parts of the Barby Formation consist of basaltic to andesitic pyroclastic rocks that record Hawaiian-style and phreatomagmatic eruptive processes. Spatter deposits dominate much of the sequences we have studied, and it is likely that the eruptive activity occurred largely from fissure vents, based on observations of modern Hawaiian eruptions. We have not located any of the actual vents yet, but the presence of large bombs and coarse spatter indicates the pyroclastic sequences must have formed in close proximity to such vents. Intercalated fine-grained volcaniclastic sedimentary packages were deposited in relatively shallow intermittent lakes in a poorly drained area of relatively low topography, possibly within an extensional intra-arc basin.

Explosive phreatomagmatic eruptions were made possible by an abundance of groundwater in the lacustrine sediments. Alternations between Hawaiian and phreatomagmatic behavior during eruptions from fissure vents are inferred to reflect variations in magma ascent rate at shallow depths beneath the surface, as documented in other studies of more recent volcanic fields (e.g., Houghton et al., 1999; Otterloo et al., 2013; Valentine and Cortes, 2013). Our study is important in hazard evaluation because it demonstrates the variability and inconsistent behavior of these types of eruptions. Hawaiian-style fire-fountain eruptions are not normally considered to be violent, but with an influx of water and a decrease in magma ascent rate can become explosive and potentially dangerous.

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