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by Károly Németh [1,2], Ulrike Martin [3], Miguel J. Haller [4,5], and Viviana I. Alric [4,5]

Cenozoic diatreme field in Chubut (Argentina) as evidence of phreatomagmatic volcanism accompanied with extensive Patagonian plateau basalt volcanism?

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In Patagonia, Argentina, at the northern border of the Patagonian Cenozoic mafic plateau lava fields, newly discovered diatremes stand about 100 m above the surrounding plain. These diatremes document phreatomagmatic episodes associated with the formation of the volcanic fields. The identified pyroclastic and intrusive rocks are exposed lower diatremes of former phreatomagmatic volcanoes and their feeding dyke systems. These remotely located erosional remnants cut through Paleozoic granitoids and Jurassic/Cretaceous alternating siliciclastic continental successions that are relatively easily eroded. Plateau lava fields are generally located a few hundreds of metres above the highest level of the present tops of the preserved diatremes suggesting a complex erosional history and potential interrelationships between the newly identified diatremes and the surrounding lava fields. Uprising magma from the underlying feeder dyke into the diatreme root zone intruded the clastic debris in the diatremes, inflated them and mingled with the debris to form subterranean peperite. The significance of identifying diatremes in Patagonia are twofold: 1) in the syn-eruptive paleoenvironment, water was available in various "soft-sediments", commonly porous, media aquifer sources, and 2) the identified abundant diatremes that form diatreme fields are good source candidates for the extensive lava fields with phreatomagmatism facilitating magma rise with effective opening of fissures before major lava effusions.

Introduction

The eruption of extensive, large volume basaltic plateau lavas was one of the most prominent volcanic events that took place during the Cenozoic geological history of extra-Andean Patagonia (Stern et al., 1990; D'Orazio et al., 2000; D'Orazio et al., 2001; Gorring and Kay, 2001; Gorring et al., 2003). The most accepted interpretation of this magmatism relates to the opening of a slab window under this sector of South America in response to the subduction of the Chile oceanic spreading ridge at the Chile Triple Junction (Ramos and Kay, 1992; Gorring et al., 1997). Large numbers of studies have focused on the general geological framework and understanding the geochemical signature of some large volume southern Patagonian volcanic areas (Figure 1) such as the Pali Aike volcanic field (Skewes and Stern, 1979); Meseta del Lago Buenos Aires (Baker et al., 1981) or the Estancia Glencross area volcanics (D'Orazio et al., 2001). However, with the exception of the Pali Aike volcanic field (D'Orazio et al., 2000; Corbella, 2002; Haller et al., 2005; Haller and Németh, 2006), we know very little about the volcanism that created such volcanic fields, especially the physical volcanology of these Patagonian volcanic fields.

In spite of the large volumes of many of the Patagonian Cenozoic volcanics, the source, vent locations and type of volcanic activity have been largely overlooked or unstudied. Here, we present the results of a field study that identified extensive diatreme fields in Northern Patagonia located near Oligocene to Miocene plateau-like lava fields, indicating a close spatial relationship between the two fields. The discovery of diatreme fields in Northern Patagonia may serve to demonstrate that phreatomagmatic volcanism, driven by magma-water interaction, may have been associated with the generation of these mafic volcanics. The vast number of phreatomagmatic volcanoes (maars and tuff rings) preserved in the Southern Patagonian Pali Aike Volcanic Field are associated with extensive lava fields, lava shields, lava spatters as well as sill and dyke complexes (D'Orazio et al., 2000; Corbella, 2002; Haller et al., 2005; Haller and Németh, 2006). Therefore, the identification of diatreme fields in the Northern Patagonia (Eocene to Miocene) extra-Andean volcanic field suggests similar volcanism occurred at both sites. We also highlight the role that erosion may have played in partially or completely removing important volcanic landforms which may have been associated with the initiation of extensive flood lava volcanism.

In maar-diatreme volcanoes a large amount of fragmented country rocks and commonly juvenile lapilli and bombs are ejected (Lorenz, 1986;White, 1991). The ejected volcaniclastic succession forms a tephra ring surrounding the crater of a phreatomagmatic volcano (Lorenz, 1986). In cases where the explosions take place in the shallow subsurface or at surface levels, only a wide crater may form, commonly referred to as a tuff ring (Lorenz, 1986). Whereas the disruption takes place below the surface, the evacuated zone may form cavities that can collapse to form a subsidence feature commonly referred to as a maar. Maar craters can be a few kilometres across and be associated with underlying diatremes also up to a few kilometres in diameter (Lorenz, 1986). Subsurface interactions of magma and water that generate tephra are attributed to thermo-

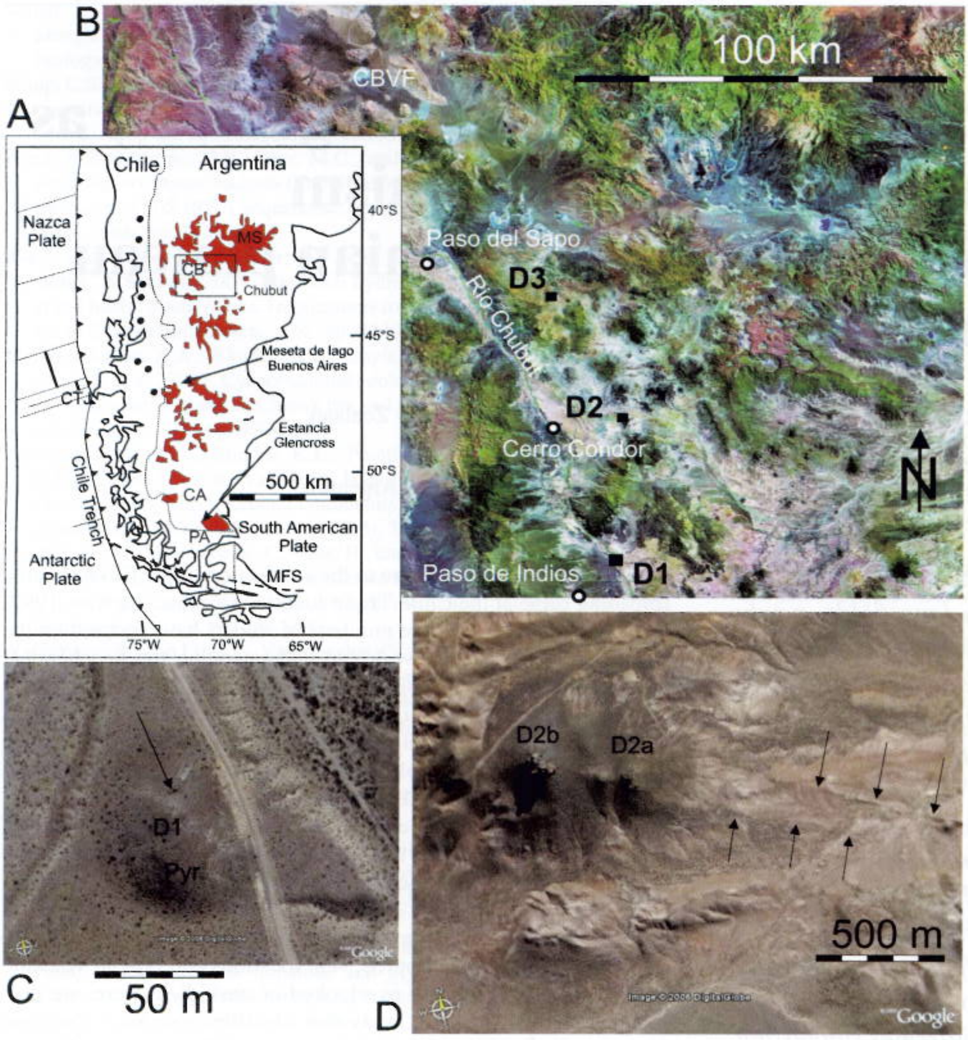

Figure 1 Overview of Southern Argentina showing major Cenozoic flood lava and associated eroded cone fields. Black dots represent active volcanoes in the Andes. Abbreviations: MS—Meseta Somuncura; CB—Crater Basalt Volcanic Field; CA—Camasú Aike Volcanic Field; PA—Pali Aike Volcanic Field; CTJ—Chile Tripple Junction; MFS—Magallanes Fault System (A). On the satellite image (MrSid NASA) of Chubut, clearly visible dark zones of flood lava fields and point-like eruptive sources (B) recently identified to be diatremes (D1, 2 and 3 studied sites). One of the youngest volcanic fields in the region is the Crater Basalt Volcanic Field (CBVF). In close-up satellite images (Google Earth), small hill along the Rio Chubut (C) and dykes terminating to small volcaniclastic rock dominated hills (D2a and D2b) interpreted to be diatremes. Arrow on C (D1 diatreme) points to a contact between coherent magmatic body and pyroclastic (Pyx) unit. Arrows on D point to a line of dykes terminating into the diatremes.

hydraulic explosions in the root zones of the diatremes (Kurszlaukis and Lorenz, 1997; Zimanowski, 1998; Lorenz et al., 2002). Diatremes exposed after long lasting erosion reveal the subsurface architecture of a phreatomagmatic volcano (White, 1991). The shape, size and componentry of diatremes are diverse and depend on the style of magma-water interaction; the country rock types, the hydrogeology of the country rocks, the water content and the magma supply rate (Lorenz, 1984). The study of the diatremes may give vital information of the syn-eruptive paleoenvironment of a volcanic field and the hydrogeological conditions of the strata the uprising magma encountered. Therefore, their identification in Patagonia is a significant new discovery that may aid in understanding the formation and evolution of the extensive Cenozoic volcanic fields of Patagonia.

Geological setting

The basement in the study area called Somuncura Massif is an important geological unit of Northern Patagonia. It is limited to the west by the Andean thrust fault. The basement consists of schists and gneisses metamorphosed to amphibolite facies during the early Paleozoic in the east (Linares et al., 1990) and the late Paleozoic (Hervé et al., 2005) in the west. This basement is intruded by the Mamil Choique granitoids of Devonian (Cerredo et al., 2000) and early Permian age (López de Lucchi et al., 2000). These rocks are covered by Jurassic volcanics whose composition varies from acidic in the east to intermediate-basic in the west. The acidic volcanics yielded Ar-Ar ages of 186.2 to 176.9 Ma (Alric et al., 1996) and are related to the opening of the Atlantic Ocean, while the intermediate are 180–136 Ma (Page and Page, 1993) and are related to the subduction that occurred to the west. In the upper part of the section, the intermediate volcanics are interbedded with the late Jurassic Cañadón Asfalto lacustrine limestone and black shales (Cabaleri and Armella, 2005; Cabaleri et al., 2005), which are in turn overlapped by the continental sediments of Chubut Group of early Cretaceous age. These Cretaceous deposits unconformably cover the older units and consist of fluvial and continental sediments with pyroclastic intercalations (Codignotto et al., 1979). The Chubut Group is divided into a lower section (Los Adobes Formation) of epiclastic nature (conglomerates, tuffaceous sandstones with intercalations of mudrock beds and tuffs) and an upper section (Cerro Barcino Formation) consisting of tuffs, sandy tuffs, tuffaceous sandstones and claystones (Codignotto et al., 1979). Several shallow marine transgressions covered the topographic lows during the Tertiary leaving behind erodable, thin silici-clastic sedimentary layers.

Intraplate basaltic rocks of Paleocene, Eocene, Oligocene-Miocene, and Pliocene-Pleistocene age cover various localities of Northern Patagonia (Figure 1). Paleocene and Eocene subvolcanic intrusions of gabbroic composition cut the Jurassic-Cretaceous sediments and yielded ages of 62.7±0.26 to 48.82±0.41 Ma (Alric, 1996). A major alkaline flood basalt province developed on the Somuncura Massif during 36–24 Ma (Ardolino et al., 1999) before the eruption of alkaline bimodal volcanics of 15–11 Ma representing the end of the flood volcanism in Somuncura (Ardolino and Franchi, 1993). Minor basaltic effusions occurred in the area during the Pliocene-Pleistocene (Massaferro et al., 2006; Pécskay et al., 2007).

The Quaternary is present as Pleistocene piedmont deposits and Holocene alluvial, colluvial and eolian deposits (Cabaleri et al., 2005).

Morphology and locations

In three distinct locations pyroclastic successions intruded by irregular mafic dykes have been identified (Figure 1). Along the Rio Chubut, near Paso de Indio, a small hill side (D1 on Figure 1B) exposes alkaline basaltic rocks rich in mantle xenoliths of lherzolitic composition (Figures 1B, C). The hill is about 100 m across, circular, and an irregular shaped dyke crops out at its center (Figures 1B, C). The dyke has an irregular contact with pyroclastic successions, which form a collar-like distribution patter. About 50 km north of this locality, at least eight circular hills of pyroclastic rocks (D1 and D2 on Figure 1B) cut by mafic intrusions form volcanic pipe-like features, which stand about 100 m above the surrounding desert floor (e.g. Figure 1D). These locations are surrounded by plateau lava fields, preserving the syn-eruptive surface about 200 m above these hills. In the northern studied location, a large neck (called Gorro Frigio) of alkaline basalt, containing crustal xenoliths, intruded into late Jurassic and Cretaceous sediments (Figure 2A). The neck is subcircular in shape, *ca.* 600 m across and stands 180 m above the surrounding surface (Figure 2A). It has a generally sharp contact with the sedimentary host rock and is also composed of pyroclastic rocks intruded by dykes with peperitic margins (Figure 2B). The pyroclastic succession is rich in angular shaped fragments of sandstone from the Cretaceous terrestrial sedimentary units (Figure 2C).

These pyroclastic pipes cut through Cretaceous continental siliciclastic sedimentary rocks, and they are commonly interconnected with dykes (Figure 1D), that are exposed and traceable on the desert floor. The dykes commonly have sharp boundaries and en-echelon-like steps are prominent in aerial and satellite photographs (Figures 1D, 3). These dykes commonly terminate in pipe-like pyroclastic rocks (Figures 2 and 3). The northernmost site of the studied area is complex and associated with SE-NW trending dykes that make a slight turn in ESE-WNW direction showing a clear relationship between the dyke and the exposed pyroclastic successions forming an approximately 400 m long volcanic complex (Figures 1D, 3). The studied site at D2 is a dual hill slightly elongated in a ESE-WNW direction (Figure 1D). In the eastern site, the volcanic complex preserves a narrow veneer of pyroclastic rocks connected to the ESE-WNW-trending dyke and forms a small hill (Figure 1D). However, the western site exposes a more complex dyke-pyroclastic pipe architecture (Figures 1D, 4). Here the hill is volumetrically dominated by pyroclastic rocks that were intruded by the ESE-WNW-trending dyke, which forms a bulbous upper zone of ponded sill-like intrusive (Figure 4). Between the two pyroclastic-dominated hills, a connecting dyke makes an approximately 100 m long ridge where the dyke intruded Cretaceous sedimentary rocks. A characteristic peperitic zone (Figure 3) occurs adjacent to the chilled margin of this dyke.

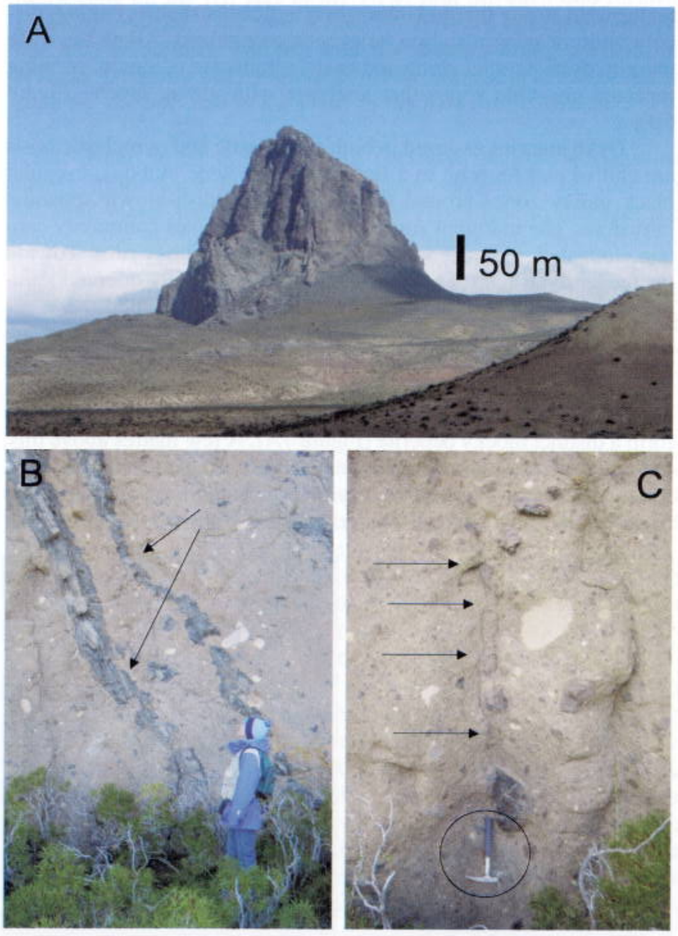

***Figure 2** Overview of the D3 diatreme (A) standing 200 m above the surrounding landscape. Irregular-shaped peperitic dykes (arrows) intrude into diatreme-filling pyroclastic units (B). The pyroclastic unit is rich in accidental lithic fragments from the host sedimentary successions (C). Arrows point to vertical clast alignment in the pyroclastic diatreme-filling succession.*

***Figure 3** Overview of a diatreme (D) group (D2 on Figure 1B) connecting to dykes cross-cutting the desert floor (arrows).*

***Figure 4** Overview of a large pyroclastic rock-dominated hill (D2b) cross-cut by a dyke (dark zones) that forms bulbous ponded lava topping the hill.*

Pyroclastic rocks

Description

Coarse-grained lapilli tuff and tuff successions are exposed in each of the studied locations. In the southernmost exposure (Figures 1C, 5A), the volume of the exposed lapilli tuff and tuff succession is small, and they are predominantly composed of angular, glassy, basaltoid lapilli with low vesicularity (Figure 5B). The lapilli-sized juvenile fragments are commonly angular, and they are glassy, in spite of the microlite content (Figure 5B). The ash-sized particles are glassy but advanced palagonitisation is prominent. Siliciclastic rock fragments as well as quartz pebbles and sand apparently represent accidental lithic fragments derived from the surrounding country rocks. This locality is rich in angular to ovoid-shaped lherzolite nodules, up to 10 cm in diameter. Angular crystal fragments of olivine and clinopyroxene from these lherzolites are common, although alteration is advanced in many cases.

Lapilli tuff and tuff breccia successions in the northern study sites (Figure 1D) are common; however, their textural characteristics are different from the rocks of the southern sites. The exposed pyroclastic rocks are unsorted and largely composed of moderately to non-vesicular basaltoid ash and lapilli (Figure 5C). The lapilli-sized fragments are commonly vesicular with vesicles being rounded to elongate in shape, frequently filled by calcite. The juvenile fragments are glassy or have characteristic glassy rims a few mm in thickness. The pyroclastic rocks contain fine sand and silt in their matrix, and occasional lapilli to block-sized sandstone fragments (Figure 5D). The intact sandstone fragments still preserve their bedding structure; however, their margins are often rounded and original bedding in this marginal zone is destroyed. The pyroclastic rocks of this site lack lherzolite nodules and/or megacrysts. No bedding, stratification or vertical clast alignments were observed in any of the described pyroclastic rocks (Figure 5C).

Interpretation

The pyroclastic rocks described above are interpreted to be conduit filling, massive pyroclastic breccias. The low vesicularity of the juvenile pyroclasts, as well as their chilled textural character indicates they formed by phreatomagmatic fragmentation driven by magma/water interactions. Sandstone and quartzofeldspatic mineral phases are interpreted to be accidental lithic fragments disrupted by the phreatomagmatic explosions from the surrounding conduit wall. The textural characteristics of these fragments are similar to the rocks of the Cretaceous terrestrial sediments, suggesting that the explosions took place in these units. The moderate vesicularity and slightly bulbous to angular shapes of the pyroclasts indicate that magma vesiculation was in its initial stage upon phreatomagmatic fragmentation of the magma. The relatively low proportion of accidental lithic fragments in the tuff breccias suggests that the transportation of these pyroclasts took place in a relatively open conduit, possibly during the final stage of the eruptions, when the volcanic conduit was established and stable, and therefore not prone to significant conduit wall collapses.

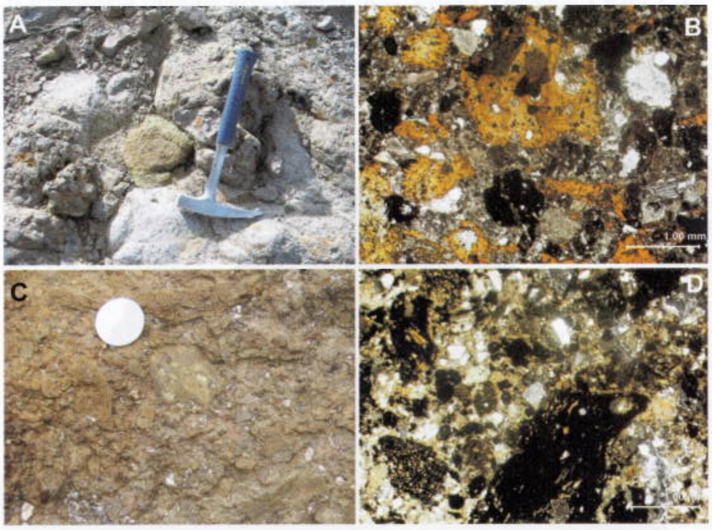

***Figure 5** A) Low vesicularity volcanic lithic lapilli and lherzolite nodules are characteristic for the pyroclastic rocks preserved in the southernmost diatreme. B) Weakly vesicular lapilli tuff forming the main mass of the fragmented volcanic rocks preserved in the southern diatreme, rich in angular glass shards (light grey fragments). C) Pyroclastic succession of massive lapilli tuff preserved under bulbous dyke in the D2 diatremes. D) Moderately vesicular glassy pyroclasts of the diatreme-filling lapilli tuffs.*

Dyke-host sediment interfaces

Description

Contact features between dyke and host sediment (either siliciclastic or pyroclastic) are exposed in the volcanic pipe-like structures in the north (Figure 6A). The two characteristic circular hills are connected by a narrow ridge, about 100 m long, formed by an irregular, dm-to-m wide dyke. This ridge is about 30 m below the level where pyroclastic breccia is well exposed in the westernmost volcanic hills. The dyke has a chilled margin between cm and dm in width (Figure 6A), which is very irregular, commonly bulbous, and detached mm-dm size fragments of the chilled dyke are hosted in the surrounding fine sandstone (Figure 6A). Along the dyke rim, in the exposed sandstone sections, bedding or stratification of the host sedimentary rock is disturbed, and the sandstone shows an homogenised texture. No strong thermal interaction indicators such as baking, discoloration or mineralization have been recognized. Along the dyke margin, dyke-parallel elongated vesicle trains are common, forming repeated cm-wide zones that alternate with glassy layers (Figure 6B).

Dyke margins exposed in both siliciclastic and pyroclastic hosts are chilled and form up to a few centimetre wide bulbous, irregular black glassy zones around the otherwise reddish-brown aphanitic intrusions. The marginal zones of the feeding dykes commonly contain elongated, mm-size vesicles just below the glassy rims. Toward the feeder dyke centres more pronounced horizontally oriented jointing pattern and a general massive texture is characteristic.

The dyke and host pyroclastic breccia interaction textures are observed within the three distinct pyroclastic material dominated hills (Figure 7). In lower exposures the dyke intrudes into the host siliciclastic sediment and along its margin large blocks of dyke fragments form a distinct blocky peperite (Figure 7A). A few metres above this, the dyke clearly intrudes the pyroclastic breccia into which large, metre-size, elongated, detached dyke fragments form peperitic zones (Figure 7B). Finger-like, irregularly shaped lobes of low vesicularity

***Figure 6** A) Irregular peperitic (P) contact of dyke (D) hosts Cretaceous siliciclastic sediments between the two diatremes of D2. B) Chilled peperitic (P) dyke margin with aligned vesicles (arrow) at the D2 diatreme site.*

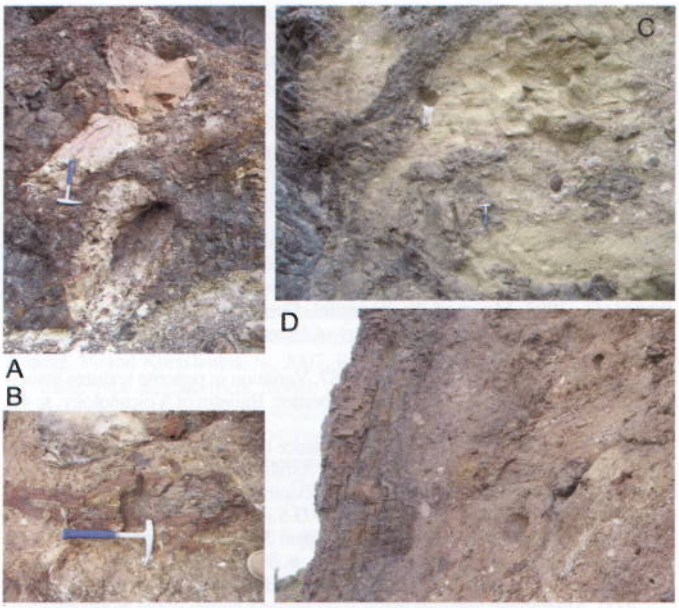

Figure 7 A) Dyke margin (dark zones) close to the interface between the pyroclastic and siliciclastic (white zones) host in the D2 diatremes. B) Elongated fluidal detached dyke finger (next to hammer) in the pyroclastic breccia. C) Siliciclastic matrix rich zone in the pyroclastic breccia (grey zone) as a host in the dyke (dark zone on the left side of the view) that intruded and formed globular peperite. This zone is near the inferred interface between the host siliciclastic conduit and the conduit-filling pyroclastic breccia. D) Sharp but irregular peperitic margin of the dyke (dark zone on the left side of the view) in the pyroclastic breccia.

basalt, meters in length, form closely packed pyroclastic breccias that clearly differ from the host pyroclastic succession, of vesicular basaltoid clasts and fine matrix (Figure 7B). Close to the interface between the irregular margin of the host siliciclastic and pyroclastic rocks, elongated protrusions form globular peperitic zones (Figure 7C). At the interface of the dyke and pyroclastic host, white sand and silt form irregular halos cm-to-dm in width. The dyke margins in the upper pyroclastic host breccia are sharp but irregular (Figure 7D).

Interpretation

Mingling of host siliciclastics with the diatreme-filling pyroclastic sediments indicates the host units were water saturated and at least partly unconsolidated (Brooks, 1995; Doyle, 2000; Dadd and Van Wagoner, 2002). The contact features of dykes and host sediment regardless of its composition (pyroclastic or siliciclastic) are interpreted to be peperitic, using peperite as a genetic term (White et al., 2000; Skilling et al., 2002; Németh and Martin, 2007). The bulbous contact between dykes and terrestrial sediments indicate globular peperite formation which is probably controlled by the grain size of the host sediment (Busby-Spera and White, 1987). The larger entrapped milled sandstone fragments in the dykes, as well as in the nearby marginal zone of the dykes intruded into pyroclastic host, indicate detachments of larger siliciclastic sedimentary blocks from a soft and wet host (Busby-Spera and White, 1987; Hooten and Ort, 2002). Sections of fragmented country rocks may collapse or slide into the partially evacuated root zone forming subterranean peperites associated with a diatreme (Hooten and Ort, 2002; Lorenz et al., 2002). The relatively intact shape of such blocks suggests that the country rock succession might have been inhomogeneously water saturated and/or partially consolidated. Alternatively, the heat of the intruding dykes may lead to the formation of dry zones along the conduit, which may have acted in a brittle fashion against the mechanical stress generated by the subsequent dyke intrusion. Such processes have been inferred from dykes and sills initiated from a lava lake emplaced in a tephra ring crater (c.f., Martin and Németh, 2004, 2007). Lack and/or changing position of further explosions across the diatreme pipe, but continued rise and intrusion of magma, caused emplacement of peperite masses as plugs as inferred from other diatreme settings (c.f., Lorenz et al., 2002).

Close to the feeder dykes there are zones of mixed basalt/sediment breccias showing features of basalt/sediment mingling in the liquid state. The intimate mingling took place between basalt lava and fluidized sedimentary material regardless of its composition or grain size. The mm-m scaled mingling between dykes and the host siliciclastic sediments resulted in the transportation of larger sedimentary clasts deep into the pyroclastic material-dominated zones that are connected to zones of siliciclastic sediment-rich channels, indicating ongoing fluidization during the emplacement of the dykes.

The master feeder dykes are commonly traceable for tens of kilometres across the desert floor. Individual curved sections of these dykes form an en-echelon array where diatremes are seemingly located in the major steps between dyke segments. This geometry indicates a possible relationship between diatreme formation, and structurally and rheologically controlled syn-eruptive hydrogeology of the host rock similar to other well-known phreatomagmatic volcanic fields such as the Eifel in Germany (c.f. Lorenz, 1984; Büchel, 1993).

Diatreme field in Northern Patagonia

The volcanic pipe-like features identified in Northern Patagonia, mainly composed of pyroclastic and intrusive rocks, are interpreted as exhumed, strongly eroded volcanic diatremes (Lorenz, 1986; White, 1991). The common relationship between long dykes and the locations of diatremes suggests phreatomagmatic volcanoes developed at hydrogeologically active zones along the strike of the dykes during their emplacement. The lithofacies characteristics of the exposed volcanic rocks are consistent with features of a lower diatreme seen in similar rock associations at Hopi Butte, Arizona (White, 1991). This implies a large amount of erosion has taken place to expose the facies relationship between in situ pyroclastic breccias which formed by phreatomagmatic fragmentation of the magma and subsequently intruded dykes and sills. The volcanic successions inferred to be conduit-filling pyroclastics are associated with intra-vent peperites. The closely spaced two diatremes in the northern study site are connected by a narrow, but irregularly shaped dyke that intruded into the host siliciclastic succession. Along the contact zone of this dyke, a wide peperitic contact formed. The peperitic dykes and the location of the pyroclastic rocks intruded by the same dyke indicate a close relationship between dyke intrusion and the development of peperite as well as phreatomagmatic pyroclastic rocks. This suggests that the present level of exposure represents more or less the level of phreatomagmatic fragmentation initiated in the pre-volcanic sedimentary succession.

The 3D relationship between the locations of the dykes and the surrounding plateau-like lavas suggests that the present day exposures are at least 200 m below the surface zones of former volcanoes. Because erosion removed the former volcanic edifices, we cannot give further details of the style, size and distribution pattern of volcanic landforms that may have been associated with the described lower diatremes. Recent work has also demonstrated that intra-sedimentary debris jets could form in continental phreatomagmatic volcanoes (Ross and White, 2006). The resulting subterranean deposits are documented and expected to be very similar to those of deposits formed at the surface. Therefore the recent discovery in Northern Patagonia suggests magma/water interaction, where both non-explosive peperite and explosive debris jet-forming events occurred during dyke intrusions through wet and unconsolidated siliciclastic and pyroclastic country rocks.

The identification of diatremes associated with Northern Patagonian flood lava fields indicates that phreatomagmatism is likely a common process associated with flood lava volcanism as has been postulated on the basis of the Karro-Ferrar Provinces (Ross et al., 2005; Ross and White, 2005a; McClintock and White, 2006). However, the present erosion state of the volcanic fields in Patagonia does not allow for further interpretations of the style and timing of phreatomagmatism in relationship to the formation of the extensive lava fields. The lack of comprehensive studies of the volume and duration of the Patagonian Cenozoic flood lava volcanism also hinders further interpretations with regard to the scale of the volcanism. At present, it seems that the extra-Andean lava fields are associated with the formation of distinct volcanic fields that were active for long periods of time, with a relatively low magmatic output rate. These fields may be dominated by either phreatomagmatic activity, similar to Pali Aike in South Patagonia (D'Orazio et al., 2000; Corbella, 2002; Haller et al., 2005) or lava effusion similar to Crater Basalt in Northern Patagonia (Massaferro et al., 2006; Pécskay et al., 2007).

Conclusion

In this short note we identify a volcanic episode that occurred during the formation of the older (Oligocene/Miocene) Patagonian extensive lava fields, when driven volcanic processes, driven by magma/water interaction, surely accompanied ongoing effusive volcanism. The identification of peperite along irregular dyke margins intruded into Cretaceous terrestrial sediments suggests that those sediments were still loose and water saturated. The exposed pyroclastic successions document phreatomagmatic explosive events driven by magma/water interactions. These successions also indicate a water saturated state for both the host terrestrial and conduit-filling pyroclastic sediments upon intrusion by subsequent feeder dykes which led to the formation of peperite. The identification of these pyroclastic successions, however, does not necessarily mean that surface manifestations such as maars and tuff rings existed over these volcanic pipes. They also could represent only subterranean deposits formed by debris jets generated by subterranean explosions in the unconsolidated and water saturated country rock units (Lorenz et al., 2002; Ross and White, 2005b; Ross and White, 2006; Lorenz and Kurszlaukis, 2007). However, the large volumes of moderately vesicular, angular and glassy juvenile lapilli in the volcanic conduit-filling deposits suggest that the phreatomagmatic fragmentation generated enough energy to form an open conduit relatively quickly that was then filled by the pyroclasts and therefore potentially connected to a maar or tephra ring volcano at the surface. Here we demonstrated that the studied volcanic fields in Chubut were formed by more complex volcanic processes than just dyke-fed effusive events. Large numbers of apparently similar volcanic pipes can also be identified from satellite images, which may suggest the existence of an extensive diatreme field in the Chubut area. This discovery highlights the need for further investigations in the area to refine the eruptive mechanism of the Patagonian Cenozoic volcanism.

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