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40 Abstract

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RESEARCH ARTICLE

Basaltic maar-diatreme volcanism in the lower carboniferous of the limerick basin (Southern Ireland)

H. A. L. Elliott[1] · T. M. Gernon[1] · S. Roberts[1] · C. Hewson[2]

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Abstract Lead-zinc exploration drilling within the Limerick Basin (Southern Ireland) has revealed the deep internal architecture and extra-crater deposits of five alkali-basaltic maar-diatremes. These were emplaced as part of a regional north-east south-west tectonomagmatic trend during the Lower Carboniferous Period. Field relationships and textural observations suggest that the diatremes erupted into a shallow submarine environment. Limerick trace element data indicates a genetic relationship between the diatremes and extra-crater successions of the Knockroe Formation, which records multiple diatreme filling and emptying cycles. Deposition was controlled largely by bathymetry defined by the surrounding Waulsortian carbonate mounds. An initial non-diatreme forming eruption stage occurred at the water-sediment interface, with magma-water interaction prevented by high magma ascent rates. This was followed by seawater incursion and the onset of phreatomagmatic activity. Magma-water interaction generated poorly vesicular blocky clasts, although the co-occurrence of plastically deformed and highly vesicular clasts indicates that phreatomagmatic and magmatic processes were not mutually exclusive. At a later stage, the diatreme filled with a slurry of juvenile lapilli and country rock lithic clasts, homogenised by the action of debris jets. The resulting extra-crater deposits eventually emerged above sea level, so that water ingress significantly declined, and late-stage magmatic processes became dominant. These deposits, largely confined to the deep vents, incorporate high concentrations of partially sintered globular and large 'raggy' lapilli showing evidence for heat retention. Our study provides new insights into the dynamics and evolution of basaltic diatremes erupting into a shallow water (20–120 m) submarine environment.

Keywords Raggy · Maar-diatremes · Lower Carboniferous Period Q2

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Q1

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Introduction

Maar-diatremes are formed during explosive eruptions and are pre-dominantly associated with alkaline magmas including kimberlites, lamproites, and alkali basalts. Our knowledge of the behaviour of these systems is based mainly on the study of either extra-crater maar or eroded diatreme deposits. Due to their association with diamonds, kimberlites are well studied, contributing a large amount to our understanding of diatreme eruptions and their associated deposits (Mitchell 1990; Sparks et al. 2006; Walters et al. 2006; Brown et al. 2008a). In addition, maar-diatremes, although the second most common type of volcano (Lorenz 1985; Cas and Wright 1988; Lorenz 2007), tend to be eroded and poorly preserved in older sequences. In rare cases, exposures of the lower diatreme zone enables detailed investigation of the internal architecture and structure of the system (e.g., Francis (1970), Hawthorne (1975), Kurszlaukis and Lorenz (1997), Davies et al. (2008), Gernon et al. (2013), Lefebvre et al. (2013), and Mundula et al. (2013)) or preservation of extra-crater tephra deposits allow a detailed insight into depositional processes (e.g., Fisher and Waters (1970), Aranda-Gómez and Luhr (1996), Sohn (1996), Gernon et al. (2009a), Calvari and Tanner (2011), and Lefebvre et al. (2013)). Rarely can the maar-crater and diatreme facies be studied at a single site.

Diatremes are irregular, cone-shaped pipes up to 2.5 km deep, that erupt through country rock stratigraphy (Lorenz 2003; Valentine 2012). Different volcaniclastic lithofacies characteristically form at different levels in the diatreme (see Fig. 1); for example, the root zone consists of a series of intrusions 'feeding' diatreme eruptions. Typically, the central zone (Fig. 1) is characterised by a massive volcaniclastic infill consisting of accumulated pyroclasts, crystals and country-rock lithic debris trapped in the pipe (Sparks et al. 2006). Diatremes are expressed at the surface as maar-craters and tephra rings, typically comprising bedded dilute pyroclastic density current (PDC) and fallout deposits (Lorenz 1975). There are two plausible methods for the presence of bedding in the upper diatreme. Firstly, undercutting of the tephra ring by vent widening and subsequent subsiding can form a marginal bedded facies, commonly comprising megablocks (Sparks et al. 2006; Lorenz and Kurszlaukis 2007; Brown et al. 2008b; Valentine and White 2012). Alternatively, the upper thinly bedded diatreme facies may have been deposited by dilute density currents in the base of the maar-crater, originating from the same or neighbouring vents (Lorenz 1986; Lorenz and Kurszlaukis 2007; Gernon et al. 2009a; Gernon et al. 2013; Delpit et al. 2014).

Two key models have been proposed to explain the emplacement of diatremes. The first, common in kimberlitic diatreme models, involves the explosive expansion of volatiles propagating down rising intrusions. This creates a deep pipe resulting from a series of sub-Plinian to Plinian eruptions (Field and Scott Smith 1999; Sparks et al. 2006; Porritt et al. 2008). The second model involves diatreme excavation during phreatomagmatic eruptions as magma propagating to the surface encounters water (Lorenz 1985; Kurszlaukis and Lorenz 1997; Kurszlaukis et al. 1998; Lorenz and Kurszlaukis 2007; Brown et al. 2008a).

Phreatomagmatic activity can cover a range of eruption styles with varying water to magma ratios. The two main end members are briefly described here but many eruptions lie somewhere along this scale. The first consists of eruptions that involve magma explosively interacting with groundwater or wet sediment, with a low water to magma ratio of <0.3 (Wohletz and McQueen 1984; Moore 1985; Kokelaar 1986), producing gas-supported jets of debris (cf. Lorenz et al. (2002) and McClintock and White (2006)). These are often referred to as 'Taalian' (Kokelaar 1986; Sohn 1996) and tend to be continental eruptions that form deep diatremes filled with volcaniclastic debris,

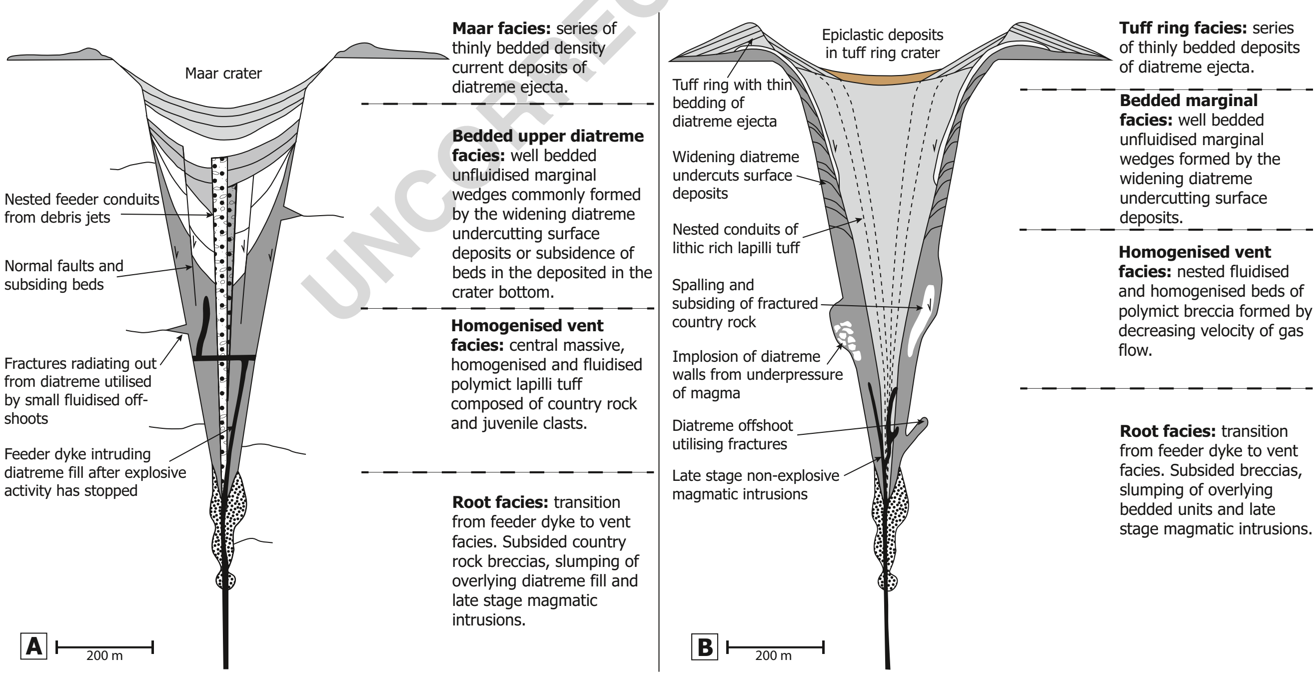

Fig. 1 **A** Schematic diagram showing the root, diatreme and maar-crater zones of a typical phreatomagmatic diatreme (modified after Lorenz and Kurszlaukis (2007)). **B** Schematic diagram showing the structure of a diatreme dominated by magmatic processes, which typically involve multiple events of waning gas velocity due to progressive diatreme widening and/or decline in magma discharge rates (modified after Brown et al. (2008b))

brecciating the surrounding country rock and incorporating these lithics into their maar deposits at the surface (White 1991; Lorenz et al. 2002; Valentine 2012). These maars can reach up to 5 km in diameter with craters several hundred metres deep. Maar deposits tend to be of shallow gradient and consist of well-developed beds and stratification with a high proportion of country rock clasts (Lorenz 1975; 2007; White and Ross 2011).

Surtseyan eruptions are at the other end of the spectrum, involving a high water to magma ratio of ~0.3-50 (Wohletz and McQueen 1984; Kokelaar 1986). This tends to produce a funnel-shaped vent containing a partially fluidised and highly mobile mix of juvenile material, water and steam termed a 'slurry' (Kokelaar 1983; Moore 1985; Ross and White 2006). Phreatomagmatic eruptions in these conditions consist of shallow short-lived pulses of tephra jets and continuous eruptions that form due to injection of magma into this water-saturated and fluidised slurry, which is rapidly flashed-heated to steam (cf. Kokelaar (1983) and Moore (1985). Surtseyan eruptions tend to form weakly bedded tuff cones with steep flanks (White 1996; Mattsson et al. 2005; White and Ross 2011) and less than a few percent of non-juvenile clasts (White and Ross 2011). These tuff cones tend to sit on a shallowly dipping platform of volcaniclastic material, commonly composed of non-explosive deposits such as pillow lavas and hyaloclastites (Moore 1985) or a combination of fallout and density current deposits from both magmatic and phreatomagmatic processes (Brand and Clarke 2009).

A suite of alkali basaltic diatremes occurs within the Limerick Basin, part of the Irish Orefield, host to world-class lead-zinc deposits (Banks et al. 2002; Redmond 2010; McCusker and Reed 2013). The Limerick Basin has recently undergone extensive mineral exploration, and borehole drilling has intersected several alkali basaltic diatremes. The drill cores, some extending to >500 metres below ground surface (mbgs), provide a unique opportunity to study deposits and the eruptive processes of basaltic diatremes.

This paper describes the volcaniclastic lithofacies, as observed in drill core, of two of the five identified alkali basaltic maar-diatremes from Limerick, and interprets these observations in the context of the magmatic and phreatomagmatic models outlined above. A model depicting a clear relationship between the diatremes and a thick sequence (up to 150 m) of extra-crater volcaniclastic deposits is proposed. This is a type locality for studying the deep internal structure of basaltic diatremes, with the potential to enhance our understanding of processes and interactions during explosive eruptions within a submarine environment.

Geological and geotectonic setting

The Limerick diatreme cluster is located in the western midlands of Ireland, immediately south of the trace of the Iapetus suture zone (Fig.2a)—a series of major NE-SW trending faults, known to have exerted a strong influence on later tectonomagmatic activity. The diatremes erupted through a sequence of Lower Carboniferous limestones, later overlain by pyroclastic deposits of Viséan age (Somerville et al. 1992). These deposits form part of the Limerick Syncline and are offset by a series of NE-SW-trending faults. This igneous activity is part of a major phase of NE-SW trending regional rifting across Europe during the Carboniferous Period (Woodcock and Strachan 2000; Wilson et al. 2004). Volcanism in Limerick was similar in style and timing to magmatic and volcanic activity in Scotland and Northern England, including East Fife (see Gernon et al. (2013)) and the Whin Sill Complex (Timmerman 2004) (Fig. 2a). The extensional regime resulted from episodic N-S back arc extension in response to a Variscan subduction zone to the south, which reactivated NE-SW trending Caledonian basement faults (Woodcock and Strachan 2000). As a result of crustal extension, small volumes of basaltic magma ascended and fractionated extensively within the upper crust before exploiting tectonic weaknesses to reach the surface (Holland and Sanders 2009).

The Limerick Basin is dominated by transgressive carbonates (Holland and Sanders 2009). The oldest country rock observed in the boreholes is the Lower Argillaceous Bioclastic Limestone (LABL), which occurs as lithic clasts within the diatreme fill. The LABL is overlain by the Waulsortian Limestone, a reef carbonate containing large cavities, with the latter thought to comprise over half the formation volume (Lees and Miller 1985; Hitzman 1995; Hitzman and Beaty 1996). Overlying the reef carbonate are the Lough Gur wackestones and cherts, the uppermost of which are interbedded with the Knockroe Formation, a series of lava flows and pyroclastic deposits (see Fig. 3) that migrate and therefore young from the west to the east (Strogen 1988; Holland and Sanders 2009). The earliest phases of Knockroe eruption are thought to be Surtseyan, initially within a submarine environment before tuff rings built up into a subaerial environment and were partially buried by subaerial basaltic lavas (Holland and Sanders 2009). Using microfauna, (Somerville et al. 1992) assigned a Lower Viséan to Chadian-Arundian age (345–339 Ma) to the Knockroe Formation. Irish Waulsortian-hosted Pb-Zn deposits are precipitated in hydrothermal breccia bodies (Wilkinson et al. 2005), termed Black Matrix Breccias (BMB), which appear to have a close spatial and temporal relationship with the diatremes in Limerick. The nature of this relationship remains unclear and highly controversial.

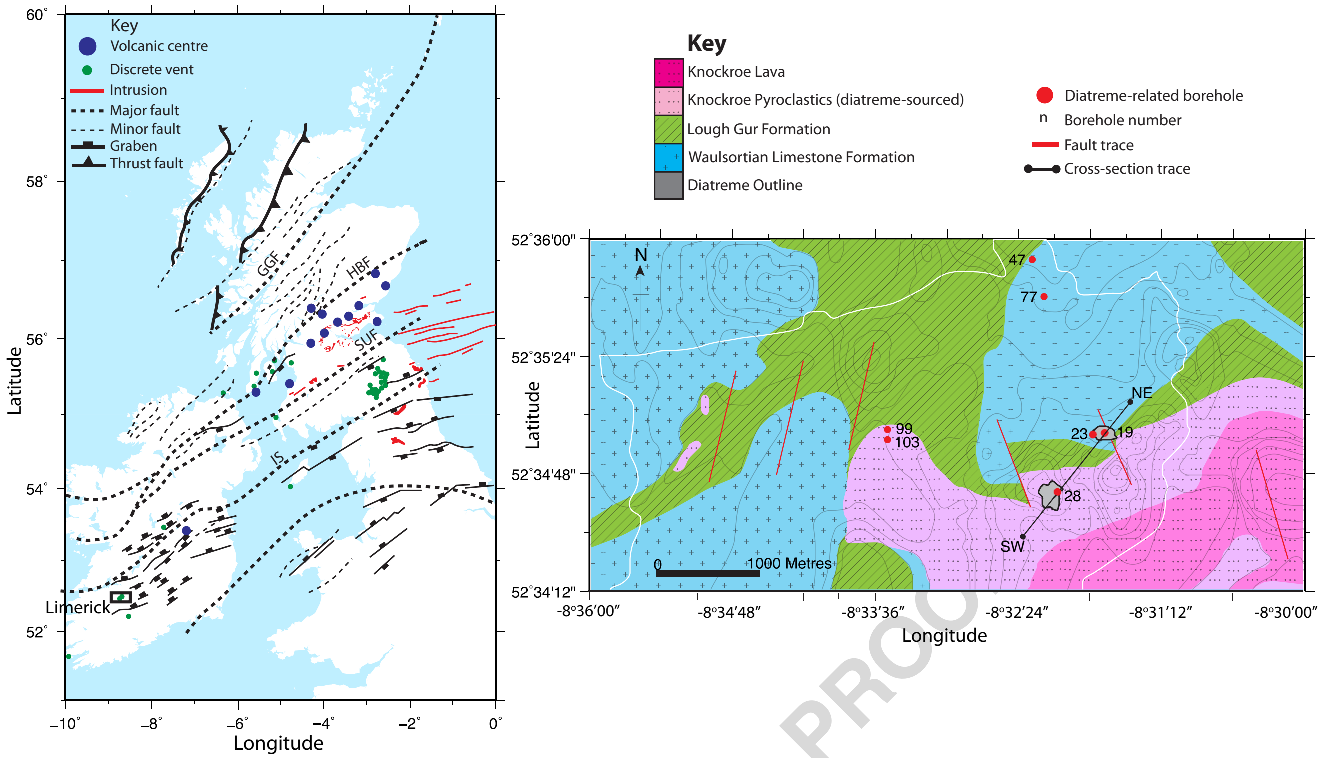

Fig. 2 **A** Regional map of the British Isles showing major NE-SW trending faults and significant volcanic centres. This tectonic and magmatic trend reflects reactivation of Caledonian basement faults by episodic N-S back arc extension related to the Variscan subduction zone to the south. *GGF*, Great Glen Fault; *HBF*, Highland Boundary Fault; *SUF* Southern Uplands Fault and *IS*, Iapetus Suture. **B** Summary geological map of the study area outlined by rectangle in (**A**), showing diatreme-related boreholes and outline of diatremes as resolved by magnetic surveys. Contours represent topography of study area

The Irish Orefield has not previously been linked to high levels of magmatic activity during the Carboniferous (Redmond 2010; McCusker and Reed 2013).

Previous studies

The first detailed description of the Limerick Basin was provided by Geikie (1897) and Ashby (1939) who correlated the diatremes they termed ‘vent-agglomerates’ to a younger Knockseefin Formation, which was deposited during the Early Asbian (Somerville et al. 1992). However, textural and geochemical evidences now suggest a strong relationship with the Knockroe Formation (see Fig. 5). Somerville et al. (1992) found that the Knockroe volcaniclastic rocks are interbedded with shallow water ooids and bioclastic carbonates, suggesting deposition in a shallow marine environment (Strogen et al. 1996). Strogen (1983,1988) determined that the Knockroe Formation pyroclastic rocks generally young from west to east and identified seven breccia-filled vents across the Limerick Basin. Strogen (1983) showed that these vents were filled with coarse vitric-lithic tuff-breccias containing clasts mainly of phreatomagmatic appearance (described as vitric incipiently vesicular lapilli and ash with curvi-planar surfaces and containing feldspar microphenocrysts) and lacking substantial quantities of vesicular tephra. Strogen (1983) attributed the homogeneity of the deposits, lack of bedding and presence of marginal layering to fluidisation processes during emplacement.

Methods and terminology

Fieldwork

Although there is a little surface exposure of diatremes in the studied area of Ballyneety, Limerick (Fig. 2b), six exploration drill cores intercepted diatremes and another six intercepted volcaniclastic rocks of the Knockroe Formation. Graphic logging recorded the characteristics of the volcaniclastic rocks including maximum clast length, clast composition, vesicularity, colour, angularity, degree of sorting, proportion of ash-grade matrix, alteration and textures. These characteristics were used

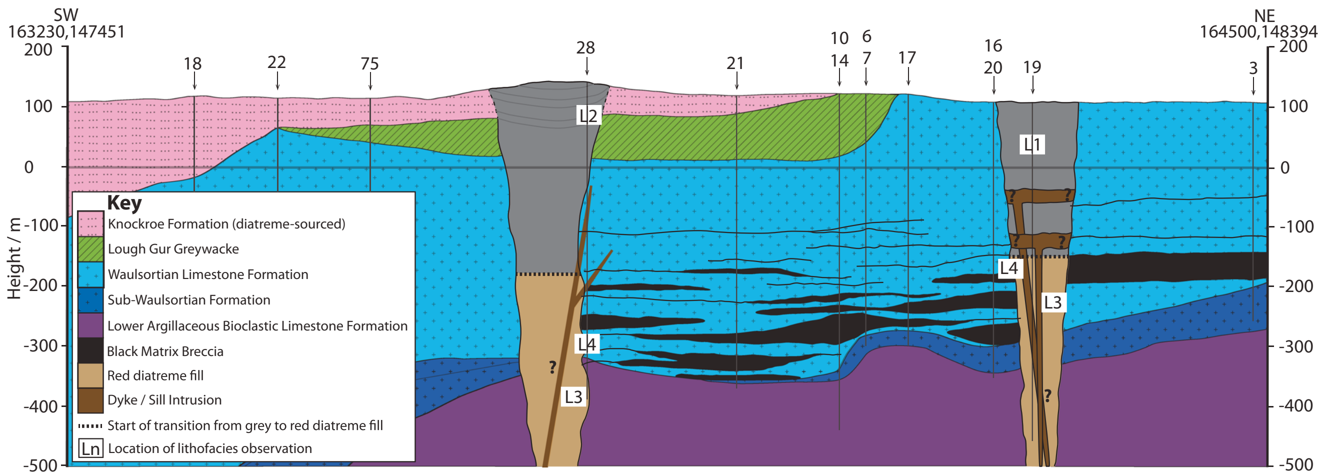

Fig. 3 Cross section showing the relationships between diatremes and the country rock sequence. The cross section shows the levels of BMB within the Waulsortian Formation and the level of major sills within the diatreme. Diatreme 28 does not intrude through the Knockroe Formation, but infills accommodation space created by the maar-crater. The lower section of the diatremes overprinted by dolomitisation are indicated. *Boxed numbers* indicate where LFAs described in Table 2 have been observed. *Numbers* indicate the locations of boreholes drilled through the sequence (borehole data courtesy of Teck Ireland)

to correlate lithofacies between logs, particularly for the Knockroe Formation where beds are more laterally continuous.

Laboratory work

Representative samples were taken from each lithofacies and thin sections investigated using transmitted light and scanning electron microscopy (SEM). A study of vesicle size distribution was performed on the different lithofacies.

Variations in vesicle proportions within a deposit or multiple vesicle populations within a juvenile clast can be used to elucidate magma evolution over the timescale of the eruption (Shea et al. 2010), and help to determine the eruptive style (Houghton and Wilson 1989; Ross and White 2012). Vesicularity estimates were made by manually digitising vesicles both in scaled photographs of thin sections and drill core. Vesicle measurements were obtained using image analysis software ImageJ and the protocols of Sahagian and Proussevitch (1998) and Shea et al. (2010). Non-vesicular lapilli are defined as 0–5 % and incipiently vesicular as 5–20 % vesicles, poorly vesicular ranges between 20 and 40 %, moderately vesicular 40–60 %, highly vesicular ranges between 60 and 80 % and >80 % vesicles is termed extremely vesicular (Houghton and Wilson 1989).

Trace element analysis was undertaken by solution ICP-MS on volcanic material repeatedly digested with HF and HCl and cross-referenced using several international standards (including BHVO2, BIR-1, JB-1a and JA-2).

Terminology

Clast types and sizes were described using the protocols outlined in Fisher (1961) and White and Houghton (2006). Terms used to describe diatreme deposits follow the procedure of Branney and Kokelaar (2002) and Lorenz and Kurszlaukis (2007). The term 'autolith' is used to describe clasts of pre-existing partially lithified diatreme fill, lapilli tuff or tuff, that have been incorporated into later deposits of similar composition (Cas et al. 2008). 'Pelletal lapilli' is a term used to describe a core of material, for example, an autolith, phenocryst or lithic clast, that was coated in single or multiple layers of juvenile magma (Gernon et al. 2012). We follow the terminology proposed by Ingram (1964) in describing bed thickness, grain size classification after (White and Houghton 2006) and degree of vesicularity of volcanic rocks after (Houghton and Wilson 1989). Lithofacies associations are named and abbreviated based on the non-genetic scheme proposed by Branney and Kokelaar (2002).

Drillcore observations and interpretations

Diatremes

Boreholes drilled down the margins and centres of five diatremes in the study area provide insights into diatreme architecture. The diatremes lack surface expression because the landscape has been modified by glacial and fluvial erosion during the quaternary period. The diatremes appear to have experienced late-stage fluid flow, forming a range of alteration products. Based on a magnetic survey, diatreme 19 (named from intersecting borehole number) has a minimum diameter of ~170 m and a surface area of ~1.3 $\times 10^4$ m^2, and diatreme 28 has a minimum diameter of ~240 m and a surface area of 2.6 $\times 10^4$ m^2 (see Fig. 2b). Measured wall angles vary between 42 and 83°, similar to the commonly observed range of 60–85° for diatremes emplaced in hard rock (Hawthorne 1975; Lorenz 2007). Assuming a maximum wall angle of 83° gives an estimated minimum volume of 5.2 $\times 10^6$ and 7.4 $\times 10^6$ m^3 for diatremes 19 and 28, respectively. Borehole drilling ceased at < 600 m; therefore, this volume is a minimum estimate.

Figure 3 shows diatreme 28 with adjacent rocks of the Knockroe Formation ~40 m thick. We attribute the Knockroe Formation to diatreme eruptions, based on their textural, petrological and geochemical similarities (see Fig. 5). The upper bedded lithofacies at the top of the diatremes, adjacent to the extra-crater Knockroe deposits (see Fig. 3), has most likely formed by debris currents, remobilisation of maar material and fallout from the water column, gradually filling up accommodation space within the maar-crater. Analogous crater deposition has been described by Lorenz (1986), Lorenz and Kurszlaukis (2007), Gernon et al. (2009a), Gernon et al. (2013) and Delpit et al. (2014). Diatreme 28 has experienced partial erosion of the extra-crater sequences; however, the entirety of the maar deposits surrounding diatreme 19 has been removed. If the same upper bedded deposits observed at the top of diatreme 28 were also originally deposited in diatreme 19, a minimum of between 80 and 100 m has been eroded from the upper diatreme, excluding the height of the surrounding tephra ring.

The volcaniclastic diatreme infill has been categorised into eight lithofacies that have been grouped into five lithofacies associations (LFA) (Fig. 4 and Tables 1–2). These distinctions are based on differences in composition and textural characteristics. The diatremes appear to have a

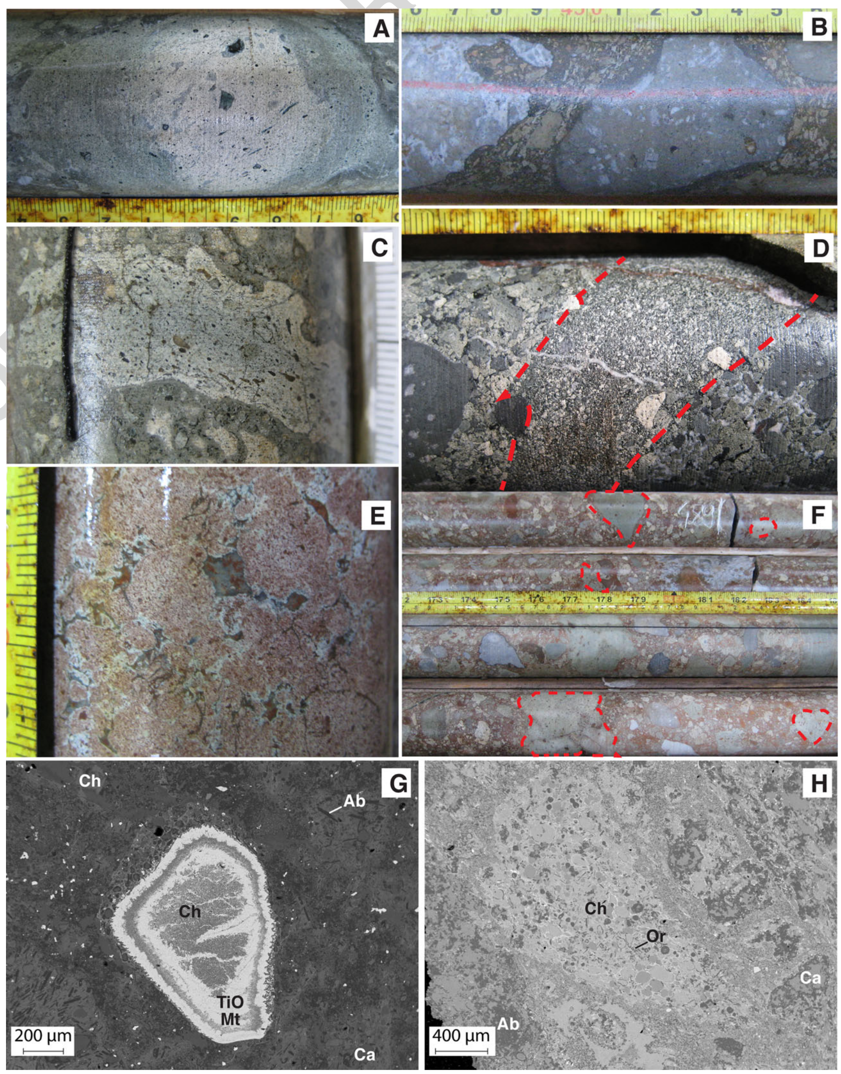

Fig. 4 **A** Photograph of a pelletal lapillus with multiple coatings of basalt within structureless mlLT (Borehole 28, 139.6 m). **B** Large Waulsortian Limestone clasts with alignment of smaller clasts around embayed edges in mLT (Borehole 28, 514.5 m). **C** 'Raggy' juvenile lapillus with flattened, irregular shape (Borehole 19, 54.9 m). **D** Well-sorted fines-rich pipe intruding into lapillistone within the bLT, outlined in *dashed red lines* (Borehole 28 , 26.7 m). **E** Equal-sized globular juvenile lapilli with no interstitial ash matrix and slight welding within mlLT (Borehole 19, 553.0 m). **F** Lithic-rich poorly sorted massive lapilli tuff with Waulsortian Limestone and dyke clasts as well as blocky juvenile lapilli (examples outlined in *dashed red lines*). Pervasive red discolouration is attributed to dolomitisation of mlLT (Borehole 19, 491.7 m). **G** SEM image of a deep crustal xenolith comprising titanium oxide and magnetite coated with vesicular basalt (Borehole 19, 274 m). **H** Vesicular lapillus in the upper diatreme containing feldspar micro-phenocrysts and vesicles filled with chlorite (Borehole 19, 50 m). *Ab*, Albite; *Ca*, Calcite; *Ch*, Chamosite; *Mt*, Magnetite; *Sa*, Sanidine; *TiO*, Rutile

Table 1 Summary of lithofacies characteristics, context and interpretation for each lithofacies association in the diatremes

LFA	Litho	Description	Interpretation
1	Massive lapilli tuffs (mLT)	Predominantly massive, well-sorted lithofacies with high proportion of juvenile fine ash matrix altered to chlorite and locally infilled by carbonates.	Mass wasting of maar-diatreme walls and deposition by gravity flows in an open crater; possible elutriation of ash from lower in the system.
1	Lapillistones (Lf)	Structureless and clast supported with small lapilli and a low proportion of matrix; juvenile bombs and large lithic clasts present. Localised 'raggy' juvenile lapilli, preferred vertical orientation of clasts and apparent welding.	Fluidisation of hot lapilli in the central diatreme and transportation of outsized lithic clasts from lower in the stratigraphy
2	Bedded lapilli tuffs (bLT)	Highly heterogeneous lithofacies consisting of both massive and normally graded beds containing a high proportion of juvenile lapilli and highly variable proportion of fine ash matrix. Locally pockets of fine ash, pyrite and secondary calcite occur.	Subsided maar strata deposited near-vent as dilute density currents and later undercut by diatreme widening, leading to downward slumping along margins.
3	Massive lithic-rich lapilli tuffs (mlLT)	Structureless lithofacies locally with abundant lithic clasts and blocks, pervasive red-brown discolouration and fines-rich pockets and pipes.	Homogenous and structureless nature and degassing structures indicate fluidisation of diatreme fill.
3	Lithic-rich graded lapilli tuffs (l(n)LT)	Very poorly sorted, containing a high proportion of ash matrix and abundant juvenile lapilli and lithic blocks. Graded bedding with clast alignment, fines pockets and localised red-brown discolouration.	Accumulation through collapses of the country rock walls and overlying maar.
4	Lapilli tuffs (LTf)	Well-sorted highly altered lithofacies with a large proportion of matrix and lithic clasts. Localised small-scale grading, alignment of clasts, orange-red discolouration and localised injection of the tuffs into cracks in the country rock.	Deposited by a high pressure fluidised flow capable of dilating cracks in country rock.

central massive section with localised country rock breccias toward the base. The upper parts of the diatremes and margins consist of bedded lapilli tuff. Intrusions of variable thickness occur within the diatremes and to a lesser extent in the adjacent country rock. Juvenile lapilli lack macroscopic phenocrysts and are characterised by a low proportion of vesicles (typically 2–25 %). The majority of volcaniclastic material has been altered to clay, overprinting most primary textures and micro-phenocrysts. Ore forming minerals such as sphalerite and galena occur within the base of the diatremes in small quantities, visible under the SEM. This study focused on diatremes 19 and 28 as these preserve the most complete records and are covered by magnetic surveys and drill cores intersecting the central and marginal facies down to 560 m. In contrast, diatremes 47 and 77 were only sampled intermittently, as the drill core alternates been limestone and volcaniclastic material which has been brecciated and remobilised by later hydrothermal fluids forming polymict BMBs.

Table 2 Summary of measured characteristics of juvenile lapilli and lithics clasts, and vesicle size and percentage for each lithofacies association in the diatremes

LFA	Lithofacies	Juv. %	Juv. size (mm)	Lithic %	Lithic size (mm)	Matrix %	Ves. %	Ves. Av %	Ves. size (μm)
1	mLT	95–100	2–11	0–3	3–7	50–60	8–23	15	30–3000
1	Lf	98–100	2–48	0–2	5–16	15–25	12–24	19	12–2000
2	bLT	80–99	2–18	1–4	10–39	15–60	2–33	13	119–23,500
3	mlLT	65–90	2–52	10–17	3–71	15–70	4-58	17	6–11,300
3	l(n)LT	65–95	2–76	4–35	5–1670	20–30	4–8	15	134–3200
4	LTf	71–87	2–8	11–29	5–25	60–70	–	5–25	–

Lithofacies characteristics

LFA 1: massive lapilli tuffs (mLT) and lapillistones (Lf)

This lithofacies association is exemplified within the upper 130 m of the centre of diatreme 19, consisting of two key lithofacies, massive lapilli tuffs and lapillistones that grade into each other with no visible bedding. The massive lapilli tuffs (mLT) consist of well sorted fine to coarse ash, lack structure and grade downwards into a more lapilli-rich tuff. The proportion of juvenile material is high at approximately 95–100 % with only 0–3 vol. % country rock limestone fragments (see Table 2) and < 5 % pelletal lapilli (see Fig. 4a). These predominantly subspherical pelletal lapilli consist of as many as three rims of incipiently vesicular juvenile material surrounding lapilli of volcaniclastic material, carbonate country rock, or highly crystalline metamorphic lithic fragments. The rocks contain 40–72 % lapilli and 1–4 % blocks, with matrix proportion varying between 30 and 70 % but averaging around 60 vol. %, consisting mainly of fine ash. Clasts are sub-angular to sub-rounded and vary between 2–11 mm. Juvenile lapilli tend to be blocky and incipiently to poorly vesicular (8–23 %, Table 2). The lithofacies has a pervasive green colouration due to extensive alteration of ash and lapilli to chlorite. Localised areas (decimetre to metre scales) have experienced Fe stained carbonate replacement of the ash matrix.

The lapillistones (Lf) are similar in composition and structure to the more lapilli-rich mLT but contain 75–81 % lapilli, < 1–4 % blocks and only 15–25 vol. % matrix, which predominantly consists of fine ash altered to chlorite. Although the average juvenile lapillus is ∼4 mm, the occasional limestone block reaches 48 mm. The juvenile lapilli have a measured vesicularity of 12–24 % (Table 2) similar to the mLT, and a low proportion of feldspar microphenocrysts (see Fig. 4H). Within the lithofacies, larger 'raggy' juvenile lapilli (see Ross and White (2012)) occur in addition to a localised sub-vertical clast orientation and partial welding.

Interpretation of LFA 1

The lapilli tuffs and lapillistones may have accumulated through a combination of progressive mass-wasting of the maar-crater walls (Gernon et al. 2009a) and preferential transport of fine ash to the upper part of the diatreme via gas-particle dispersions (Gernon et al. 2009b). Winnowing of fine ash from areas of LFA1 formed a large proportion of secondary pore space and high permeability allowing precipitation of a carbonate infill surrounding the lapilli (Davies et al. 2008). The blocky nature and incipient vesicularity suggest the lapilli were formed by fragmentation as a result of magma-water interaction (Houghton and Wilson 1989; Mattsson 2010).

The pelletal lapilli most likely formed when a dyke or sill intruded earlier water saturated volcaniclastic infill. Intense magma degassing combined with vaporisation of the diatreme fill produced powerful gas jets in which globules of melt-coated clasts scavenged from the adjacent deposits (cf. Gernon et al. (2012)). Another theory suggests agglutination of small melt droplets to a core in the deep magma plumbing system (Lloyd and Stoppa 2003). These lapilli were likely transported from depth to the top of the diatreme by debris jets (Ross et al. 2008a; Valentine 2012) as evidenced by the vertical orientation of clasts (cf. White (1991)) and partial welding.

LFA 2: Bedded lapilli tuffs (bLT)

Bedded lapilli tuffs occur near the margins in the upper ∼80 m of diatreme 28. Bed thickness varies considerably, averaging between 2 and 8 cm, but reaching up to several metres thick and generally increasing with depth. Transitions between beds are either sharp or diffuse, with normal and inverse grading observed, typically towards the base of beds. Bedding angles vary between 4 and 52°. On average, beds contain 50–60 % ash matrix, pervasively altered to chlorite with pockets of secondary calcite and pyrite, decreasing to <15 % in clast supported beds. Lapilli proportions vary from 40 to extremes of 85 % and blocks <1 %. The degree of sorting decreases with depth, with uppermost beds well sorted and the lowest moderately sorted. Clasts are predominantly rounded and consist of 80–95 % juvenile material, 1–4 % limestone clasts and 3–20 % dark and blocky lapilli of low average vesicularity and possible juvenile origin. Clast sizes vary from 2 to 40 mm but most juvenile particles are small, averaging between 2 and 4 mm. Juvenile lapilli are non to incipiently vesicular (2–25 % vesicles), typically altered to chlorite and many have a dark green outer rim.

Interpretation of LFA 2

The sequence of thin beds is characteristic of frequent, small-scale phreatomagmatic eruptions (Lorenz 1986; Sohn 1996; McClintock and White 2006). The nature of bedding, high degree of sorting, grading and rounded nature of clasts within this lithofacies suggests they were deposited in the maar crater from a series of dilute density currents (Cas and Wright 1991; White 2000). Very thin beds of tuff may be attributed to fallout of ash from suspension in the water column (White 2000). The rounded nature of the clasts suggests mechanical alteration of their shape by collisions and abrasion during transport in currents and debris jets (Calvari and Tanner 2011) or by recycling of juvenile material by later eruptions (Houghton and Smith 1993; Leahy 1997). Alternatively, mass wasting of the maar-diatreme walls and introduction of water-supported gravity currents could have introduced this material into the open crater (cf. Gernon et al. (2009a)). The dark green rims to juvenile lapilli are interpreted as altered glass, thought to represent quenched margins that formed during ejection of hot pyroclasts into the water column. These quenched margins suggest that the lapilli were ejected molten and therefore capable of plastically deforming during the expansion stage of magma-water interaction, providing another possible explanation for their round shapes (Kokelaar 1986). Progressive deepening of the diatreme would have caused widening and undercutting of the maar and slumping along the diatreme margins (Lorenz and Kurszlaukis 2007). These wedges of pyroclastic material and their associated bedforms (Fig. 1) are commonly preserved along the margins of diatremes and may result from fluidisation of a central region, which effectively destabilises the marginal deposits causing them to slump downwards (Gernon et al. 2008). The dark non-vesicular lapilli that comprise up to 20 % of this lithofacies are similar to 'blocky' clasts described by Fisher (1984), Houghton et al. (1999) and Ross and White (2012). These are interpreted as cognate clasts of either fragmented dykes intruded into the diatreme-fill (cf. Gernon et al. (2013)) or poorly vesicular magma that experienced brittle fragmentation (cf. Ross and White (2012)).

LFA 3: Massive lithic-rich lapilli tuffs (mlLT) and lithic-rich graded lapilli tuff (l(n)LT)

The central part of the diatremes (e.g. diatreme 19) consists largely of massive lithic-rich lapilli tuffs with localised lithic-rich graded lapilli tuffs, penetrated by many late-stage vesicle and phenocryst poor intrusions, commonly exhibiting undulating contacts. Intrusions vary in thickness from tens of centimetres to 45 m, averaging at 2.5 m thick. However, intrusion angles vary between 2 and 69° from the horizontal, averaging 37°. Changes within the mlLT lithofacies are gradual with no visible beds and an increasing proportion of matrix with depth from 15 to 70 % and 30 to 85 % lapilli and no blocks between ~110–330 mbgs with localised variations. The lower part of diatreme 19 (c. 390–560 mbgs) contains a high proportion of clasts and only ~35 % matrix consisting of varying proportions of medium grained ash, limestone lithic clasts and localised patches of pyrite disseminated within the matrix. Clasts have angular shapes towards the top of the lithofacies but become rounded with depth, with 26–73 % lapilli and 3–7 % blocks at the diatreme base. Juvenile lapilli remain dominant (65–90 %), with higher proportions of limestone country rock clasts (up to 17 %) and < 1 % lower crustal xenoliths coated with juvenile material (Fig. 4G). Limestone clasts frequently exhibit embayed edges and a thin dark rim, possibly consisting of a mud coating (Houghton et al. 1999; Brown et al. 2008a). The average juvenile lapilli size is larger (6–13 mm) than within the upper diatreme, with local variations in sorting and maximum clast size reaching 76 mm. The proportion of dark incipiently vesicular material varies considerably between <5 and 90 % of the clast population and includes small lapilli to large blocks. The upper lithofacies is lacking in fine ash while the lower section contains isolated pockets and pipes rich in ash sized particles. Juvenile lapilli exhibit vesicularity ranging between 4 and 58 % and show a wide diversity in habit throughout the lithofacies. These include blocky with fracture-defined edges, areas of equigranular lapilli with little or no interstitial ash matrix and large 'raggy' lapilli. Pelletal lapilli commonly display multiple coatings of pale and dark magmatic material. Thin lapilli-rich and fines-rich pipes (1–4 cm wide) and partial welding are visible within the sequence. These partially welded areas are usually found adjacent to boundaries such as dykes, veins or fractures and involve elongation parallel to the boundary and partial merging of juvenile particles.

An orange colouration, initially related to alteration of juvenile lapilli, starts at ~288 mbgs in borehole 19, locally at 182 mbgs in borehole 28 and intermittently at 295 mbgs in borehole 23. Towards the base of the diatremes, the alteration and discolouration of both clasts and matrix becomes more persistent and juvenile lapilli appear bleached (e.g. Fig. 4F). XRD analysis has shown that this alteration is the result of increasing dolomitisation with depth (Elliott et al., unpublished data).

The l(n)LT units have sharp contacts with the surrounding mlLT and are characterised by a high concentration (up to 23 %) of blocks up to 1.7 m in diameter (79–100 % of which are country rock clasts) and 57–79 % lapilli. These units are poorly sorted with clast sizes averaging 11 mm, and a large range in angularity from subangular to well rounded. The units are lithic-rich with 4–30 % limestone clasts and approximately 3 % dark LABL clasts and between 65 and 95 % juvenile lapilli, including up to 10 % dark, blocky incipiently vesicular clasts. Beds are typically graded with alignment of smaller clasts around larger clasts, and fines-rich pockets are also observed (Fig. 4D).

Interpretation of LFA 3

The massive nature of mlLT is consistent with the homogenisation of a large part of the diatreme fill, partly through the action of debris jets (Lorenz 1975; Valentine 2012; Delpit et al. 2014) and gas-fluidisation (Walters et al. 2006; Gernon et al. 2008).

The majority of lapilli found within this lithofacies are blocky with fractured boundaries, and likely result from phreatomagmatic fragmentation (Fisher 1984; Houghton et al. 1999; Ross and White 2012). 'Raggy' clasts retain enough heat to remain in a hot plastic state (Ross and White 2012) as evidenced by their elongate shape and uneven edges, effectively moulding around adjacent clasts during transport (Fig. 4C). Globular lapilli are considered to result from gas streaming through magma, fragmenting and depositing hot lapilli and welding grain boundaries (Fig. 4E). This process is similar to that described by Gernon et al. (2012) for the formation of pelletal lapilli and is consistent with the high degree of sorting and paucity of fines.

The localised lithic-rich graded lapilli tuffs within the mlLT are thought to be lenses of material resulting from episodic diatreme wall collapses or formed from explosions near the diatreme-country rock margin (Ross and White 2006). The proportion of country rock is higher toward the base of the mlLT (>250 mbgs), possibly because the limestone clasts are larger and denser and cannot easily be propelled by fluidising gases or debris jets (Valentine 2012). The undulating nature of intrusion margins indicates that they were emplaced prior to consolidation of the diatreme fill (Valentine 2012).

LFA 4: Lapilli tuffs (LTf)

This lithofacies is closely associated with the brecciated country rock-diatreme contact, either as undulations in the diatreme walls or injected into fractures in the country rock. This lapilli tuff commonly grades downwards into a polymict black matrix hydrothermal breccia, not discussed in this paper. Defining characteristics include a high proportion of fine juvenile ash and limestone matrix (60–70 %), large clasts (Fig. 4B) and alignment of small juvenile lapilli around the country rock contacts. Proportions of clasts are variable with ~70–90 % juvenile lapilli and a high proportion of limestone (~10–30 %). Both juvenile and lithic clasts are sub-angular to well rounded and limestone clasts frequently show embayed edges (see Fig. 4B). Clast sizes range from 2 to 86 mm with a low degree of vesicularity (5–25 %). This unit is highly altered with red-brown dolomitisation increasing with depth and proximity to country wall contact.

Interpretation of LFA 4

Brecciation of the diatreme walls may be due to late-stage mass wasting (Gernon et al. 2009a), wall rock collapses during pipe excavation (Sparks et al. 2006), or alternatively by phreatomagmatic explosions when rising magma interacts with water-saturated diatreme fill (Lorenz et al. 2002; Lorenz and Kurszlaukis 2007). These processes would create a highly permeable network of fractures, exploitable by fluidised lapilli tuff and magmatic intrusions. Smaller-scale features of ash and lapilli injected into cracks suggest that the lapilli tuff was fluidised and under sufficient pressure to further fragment the country rock. Irregular, embayed edges of larger limestone clasts suggest they have encountered acidic hydrothermal fluids after brecciation (Hitzman et al. 2002; Redmond 2010). The increased evidence for fluid interaction in this lithofacies suggests these fluids preferentially flowed along the limestone-diatreme contact.

Knockroe Formation

The Knockroe Formation within the Limerick study area is a 5 to 155-m-thick suite of alkali basaltic pyroclastic strata and lavas (Fig. 7). Several boreholes <1 km from the diatremes containing Knockroe pyroclastic rocks were sampled at a range of depths between 6 and 178 m and analysed for trace element concentrations by solution ICP-MS. Our data shows the Knockroe Formation to exhibit very similar trace and REE patterns to that of the diatremes (Fig. 5a). The Knockroe average lies consistently below that of the diatremes, which may represent dilution by the uptake of Mg and other elements during alteration in seawater (Humphris and Thompson 1978; Seyfried and Mottl 1982; Utzmann et al. 2002). Zr is plotted against Nb (Fig. 5b) as Zr is considered relatively immobile under hydrothermal conditions (MacLean 1980; Rollinson 1993; Zhou et al. 2000), and Nb is highly incompatible and will therefore be enriched in early mantle melts. The Knockroe samples clearly follow the same linear pattern and Nb/Zr gradient as the diatreme samples, indicating that they follow a similar fractionation trend. These data show a clear genetic link between the diatreme and Knockroe Formation, suggesting the latter formed predominantly by diatreme sourced material.

Various parts of the sequence are interbedded with cherty wackestones of the Lough Gur Formation. The Knockroe Formation is divided into five different lithofacies based on their textural characteristics and depositional processes and numbered in depositional order (Fig. 6). The fine-grained lithofacies 1 occurs at the base of three of the boreholes but thins out toward the SE, exhibiting normal grading and commonly fine laminations in beds that vary from <0.1–1 m thick. Typically, these beds are overlain by dark lapilli-rich lapilli tuff (lithofacies 2). Lithofacies 2 grades upwards into a fines-poor unit (lithofacies 3) with larger rounded lapilli with clay or ash matrix near the base and small lapilli with ash matrix near the top. The overlying lithofacies 4 is typically interbedded with fines-poor material. Here, lapilli are sparse within the wackestones

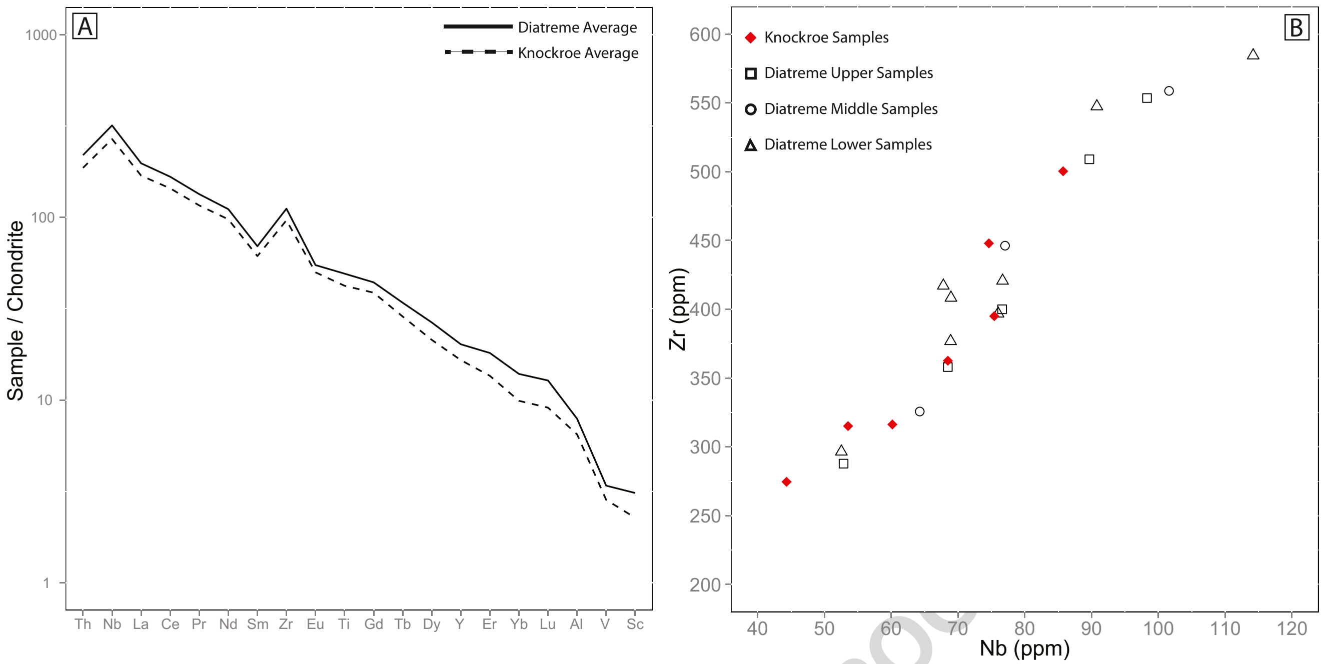

Fig. 5 Trace element data obtained by ICP-MS for diatremes (19 and 28) and the Knockroe Formation. **A** Multi-element plot shows two very similar trace element patterns for the two deposits. The Knockroe average data are consistently slightly more diluted than that of the diatreme for all elements, most likely due to alteration in seawater, e.g., uptake of Mg. **B** Nb versus Zr plot showing very similar trends and trace element data for diatremes and the Knockroe Formation

or are interbedded with crinoidal debris in more concentrated, thin beds and contain occasional volcaniclastic autoliths. At the top is lithofacies 5, a matrix-supported and poorly sorted massive unit, which predominantly contains altered volcaniclastic material and limestone clasts, texturally and compositionally resembling deposits of the upper diatreme. This lithofacies increases in thickness toward the SE from 1 m in borehole 24 to 25 m in borehole 6 (Fig. 7) with beds typically dipping between 3–50°, averaging ~30°.

Interpretation of the Knockroe Formation

To the SW, the thickened Knockroe Formation truncates the carbonate formations, infilling a pre-existing topography most likely formed by carbonate mounds of the Waulsortian Limestone. Greywacke beds within the Knockroe Formation were deposited during the Lower Viséan (345–399 Ma) (Somerville et al. 1992) in a shallow water submarine environment (Lees and Miller 1985; Holland and Sanders 2009). Deposition of these greywackes at Limerick is estimated to have occurred at water depths between 20 and 120 m. This upper limit is based on the depth ranges proposed by Wood (1957), Riding (1975) and Gallagher and Somerville (2003) for foram and algae (taxa *Draffania* and *Girvanella*) observed in the Lough Gur beds by Somerville et al. (1992). The lower depth limit is based on the lack of ooids in the Limerick upper Waulsortian that have been observed in other areas where this Formation has reached depths <120 m (Lees and Miller 1985), and also reflects the underlying carbonate bathymetry seen in Fig. 7. The thin to medium cross-laminated tuff beds of lithofacies 1 were most likely deposited from dilute turbidity currents linked to density flows. The thin discrete beds likely formed by ash fall from suspension in the water column after Surtseyan-type pulses of activity (White 2000). The lithic content is negligible at <1 % indicating that any magma-water interaction was not diatreme-forming, due to the lack of country rock fragmentation. Any explosive magma-water interaction therefore most likely occurred at the water-sediment interface, rather than being confined within solid rock (Kokelaar 1986). Magma fragmentation within the submarine environment would also most likely involve cooling-contraction granulation processes (Kokelaar 1986), explaining the fine-grained lapilli and ash within this lithofacies.

Lithofacies 2 contains a high proportion of dark, blocky, non- to incipiently vesicular clasts that appear fresh compared to the surrounding juvenile material and contain small proportions of microcrystalline feldspar. These could represent country rock lava fragments (Kurszlaukis et al. 1998; Gernon et al. 2013), disrupted sills (Nemeth et al. 2001) or fragmentation of a rapidly cooled melt (Ross and White 2012). The appearance of limestone clasts possibly indicates

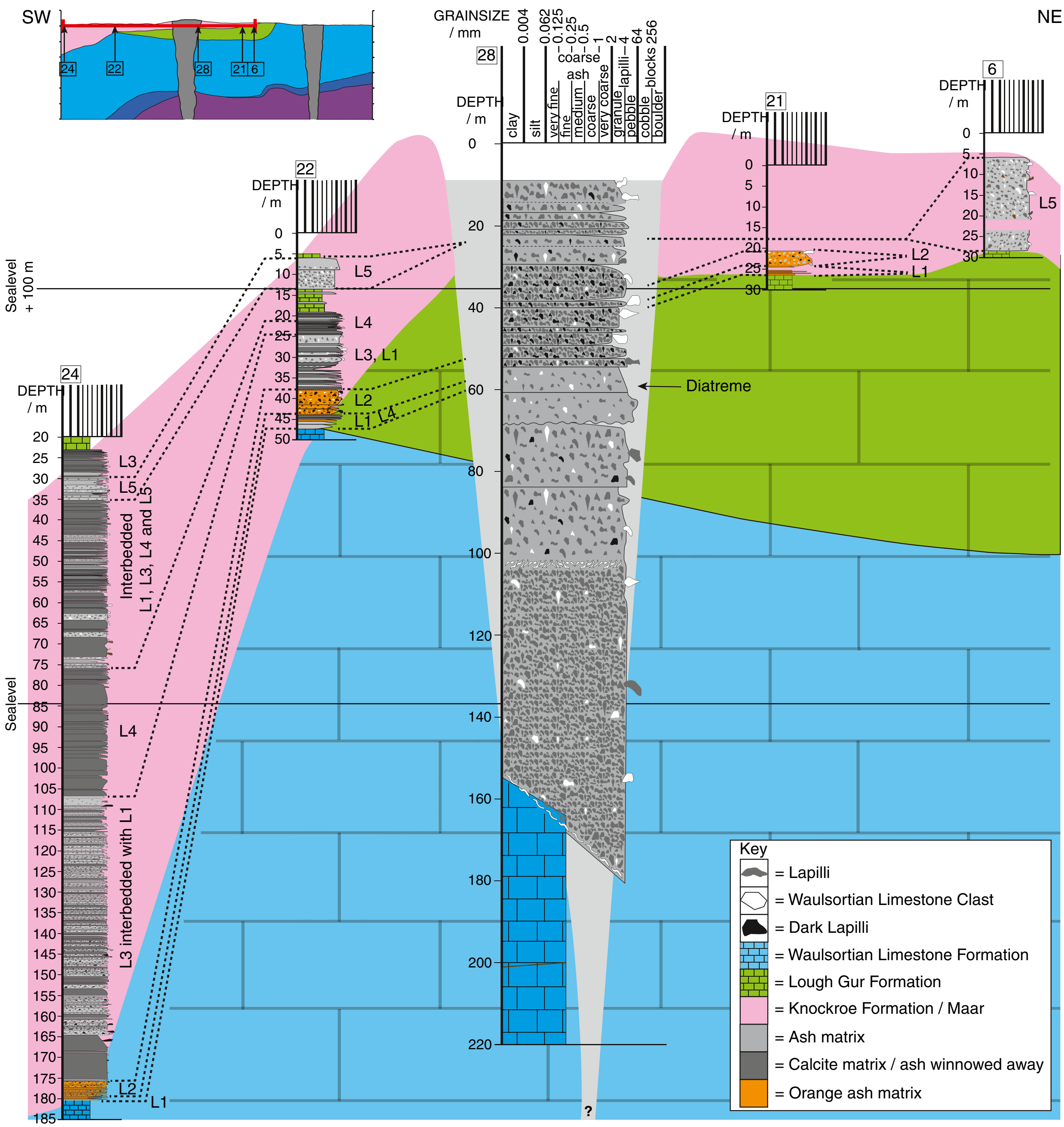

Fig. 6 Photographs of the Knockroe volcaniclastic formation divided into five lithofacies. *Arrows* indicate sample orientation, pointing toward the top of the borehole. **L5** Upper Knockroe, surrounding the diatreme, consisting of poorly sorted lapilli tuff with an altered *green ash matrix*. Lapilli are subrounded and incipiently vesicular, containing aligned feldspar phenocrysts. Clasts consist primarily of juvenile lapilli, dark blocky lapilli and Waulsortian Limestone. Beds tend to be very thick varying between 0.5 and 25 m. **L4** Greywacke beds with thin layers of volcaniclastic material. Beds vary greatly in thickness between 0.1 and 7 m and are matrix supported, containing 0–50 % lapilli and crinoidal debris. Lapilli are altered, incipiently vesicular and sub-rounded to rounded. Some beds contain rounded autoliths. **L3** Clast supported and normally graded beds usually 0.5–2 m thick, predominantly juvenile lapilli with occasional limestone or crinoidal clasts. Clasts are sub- to well-rounded and range from pebble sizes at the base to sand grades of ash at the top. Spaces between the lapilli are filled with dark clays or calcite. Lithofacies may grade vertically into sections with an ash matrix. **L2** Typically occurs above the laminated tuff: packages of lapilli tuff between 5 and 10 m thick containing high proportions of blocky non to incipiently vesicular dark clasts. Other clasts include rounded chloritised juvenile lapilli and Waulsortian limestone; occassionally, altered orange and containing diatreme autoliths. **L1** Thin to medium beds (0.1–1 m thick) of often laminated and normally graded ash interbedded with lithofacies 2. Ash is moderately to poorly sorted and consists of non-vesicular juvenile material and blocky dark fragments

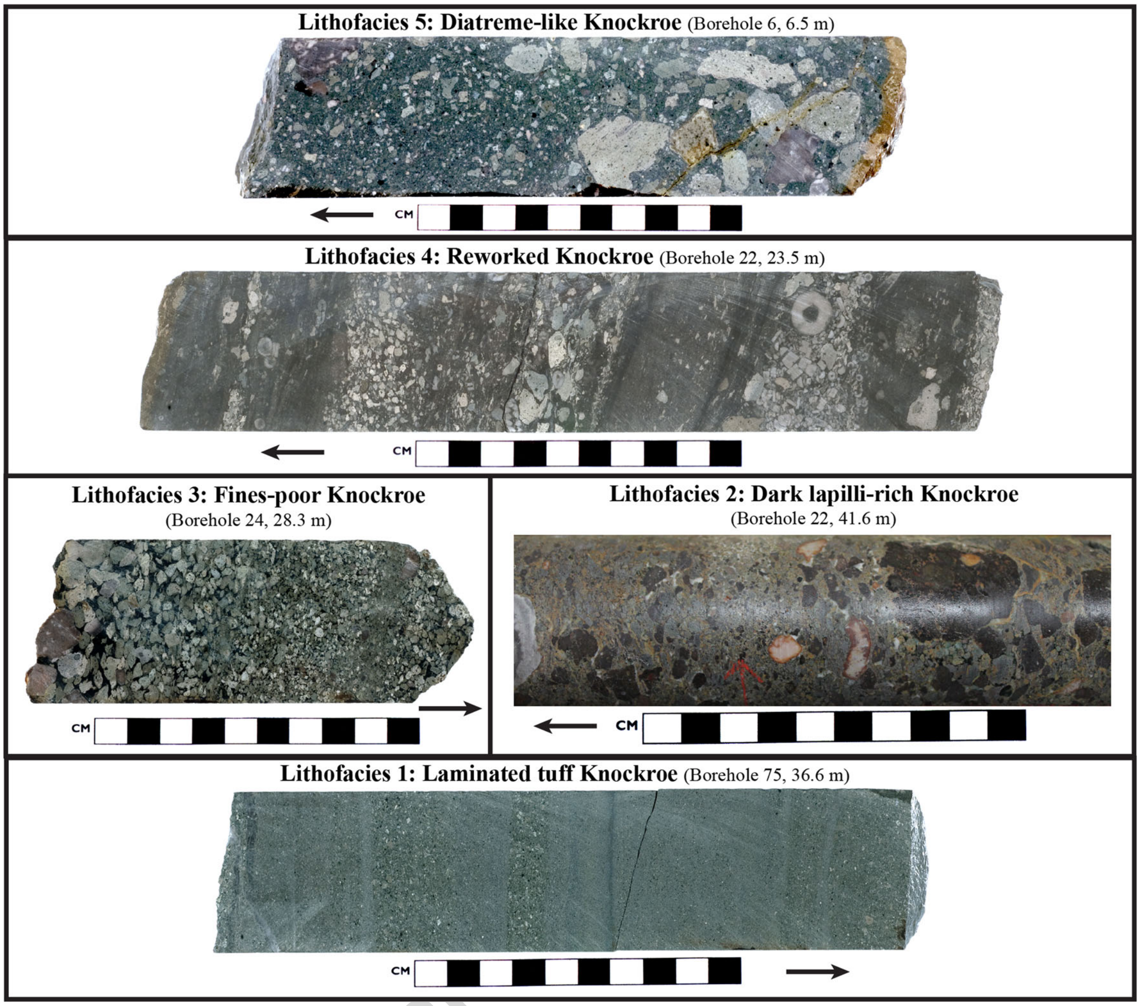

Fig. 7 Cross section from SW to NE, showing 4 logs of drillcore of the Knockroe Formation and their spatial relationship to a diatreme (shown in centre). The lateral extent of the diagram is indicated by the *red line* on the cross section (inset). *Numbers in boxes* at the top of the logs indicate the borehole number. *Dotted lines* indicate where packages of beds have been correlated between the logs. Ln indicates the lithofacies package and relates to the lithofacies described in Figure 5

the onset of country rock fragmentation and diatreme-forming phreatomagmatic activity (Lorenz et al. 2002; Ross and White 2006).

The normally graded beds of lithofacies 3 most likely formed in debris currents related to eruption column collapse in water, that may or may not have breached the water surface (Fiske et al. 1998). In this submarine environment, these density currents would have been water-supported (White 2000). These currents can be eruption-fed, formed by rising tephra jets expanding and ingesting water (White 2000), subsiding and flowing outward from the volcanic centre. Alternatively, where the eruption column breaches the water surface, tephra and particles can be deposited subaerially. High concentrations of particles in the water column can lead to gravitational instabilities and, forming vertical density currents (Fiske et al. 1998) that would be hard to distinguish from other deposits. These water-supported currents deposit Bouma-type sequences with concentrated basal flows depositing massive unsorted units, grading up into stratified ash beds deposited by the more dilute particle current above (Mueller and White 1992; White 2000). The bases of such sequences are not observed at Limerick, due to direct injection of tephra jets into the water column. This created multiple pulses of more dilute eruption-fed flows depositing a series of unwelded and graded beds (Kneller and Branney 1995; White 2000), similar to the typical upper sequence.

Isolated beds of lithofacies 4, interbedded with fossiliferous debris, indicate a submarine eruption environment. The lithofacies is attributed to re-working of pre-existing pyroclastic deposits, which were saturated, highly

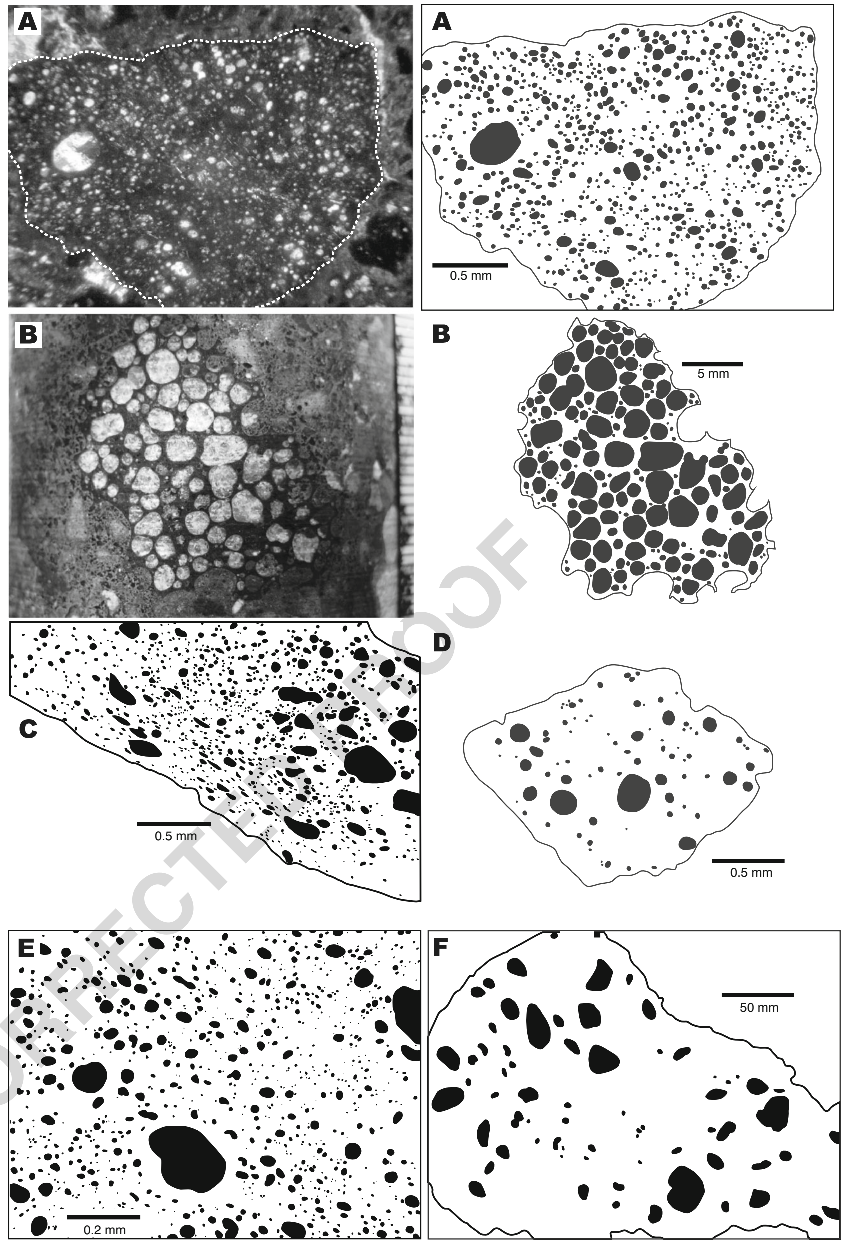

Fig. 8 Examples of typical lapilli and digitised vesicles used in image analysis (vesicularity values shown in *brackets*). **A** Lower diatreme lapillus (11 %) in an ash and disseminated limestone matrix (Borehole 19, 274 m). **B** Upper diatreme lapillus (64 %) infilled with calcite (Borehole 28, 33.7 m). **C** Middle diatreme lapillus (21 %) with calcite infilling elongated vesicles (Borehole 19, 102 m). **D** Lower diatreme lapillus (21 %) with a high number density of small vesicles (Borehole 19, 274 m). **E** Knockroe lapillus (17 %) (Borehole 24, 86.7 m). **F** Knockroe lapillus (12 %) (Borehole 24, 28.2 m)

mobile and liable to slump (Fiske et al. 1998; White 2000; Pittari et al. 2008). The Knockroe lithofacies are broadly comparable to the deposits of Bridge Point, New Zealand, where pauses in the Surtseyan-type eruption sequence are recorded by gradual resumption of normal sedimentation and re-working of abraded clasts and fossils (White 2000).

Beds of lithofacies 5 typically show normal grading at the top and inverse to non-graded bases, indicative of deposits of subaqueous debris flows (Nemec and Steel 1984) similar to those observed at the Costa Giardini diatreme, southern Italy (Calvari and Tanner 2011). The presence of Waulsortian Limestone clasts indicates brecciation of country rock at least 80 m below the seabed. This can occur during phreatomagmatic explosions (Lorenz et al. 2002; Lorenz and Kurszlaukis 2007), and/or diatreme expansion by implosion, spalling or undercutting (Sparks et al. 2006). Juvenile lapilli reveal incipiently vesicular blocky shards (Fig. 6) suggesting magma fragmentation by explosion rather than intense vesiculation (Heiken 1972; Houghton and Wilson 1989; Ross and White 2012). All these features suggest the uppermost lithofacies resulted from high-density debris currents sourced from the diatremes.

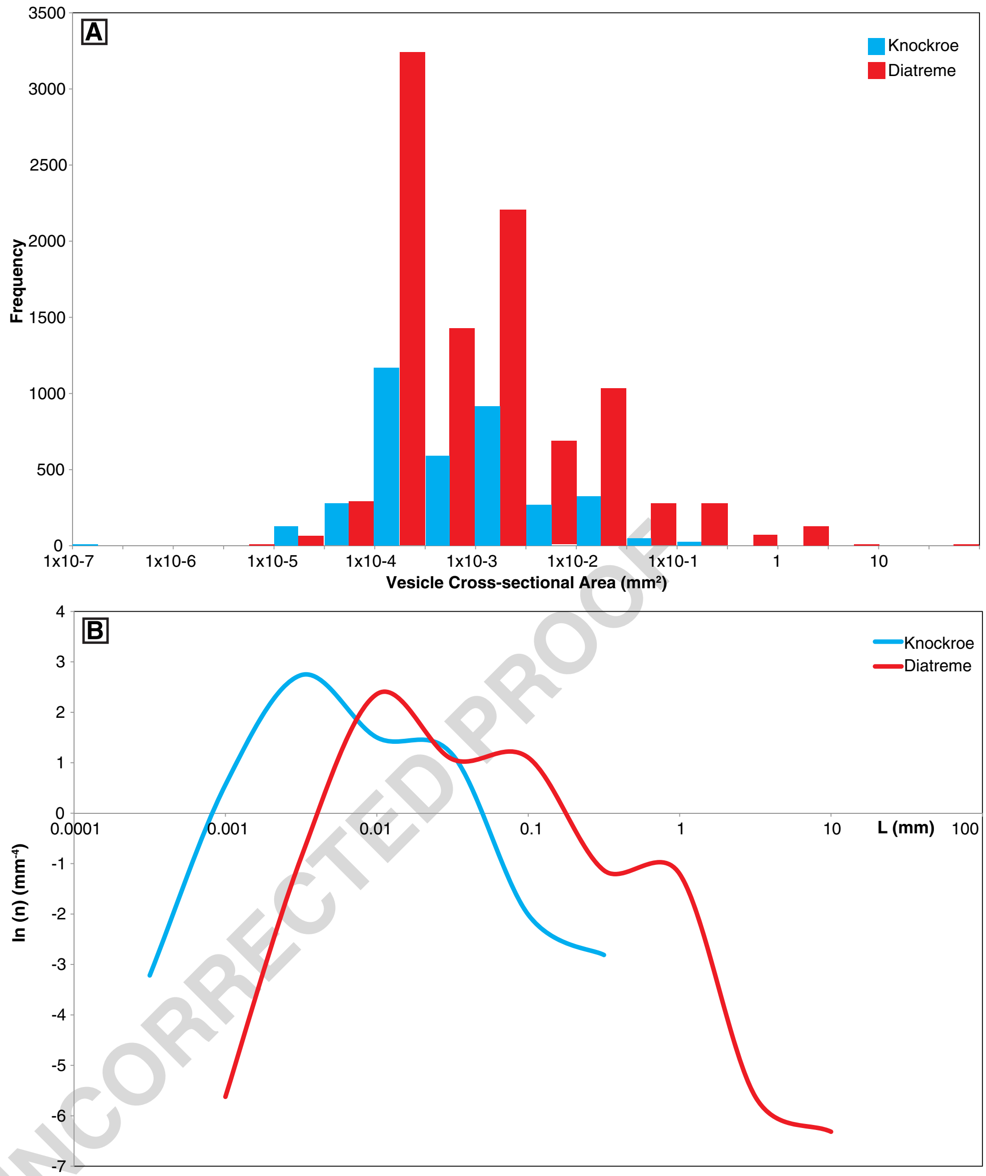

Fig. 9 **A** Histogram of vesicle cross-sectional area versus frequency for juvenile lapilli from both the Knockroe Formation and diatreme deposits. Three modal categories are observed for the diatreme samples and two for the Knockroe samples, indicating separate nucleation events. **B** Plot of equivalent length against the natural log of the vesicle number density. The same nucleation events can be seen as modal values of the equivalent length and upturning at the end of the lines are interpreted as due to vesicle coalescence

Vesicle distributions

In general, the vesicularity within both diatreme 19 and Knockroe juvenile clasts is low. Vesicularity within the Knockroe Formation ranges between 6 and 50 %, averaging ∼17 %, and in the diatremes varies between 2–63 %, averaging ∼30 % (Fig. 8). Although, vesicularity is slightly lower in the Limerick samples, values are comparable to the emergent Surtseyan-type phreatomagmatic eruptions at Capelas, Azores (18–58 vol. %) and the phreatomagmatic deposits of Miyakejima, Japan containing 20–70 vol. % (Shimano and Nakada 2006; Mattsson 2010). The higher Limerick values lie within the range required for explosive magmatic activity (50–80 %; Houghton and Wilson (1989)) and tend to be found at the base of the Knockroe Formation and in the lower parts of the diatremes (∼350–520 m) (Fig. 10). The magma fragmenting to form these lapilli at the base of diatreme 19 was likely more mature, having undergone a higher degree of coalescence.

Image analysis has captured a total of $\sim 0.0135 \times 10^6$ vesicles (Fig. 9a). Figure 9b plots L, the equivalent vesicle length, against the natural log of n, the vesicle number density for vesicle lengths placed into the same categories used in Fig. 9a. The multiple modal values can be seen by the two changes in gradient for the Knockroe Formation, and three for the diatreme, and indicate multiple nucleation events took place before magma fragmentation (Shea et al. 2010).

Clasts of the Knockroe Formation contain a population of smaller vesicles relative to diatreme 19 (Fig. 9) and exhibit two nucleation events, most likely material ejected at an early eruptive stage. Diatreme deposits record a third population of larger vesicles which may reflect an additional nucleation event or inflation of vesicles due to later outgassing as diatreme lapilli are insulated and capable of sustained plastic deformation. Both a positive and a negative gradient are shown (Fig. 9b), suggesting the vesicles were in the early stages of ripening (Shea et al. 2010)—the process by which volatiles diffuse from high pressures present in smaller bubbles to regions of low pressure in larger bubbles (Mangan and Cashman 1996). Alternatively, these larger vesicles may have formed by maturing from nucleation to coalescence before eventual bubble wall relaxation. An upturning of the trend line (Fig. 9b) is interpreted as due to bubble coalescence (Shea et al. 2010). Figure 9a shows the majority of vesicles are smaller than 1.5×10^{-2} mm^2 cross-sectional area. Tsukui and Suzuki (1995) suggested that vesicles smaller than 2×10^{-1} mm^2 are the result of super-cooling-related nucleation resulting from quenching during phreatomagmatic eruptions (Mattsson 2010). However, (Shimano and Nakada 2006) suggest that smaller bubble fractions are unrelated to fragmentation method and solely represent the high rate of magma decompression and eruption (Mattsson 2010).

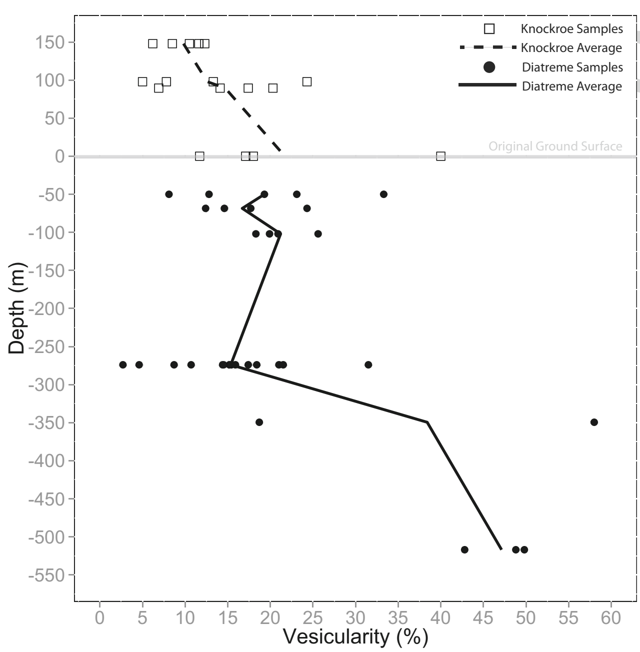

Fig. 10 Graph showing ranges and mean values of clast vesicularity in both Knockroe and diatreme deposits. Knockroe borehole 24 and diatreme borehole 19 have been used for this graph as they contain the most complete records of volcaniclastic material. Note that vesicularity generally increases with depth in both environments. The *zero line* represents the original ground surface upon which the Knockroe extra-crater material would have been deposited, creating positive topography. Diatreme sample depths are indicated by negative numbers

In general, vesicularity increases with depth within diatreme 19 (Fig. 10) indicating an increasing importance of exsolving gas in the eruption processes. However, the majority of lapilli within the central diatreme and Knockroe Formation exhibit incipient to poor vesicularity (averaging 14–21 %), well below that required for fragmentation by rapid bubble growth, suggesting fragmentation by an external water source. The Knockroe Formation only record two nucleation events, whereas diatreme 19 record three events (Fig. 9); this is attributed to more rapid quenching of ejecta in the water column, relative to thermally insulated pyroclasts in the diatreme, which are capable of more sustained degassing and vesiculation.

Discussion

On the basis of the observed structural, compositional and textural characteristics of these lithofacies associations (Table 1), we propose a multi-stage phreatomagmatic and magmatic model for the eruption of diatremes within the Limerick cluster (Fig. 10).

Initial eruption stage

The thin, well-sorted and graded beds deposited near the base of the Knockroe Formation by dilute density currents (see Fig. 8) show similarities with well-documented subaqueous and submarine eruptions such as those of Iblean, Southern Italy (Calvari and Tanner 2011) and Pahvant Butte, Utah (White 1996), resulting from Surtseyan-type eruptions (White 2000; White and Houghton 2006; Calvari and Tanner 2011). The paucity of lithic clasts in lithofacies 1 indicates initial eruptions did not involve significant country rock brecciation and were not diatreme forming.

Diatreme juvenile lapilli contain very low concentrations of feldspar micro-phenocrysts (Fig. 4h). This paucity of phenocrysts might suggest that the parent magmas experienced rapid volatile driven ascent from lower crustal levels, as evidenced by the presence of deep crustal xenoliths in the diatreme fill (Fig. 4g) and in the Knockroe Formation (Redmond 2010). Rapid magma ascent rates would prevent both extensive crystallisation and interaction with water (Valentine 2012), preventing country rock brecciation (cf. Gernon et al. (2013)) (Fig. 11). Explosive magma-water interaction at the sediment-water interface as well as cooling-contraction granulation (Kokelaar 1986) fragmenting the hot clasts, most likely accounts for the fine-grained nature of the basal Knockroe lithofacies.

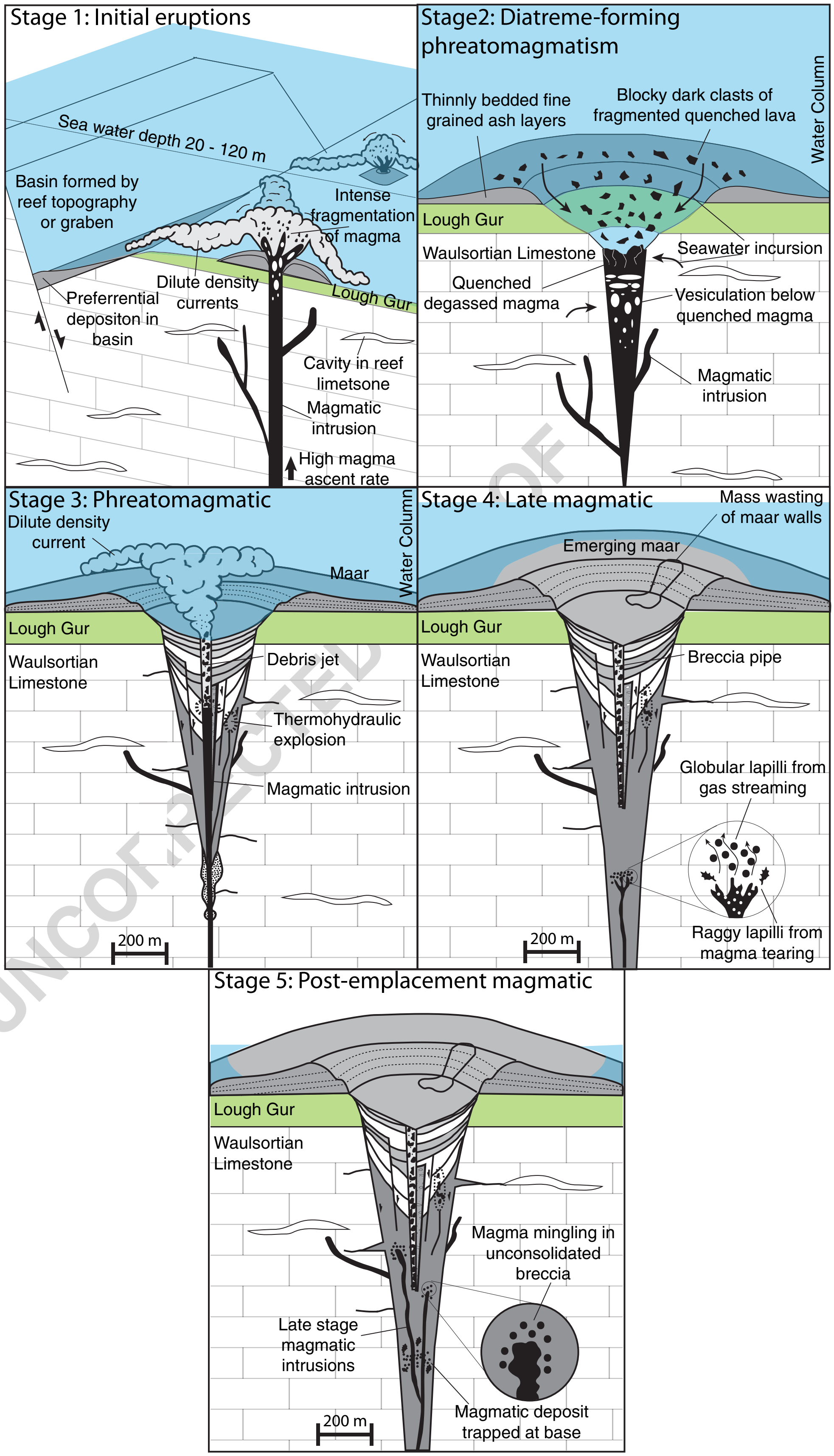

Fig. 11 Schematic cartoon illustrating the five stages of diatreme emplacement (see discussion). Stage 1 shows eruption sites shedding pyroclastic material via dilute density currents into the adjacent basin. Stage 2 depicts the onset of phreatomagmatic activity. Sea water incursion through the vent and fractured country rock forms a quenched non-vesicular body of magma which is fragmented and ejected by initial phreatomagmatic explosions. Stage 3 shows phreatomagmatic explosions producing debris jets that homogenised the central diatreme facies and widened the diatreme, undercutting overlying maar deposits. Stage 4 illustrates the late stage magmatic activity forming globular and 'raggy' lapilli, trapped at the base of the diatreme. Stage 5 involves post diatreme emplacement and non-explosive intrusion of magma into unconsolidated diatreme fill

Transition to diatreme-forming phreatomagmatic stage

Within the Knockroe Formation, beds of lithofacies 2 contain up to 40 % less-intensely altered vesicular dark lapilli and up to 10 % limestone lithic clasts. The co-occurrence of abundant juvenile clasts and country rock lithic clasts are attributed to an onset of diatreme excavation by explosive magma-water interaction. After an initially high magma flux, water incursion into the vent within a submarine environment would likely have led to rapid cooling and fragmentation of magma, degassed during initial eruptions. Further water incursion may have caused phreatomagmatic explosions, brecciating the surrounding country rock (Lorenz et al. 2002; Lorenz and Kurszlaukis 2007; Ross and White 2006; Sparks et al. 2006) and ejecting both limestone clasts and basalt in pulsatory explosions (Fig. 11).

Phreatomagmatic stage

Below the upper bLT, diatremes 19 and 28 consist of massive lithic-rich lapilli tuffs (mlLT) with localised lithic-rich graded lapilli tuffs (l(n)LT). Homogenisation of this deposit is considered to be the result of fluidisation by volatiles sourced from outgassing magma (Sparks et al. 2006; Walters et al. 2006; Gernon et al. 2009b) or alternatively by conversion of water to steam (White 1991; Lorenz and Kurszlaukis 2007), creating debris jets. The blocky, fracture bound and incipiently vesicular clasts, combined with high concentrations of lithic clasts (10–35 %) suggest eruptions were caused by magma-water interactions (Lorenz et al. 2002; Ross and White 2006).

After the initial high magma flux, seawater incursion into the vent likely formed a mobile water-rich slurry into which magma intruded (Kokelaar 1983). The rising magma would have flash heated water within this slurry to steam, creating gas propelled jets of debris and localised fluidisation of the diatreme fill (Kokelaar 1983; White 1991; Gernon et al. 2009b). Upward transport of material by these two processes and subsequent subsidence would have led to vertical mixing and large scale homogenisation of the water-rich mix (McClintock and White 2006; Gernon et al. 2009b; Valentine 2012). Such processes and creation of debris jets could explain the elutriated fines-rich pockets and pipes observed at Limerick and many other diatreme sites (cf. McClintock and White (2006), Ross and White (2006), Brown et al. (2008a), Gernon et al. (2008), and Gernon et al. (2013)).

Vesicularity studies support this interpretation, as vesicle sizes and percentages are similar to Surtseyan-type emergent phreatomagmatic eruption deposits at Capelas, Azores and Miyakejima, Japan (Tsukui and Suzuki 1995; Shimano and Nakada 2006; Mattsson 2010). This stage is recorded by multiple pulses of debris flows (Nemec and Steel 1984) recorded in lithofacies 3 of the Knockroe Formation, which contains large country rock lithic clasts and a paucity of fines due to elutriation by turbulent flows. Similar repetitive sequences are observed within maars in both subaerial settings, e.g. the Joya Honda maar, Mexico (Aranda-Gómez and Luhr 1996), and the Colli Albani maars, Italy (Sottili et al. 2009), and in submarine settings, e.g. Iblean, Southern Italy (Calvari and Tanner 2011). Pauses in pyroclast deposition are marked by the resumption of greywacke sedimentation and may represent periods of inactivity or alternatively phreatomagmatic activity that was too deep for debris jets to breach the surface and eject material (Ross and White 2006; Ross et al. 2008b; Valentine 2012; Graettinger et al. 2014). Regional deposition of the Lough Gur greywacke Formation occurred in water depths of 20–120 m, indicating these diatremes initially erupted into a significant body of water. The presence of greywacke beds within the Knockroe Formation is thought to indicate that basinal subsidence continued at rates comparable to volcanic accumulation (Strogen 1988).

The large ‘raggy’ clasts were emplaced whilst still in a hot plastic state (Ross and White 2012), after limited interaction with water. Although the majority of juvenile clasts are incipiently vesicular, a small proportion of larger clasts exhibits up to ~60 % vesiculation. Magma-water interaction can form a large range in vesicularity depending on the degree of magmatic gas exsolution at the time of fragmentation (Houghton and Wilson 1989). Although this prolonged stage is dominated by phreatomagmatic activity, the greater vesicularity of these lapilli indicates that magmatic processes were still important.

Late magmatic stage

At the lowest observed levels in diatreme 19, the mlLT contains a higher ratio of juvenile to lithic clasts. Juvenile lapilli have undergone a higher degree of vesiculation (~50–60 %) and coalescence creating ‘frothy’ lapilli also observed in the Joya Honda maar, Mexico (Aranda-Gómez and Luhr 1996). Here, this texture is attributed to low confining pressure exerted on the magma during vent excavation, allowing more advanced vesiculation before groundwater interaction (Aranda-Gómez and Luhr 1996). Proportions of ‘raggy’ and pelletal lapilli also increase, indicating a lower degree of magma-water interaction toward the base of the diatreme. These lapilli exhibit evidence for heat retention, including fluid, plastically deformed shapes and partial sintering with adjacent lapilli. A basaltic lava flow directly overlies volcaniclastic deposits of the Knockroe Formation less than

500 m to the south-west of diatreme borehole 28. The flow has not formed hyaloclastites or pillows and does not exhibit an extensive chilled margin, indicating eruption into a subaerial environment (Griffiths 1992; Gregg and Fink 1995; White 2000). This observation is consistent with the inferred decline in magma-water interaction and collectively are best explained by emergence of the system (Fig. 11) as suggested by Holland and Sanders (2009), explaining the lack of submarine fossiliferous debris in the upper Knockroe (lithofacies 5). Emergence and subsequent drying out of the diatreme may have caused a downward migration of explosion depths (Mattsson et al. 2005), prior to or during this late magmatic stage.

Post-emplacement magmatic stage

Late-stage intrusion of magma into unconsolidated diatreme-fill is a common feature of diatremes (Valentine 2012), as observed in the Gibeon Kimberlite Field, Namibia (Kurszlaukis et al. 1998), Iblean, Italy (Calvari and Tanner 2011) and Elie Ness, Scotland (Gernon et al. 2013). They represent late stage upwelling of magma soon after the cessation of explosive volcanic activity (Kurszlaukis and Barnett 2003; Lorenz and Kurszlaukis 2007; Valentine 2012). Dense dark clasts are closely associated with a ~1 m thick intrusion, and thought to result from magma fragmentation upon contact with unconsolidated diatreme fill, causing magma mingling and disintegration into blocky clasts (White 2000; Calvari and Tanner 2011).

Conclusions

The Knockroe Formation records an initial eruption stage of the Limerick diatremes, involving rapid magma ascent from lower crustal levels. High ascent rates allowed magma to reach the sediment-water interface before any appreciable crystallisation or magma-water interaction occurred, resulting initially in small (non-diatreme forming) phreatomagmatic eruptions. An extended period of phreatomagmatic activity formed diatremes of greater than 500 m depth filled with massive deposits homogenised by fluidisation and debris jet action. Evidence for this stage is recorded in the ~150-m-thick Knockroe Formation with interludes of sediment deposition (i.e. Lough Gur greywackes). These interludes may have been periods of inactivity or alternatively when phreatomagmatic activity was too deep for debris jets to breach the surface and eject material. The occurrence of lithic clasts within this deposit marks the onset of country rock brecciation and diatreme-forming phreatomagmatic activity.

A minor late phase of magmatic activity, largely affecting the lower parts of the diatremes, was most likely associated with emergence and subsequent drying out of the maar-diatreme system. Here, the presence of lapilli of apparent magmatic or low water/magma origin (e.g. ‘raggy’ and globular lapilli) suggests the diatremes lie somewhere between the two end members of magmatic and phreatomagmatic activity.

Our observations of diatreme architecture coupled with their extra-crater deposits, reveal a complicated eruption chronology of maar-diatremes initially in a submarine environment, which will have implications for the study of other volcanic systems.

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AUTHOR QUERIES

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Q1. Please check the affiliation if it was captured and presented correctly.
Q2. Keywords are required, please check if the suggested keywords ’Raggy, Maar-diatremes, Lower Carboniferous Period’ are correct.