Journal of Volcanology and Geothermal Research 184 (2009) 351–366

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

A late-Ordovician phreatomagmatic complex in marine soft-substrate environment: The Crozon volcanic system, Armorican Massif (France)

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ARTICLE INFO

Article history:
Received 9 October 2008
Accepted 4 May 2009
Available online 7 May 2009

Keywords:
volcanic breccias
phreatomagmatism
peperite
Ordovician
Armorican Massif

ABSTRACT

The mafic lavas and the diabases of Crozon (Armorican Massif, France), belong to an anorogenic Ordovician volcanic complex, emplaced on a rifted passive margin in North Gondwana. Magma passed through syn-volcanic soft sedimentary substrate, which is today mostly composed of alternating sandstones and mudstones, from Llanvirn to Ashgill in age. Field observations together with microscopic studies and geochemical analyses of magmatic rocks lead us to propose a model of volcano formation which combines hydromagmatic processes, peperitic intrusions, a shallow submarine tephra settling, eruption-fed turbidity currents, and a pillow lava effusion. The Crozon outcrops can be used to reconstruct a complete cross-section from the root of the volcanic complex to the lavas and breccias emplaced on the sea floor. The sites expose: (i) a hypabyssal breccia containing mud chunks and coarse-grained diabase clasts with amoeboidal fine-grained magmatic material; (ii) bulbous peperitic sills and pillow-like lobes bearing a great quantity of sediment-derived enclaves of fluidal morphology; (iii) volcaniclastic breccias containing near-spherical magmatic clasts that resulted from the complete fragmentation of sills in the ductile regime; (iv) a rhythmic peperitic breccia interpreted as the product of mingling between thin lava flows and soft calcareous sediment. The Crozon volcanic form, resulting from explosive interaction with subsurface/surface water, was probably a subaqueous collapsed tuff cone. This upper part of the system is synchronous with an Ashgill carbonate sedimentation, which overlies an Ordovician siliciclastic succession deposited in shelf environments.

1. Introduction

Processes and products of magma–sediment mingling (peperite) and maar–diatreme volcanism have been the subjects of two Special Volumes of *Journal of Volcanology and Geothermal Research*, respectively Skilling et al. (2002a) and Martin et al. (2007). This illustrates the recent renewal of most of the concepts associated with both themes. The application of fuel–coolant interaction (FCI) theory is appropriate for interpretation of both peperite and maar–diatreme structures (Wohletz, 2002). Magma/wet sediment interactions involve heat transfer over a wide range of rates from mingling to explosive fragmentation. Fluidal peperite results from the development of a vapor-film layer at the magma–sediment interface, acting as an insulating barrier. Explosive fragmentation occurs when the vapor film becomes unstable. The behavior of the vapor film is mainly controlled by the sediment characteristics, the hydrology, and the mass interaction ratio of wet sediment and magma. Wohletz (2002) suggested that the higher the ratio then the more unstable will be the vapor films around the hot magmatic clasts. According to Skilling et al. (2002b) and Templeton and Hanson (2003), fluidization is more efficient and vapor films are more stable when magma interacts with fine-grained, well-sorted, and loosely packed sediment. Some peperites are inferred to record frozen FCI coarse mixing-stage and thus, the mixing geometry recorded might be related to the processes governing the pre-explosive coarse mingling phase of FCI explosions (Hooten and Ort, 2002).

Inverted-cone-shaped diatremes are substructures typical of subaerial phreatomagmatic centers. They are filled with clastic debris derived from the surrounding rocks, juvenile clasts and subsided blocks, and they are typically cut by intrusive magmatic bodies (Martin et al., 2007). The volcanic forms classically associated with diatremes in subaerial environments are maars (tuff rings). Following White (1996), below sea level eruptions mainly result in either tuff cones (vigorous magmatic injection, persistent interaction of magma with sediment-laden coolant and explosivity) or pillow lavas (weak magmatic effusion, persistent interaction of magma with pure-water coolant and no explosivity). Although not excluded, diatreme formation in subaqueous environment has never been clearly established.

Within the early Palaeozoic sedimentary succession of the North Gondwana margin, the Upper Ordovician of the Medio-North-Armorican

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doi:10.1016/j.jvolgeores.2009.05.002

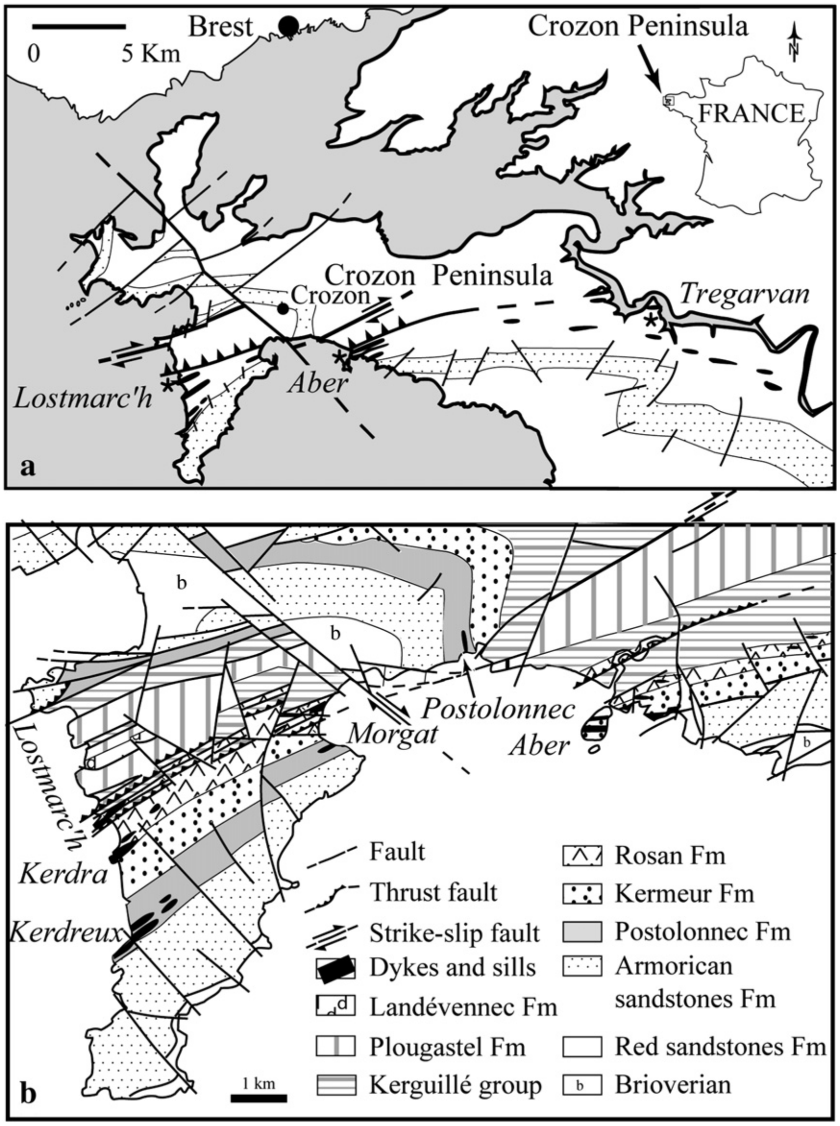

Fig. 1. Geological maps and location of the studied outcrops. (a) Simplified structural sketch of the Crozon Peninsula (Armorican Massif, France). (b) Geological map of the southern part of the Crozon Peninsula (modified after Chauris and Plusquellec, 1975, 1979), with location of the volcanic outcrops.

Domain (Western France) has been affected by an anorogenic volcanism, which is particularly well exposed in the Crozon Peninsula (Fig. 1). The four main interesting aspects of the Ordovician hypabyssal/volcanic exposures of Crozon consist in (i) the existence of several outcrops displaying features characteristic of the ancient volcanic substructure, such as normal faults, hydrothermalism, hypabyssal breccias and intrusions, (ii) the occurrence of a very well-developed set of fluidal peperites, (iii) the presence of unusually abundant sediment-derived enclaves and clasts within sills and breccias, respectively, and (iv) the existence of calcareous levels, located at key positions in the volcanic succession, which offer valuable pieces of information on the deposit environment and depth.

2. Geological context and lithostratigraphy

The Crozon Peninsula displays a remarkable Palaeozoic sedimentary succession, from Brioverian (Upper Precambrian–Lower Palaeozoic) to upper Devonian. It is made up of two structural domains, the North Crozon domain locally overthrusting the South Crozon one (Darboux and Rolet, 1979; Rolet et al., 1984; Fig. 1a). Both domains were clearly part of the same palaeogeographic area and recorded the same palaeontological and sedimentary events (Robardet et al., 1994; Paris et al., 1999), except at the base and the top of the sedimentary piles where differences exist. The northern zone was probably located less than 30 km from the southern one during Ordovician, as shown by a palaeotectonic reconstruction (unpublished). In the South Crozon area, the unconformable Palaeozoic succession starts with conglomerates and red siltstones, underlying the Armorican Sandstones (Fig. 2), whereas in the North, this latter formation rests directly on Brioverian. In both domains, Armorican Sandstones are overlain successively by Postolonnec (mudstones) and Kermeur (mainly sandstones) Formations (Llanvirn to Caradoc ages, *sensu* Fortey et al., 1995). Volcanics and limestones of the Rosan Formation (Ashgill) outcrop in the South domain only, overlain by Hirnantian sandstones (Plusquellec et al., 1999; Fig. 2). In the North area, sandstones of the Kermeur Formation are directly overlain by Hirnantian glacio-marine deposits (Bourahrouh, 2002). From Middle (mainly Llanvirn) to Upper (Ashgill) Ordovician, the South Crozon sedimentary succession contains many hypabyssal and volcanic rocks (Fig. 2): breccias and sills in the Postolonnec Formation (mainly Llanvirn), sills and dykes in the Kermeur one (Caradoc), and breccias, sills, and pillow lavas in the Rosan Formation (Ashgill).

The present study focuses mainly on four sites located on Fig. 1b: i) Kerdreux, where sills and a hypabyssal breccia crop out within the