Lamprophyres: A Short Introduction, with three examples from Cumbria

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Introduction

Lamprophyres are a diverse group of generally porphyritic, mafic or ultramafic rocks that often occur in swarms of dykes. The name, which was introduced by the German petrologist Gumbel in 1874, means "glistening porphyry" (Greek: *lampros*, glistening), and refers to the appearance of a hand specimen when light is reflected off mica phenocrysts that are abundant in some lamprophyres (Figure 1). The name was subsequently used to encompass a wide variety of shallow intrusive rocks that contain mafic phenocrysts (Mitchell, 1994).



Figure 1: A hand specimen (c. 10 cm long) of a mica-lamprophyre from a dyke in Skirwith Quarry, Ingleton, N. Yorkshire. Acadian deformation of the dyke may have imparted a slight foliation to the rock which accentuates the "glistening" of the phenocrysts.

Lamprophyres have a set of characteristics that make them sufficiently distinctive to be considered as a separate group of igneous rocks (Rock, 1987; Le Maitre, 1989):

(i) they are generally porphyritic, with phenocrysts restricted to mafic minerals dominated by biotite or by amphibole (both hydrous minerals),
(ii) felsic minerals, in particular feldspars, are restricted to the groundmass,
(iii) they usually occur as dykes,
(iv) they are often altered, particularly the groundmass, although phenocryst phases may sometimes also be selectively altered.

Traditionally, there was a tendency to regard lamprophyres as petrological curiosities with obscure origins. More recently, lamprophyres have been recognised as petrologically significant (Rock and Hunter, 1987), particularly as there appears to be an association of lamprophyre dykes with certain classes of gold deposits (Rock and Groves, 1988; Yu et al., 2020) and with diamond deposits (de Stefano et al., 2006, Wyman *et al*., 2006)). In this article I aim to provide an introduction to these fascinating and, at times, frustrating rocks.

Classification, occurrence, and UK examples

Older publications usually refer to lamprophyres as "trap dykes" (e.g., Flett, 1900). Teall (1888) has a chapter titled "Mica traps and related rocks" in his "British Petrography" in which he discusses the various attempts to classify these rocks. A systematic study of lamprophyres was carried out by Nick Rock during his doctoral studies (Rock, 1977). Much of this work was adopted by the International Union of Geological Sciences (IUGS) Subcommission on the systematics of igneous rocks, which deliberated in the 1980s (Le Maitre, 1989). The current IUGS classification distinguishes three groups of lamprophyres: calc-alkaline, alkaline and ultramafic.

1 Calc-alkaline lamprophyres

Calc-alkaline lamprophyres have biotite and/or hornblende phenocrysts with feldspar as the principal felsic mineral in the groundmass. Table 1 shows the classification of calc-alkaline lamprophyres. The classification has two "dimensions": the predominant mafic phenocryst mineral and the predominant feldspar in the groundmass. In cases where the groundmass feldspars are altered beyond recognition in thin section the terms "mica lamprophyre" and "hornblende lamprophyre" can be used.

Calc-alkaline lamprophyres are usually associated with granitoid plutons in orogenic belts. Late Caledonian mica lamprophyres are widely distributed in Northern England and Southern Scotland, where they occur as dykes intruding Lower Palaeozoic sediments (principally Ordovician and Silurian greywackes). Many

Calc-alkaline lamprophyres		Predominant mafic mineral	
		Mica (usually biotite)	Hornblende
Predominant feldspar	Alkali (orthoclase)	**Minette**	**Vogesite**
	Plagioclase	**Kersantite**	**Spessartite**

References: Nockolds *et al.* (1978), Le Maitre (1989)

Table 1. Classification of calc-alkaline lamprophyres

of these dykes have radiometric ages of 420 - 400 Ma and their intrusion often coincides with the period of Acadian deformation (Stone et al., 2010). Early Permian minettes occur in SW England, where they were emplaced along with the Cornubian batholith at the end of the Variscan orogeny (Leat et al., 1987).

2 Alkaline lamprophyres

Alkaline lamprophyres have phenocrysts of biotite, dark brown amphibole (usually kaersutite) or olivine in a groundmass that in general contains both feldspar and a feldspathoid mineral. Alkaline lamprophyres tend to be associated with regional extension. The distribution of Permo-Carboniferous alkaline lamprophyres in the Scottish Highlands and Islands was reviewed by Rock (1983). Particularly accessible examples occur in Orkney, where a high proportion of the igneous rocks are lamprophyres (Flett, 1900).

3 Ultramafic lamprophyres

Ultramafic lamprophyres, with phenocrysts of phlogopite and/or olivine in a groundmass that contains perovskite, melilite and a carbonate mineral. Ultramafic lamprophyres are associated with alkaline ultramafic-carbonatite complexes in continental rift valleys; they are much less common than the other groups of lamprophyres.

Alteration in lamprophyres

The study of lamprophyres can be frustrating as they have a tendency to alteration (Figure 2). Such alteration may be syn-intrusive (auto-metasomatic) during the slow cooling of volatile-rich residual melt after the bulk of the magma has crystallised (Lippolt and Siebel, 1991). Further alteration may occur by later stage magmatic hydrothermal fluids (Bratzdrum et al., 2009), or by subsequent infiltration of ore-bearing fluids (Lia et al., 2019). These alteration processes are distinct from any subsequent regional metamorphism that the lamprophyre and its host may be subjected to, together with the processes of atmospheric weathering that tend to afflict most mafic igneous rocks when exposed at the surface.

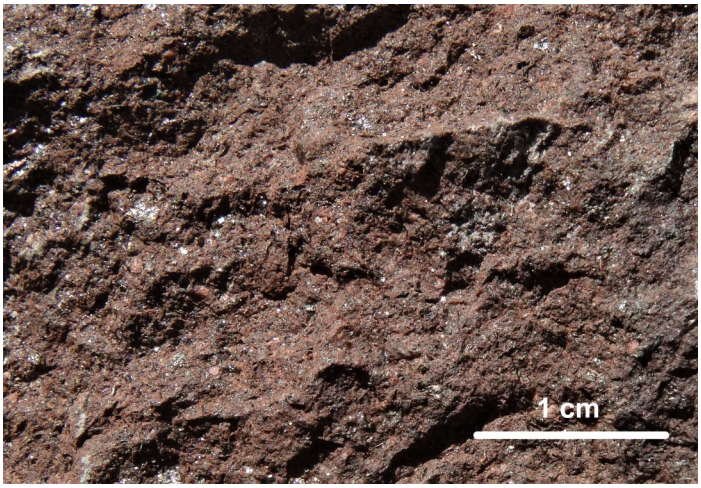


Figure 2: Part of a hand specimen of a mica-lamprophyre from St Abbs Head, Berwickshire. This specimen is much more altered than the lamprophyre in Figure 1; however, mica phenocrysts are still visible.

Examples from Cumbria

Almost all of the lamprophyres in NW England belong to the calc-alkaline group. I have chosen three examples of these lamprophyres from localities in Cumbria where alteration is moderate, or at least not too severe.

A Mica lamprophyre (kersantite?), Swindale Beck, Knock

This rather poorly exposed lamprophyre dyke crops out at NY 6875 2737 on the north bank of Swindale Beck, about 100 m upstream of a wooden footbridge. The location of the dyke is marked by a prominent grassy hump (Figure 3), some 2 m wide, that trends uphill at 340°. The lower end of the hump is truncated by the beck, which narrows at this point and flows through a set of rapids. Exposure of the dyke is restricted to a small area, about 15 m up the hump from the beck; it contains four core holes that are now partially moss-filled. There is no obvious extension of the dyke on the south bank, although this area is heavily vegetated.



Figure 3: The grassy hump, about 2 m wide, on the lower left marks the location of the mica lamprophyre dyke at NY 6875 2737 on the north bank of Swindale Beck, near Knock. A smaller hump visible on the lower right may be due to a small offshoot from the main dyke. This offshoot used to be visible in the bed of the beck, but was covered by cobbles in August 2021.

The fresh surface of a hand specimen (Figure 4) displays prominent dark brown phenocrysts of mica, typically 2-4 mm in size, that glisten when light is reflected off the perfect cleavage planes as the

specimen is rotated slightly from side to side. The groundmass is fine-grained and medium brownish-grey in colour. Some specimens have small (2-4 mm) rounded inclusions of grey, glassy quartz.

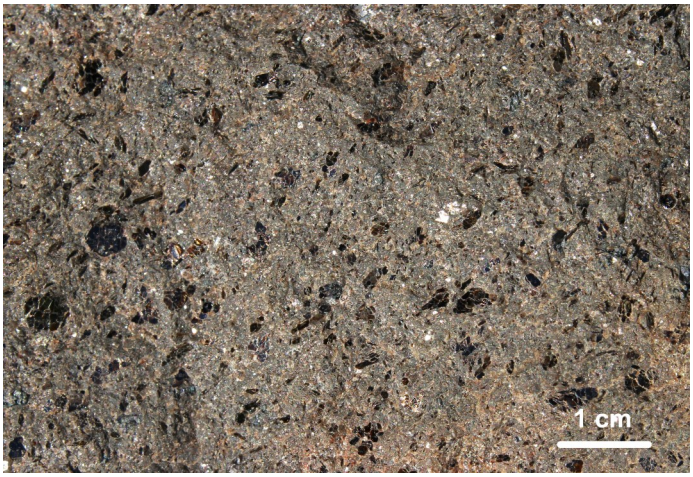


Figure 4: A hand specimen of the mica lamprophyre at Swindale Beck displays prominent dark brown phenocrysts of mica in a fine-grained, medium grey groundmass.

In thin section (Figure 5), the phenocrysts comprise fresh biotite. Elongate sections of the phenocrysts show a pale yellow/reddish brown pleochroism in plane polarised light (PPL) and have one good cleavage. Between crossed polars (XP), these crystals show high interference colours with a characteristic "rippled" effect together with extinction parallel to the cleavage. Irregular sections of phenocrysts show almost no pleochroism or cleavage and are isotropic; such sections yield an interference figure that is almost uniaxial with a negative sign. The groundmass is fine-grained and somewhat altered, comprising sericitized feldspar and a carbonate mineral. The specimen is clearly a mica lamprophyre, but the groundmass alteration precludes finer classification as a kersantite or a minette.

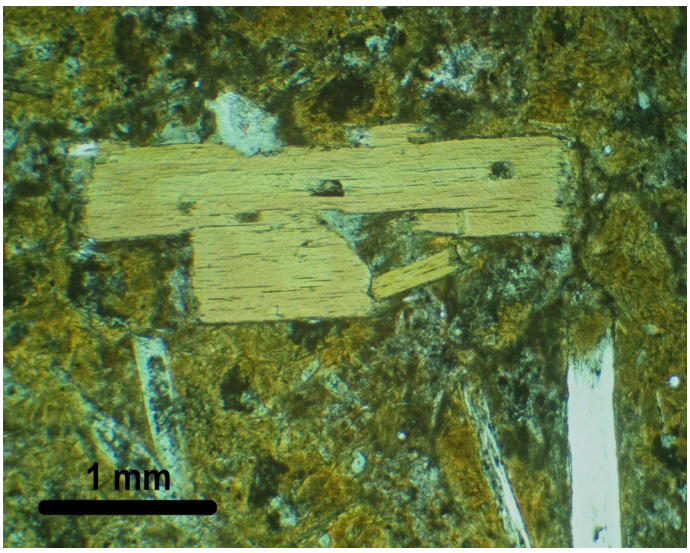


Figure 5: Thin section view of the mica lamprophyre specimen shown in Figure 4. This PPL view shows a large brown biotite phenocryst, with a single cleavage parallel to the polarization direction. The smaller phenocryst in the lower right is almost colourless. These two crystals together illustrate the strong pleochroism of the biotite phenocrysts.

Four lamprophyre specimens from this locality are listed in the Britrocks database (BGS, undated); in particular the details of specimen E36425 include a low magnification photomicrograph of a thin section. This lamprophyre dyke is shown on the extreme NE corner of the BGS Appleby 1:50000 sheet (BGS, 2004) along with another lamprophyre dyke some 800 m to the north.

The literature contains a few earlier references to lamprophyres exposed in Swindale Beck, although the locations are uncertain. Thus Shotton (1935) mentions "the well-known lamprophyre that traverses Stockdale Shales in Swindale Beck"; this presumably refers to the dyke shown on his Figure 3, which is a map that includes the location described in this section. Hudson (1937) contains a section on lamprophyres in which he mentions lamprophyres in Swindale Beck. He describes one of these (probably the dyke described above) as comprising "a dark grey groundmass with numerous dark flakes of biotite, and quartz blebs (with a coating of chlorite) are common". Significantly, Hudson (1937) mentions a large dyke farther upstream; this may correspond to the dyke exposed at NY 6893 2809, about 800 m upstream. This exposure is described in Woodcock (2020).

In conclusion, the conspicuous biotite phenocrysts in a fine-grained matrix are characteristic of mica lamprophyres; at this location there is little doubt over its classification. This contrasts with the dyke, exposed upstream, which has a similar mineralogy but is around 10 m wide and not conspicuously porphyritic.

B Mica lamprophyre (minette?), Sale Fell summit area

The main exposure of this lamprophyre, described as "one of Lakeland's most attractive rocks" (Smith, 2010), is at NY 1932 2967, on the NW side of the summit area of Sale Fell (Figure 6). Here a conspicuous pink speckled rock (Figure 7) crops out in a dyke-like body, some 2-3 m wide, and trending 070° for about 10 m. In addition, there are several fallen boulders of the same material immediately downslope.

Figure 8 shows the fresh surface of a hand specimen that displays irregular elongate grains of a dark greenish brown mineral, typically 3-5 mm long, that reflects direct light, although not to the extent of the biotite in the mica lamprophyre described in the mica lamprophyre from Swindale Beck. above. The groundmass is pink and comprises small (1-2 mm) grains, some of which show a single good cleavage.



Figure 6: Part of the main exposure of the Sale Fell minette at NY 1932 2967 immediately NW of the summit. The exposure shown is about one metre wide and shows a faint pinkish tinge.



Figure 7: A close-up view of an in-situ weathered surface on Sale Fell. The altered biotite phenocrysts are inconspicuous against the pinkish groundmass. Part of a 2p coin for scale.

A thin section displays elongate crystals of chlorite (Figure 9), typically 2-4 mm long, with a single inconspicuous cleavage and show a pale yellow-brown/ bluish green pleochroism in PPL. In XP, these crystals show anomalous purplish brown interference colours and extinction parallel to the cleavage. The groundmass comprises crystals typically 0.5 mm in size that are



Figure 8: A hand specimen of the Sale Fell minette displays irregular elongate grains of a dark greenish brown mineral, in a finer-grained pink groundmass.

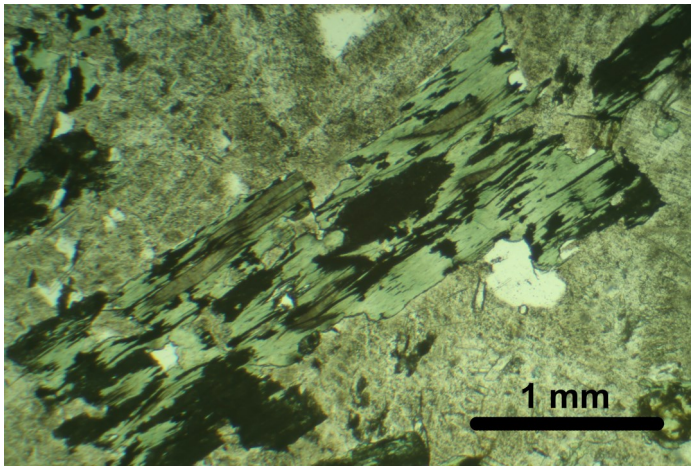


Figure 9: Thin section view of the mica lamprophyre specimen shown in Figure 8. This PPL view shows a large phenocryst that is almost completely chloritized within a groundmass that is somewhat altered.

generally turbid, although c.10 % show the lamellar twinning pattern characteristic of plagioclase feldspar. Much of the remaining groundmass is untwinned and too altered to allow the relative proportions of plagioclase and alkali feldspar to be determined. In addition, the groundmass contains minor amounts of calcite, quartz, opaques and acicular apatite.

On the assumption that the chlorite phenocrysts are pseudomorphs after biotite, the specimen can be classified as a mica lamprophyre, but the groundmass alteration precludes finer classification as a kersantite or a minette. Eastwood et al. (1968), who probably had access to less-altered specimens, records a dominance of plagioclase, indicating that the Sale Fell lamprophyre may a kersantite rather than a minette.

This dyke is not shown on the BGS Keswick 1:50000 sheet (BGS, 1999), however several specimens with the same grid reference as this locality are listed in the Britrocks database (BGS, undated), where they are variously classified as biotite-phyric lamprophyres,

kersantites or minettes. The BGS sheet description (Woodhall, 2000) mentions altered lamprophyre dykes emplaced in Skiddaw Slates on Sale Fell and quotes a K-Ar biotite radiometric age of 402 +/- 9 Ma from one sample (Rundle 1979).

The "Sale Fell minette" was described by Postlethwaite (1913) in his geology of the English Lake District. The description is reproduced in part by Alfred Wainwright (1964) in book six of his pictorial guide to the Lakeland Fells; although "AW" was somewhat bemused by the plethora of petrographic detail.

C Hornblende lamprophyre (spessartite?), Scawgill Bridge, Whinlatter

This lamprophyre is exposed in a small roadside quarry on the B5292 Whinlatter Pass road at NY 1762 2571, about 140 m west along from Scawgill Bridge. The quarry is very overgrown (Figure 10) and the face, which is c. 10 m wide and some 3-4 m high, is practically inaccessible without considerable clearance. Immediately north of the quarry, at NY 1763 2574, there is a patch of boulders which extends northwards uphill for c. 10 m before disappearing beneath dense bracken. These boulders have a similar mineralogy to samples from the quarry and may have come from a working in the same intrusion higher up the hill.

The fresh surface of a hand specimen (Figure 11) from the quarry shows crystals of a black mineral with at least one good cleavage, typically 2-4 mm in size. They are surrounded by a matrix of white grains some 1-2 mm in size with an inconspicuous cleavage. The rock is thus not obviously porphyritic.

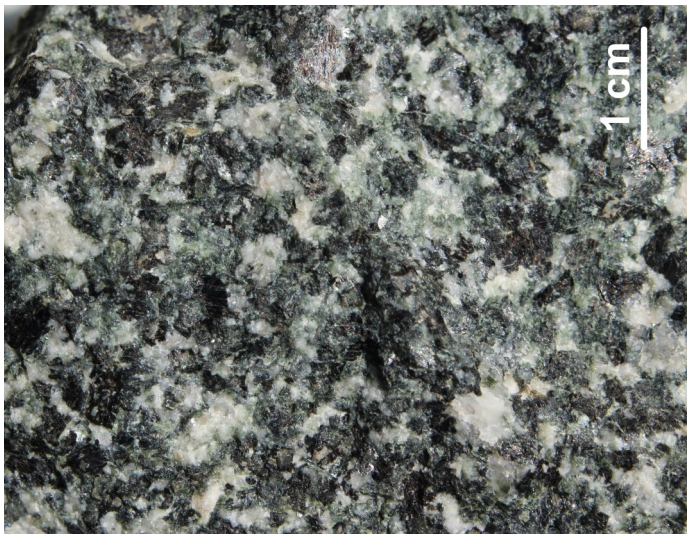


Figure 11: The fresh surface of a hand specimen from the quarry shown in Figure 10 shows crystals of a black mineral, typically 2-4 mm in size that are surrounded by a matrix of white grains. The rock is not obviously porphyritic.

A thin section (Figure 12) displays phenocrysts of hornblende, typically 2-4 mm long, with a single cleavage or with two cleavages at c. 60°. In PPL, sections with a single cleavage show a light brown/ medium red-brown pleochroism. In XP, these crystals show second order interference colours and extinction inclined to the cleavage. Some phenocrysts are partly altered to a fine-grained chlorite. The groundmass comprises crystals typically 0.5-1 mm in size that are generally turbid, although some are of lamellar-twinned plagioclase feldspar. In addition, the groundmass contains minor amounts of calcite, interstitial quartz and an opaque mineral.



Figure 10: This rather overgrown quarry, c. 10 m wide, on the B5292 Whinlatter Pass road at NY 1762 2571 is probably the main exposure of an elongate intrusion shown on the BGS map as a lamprophyre.

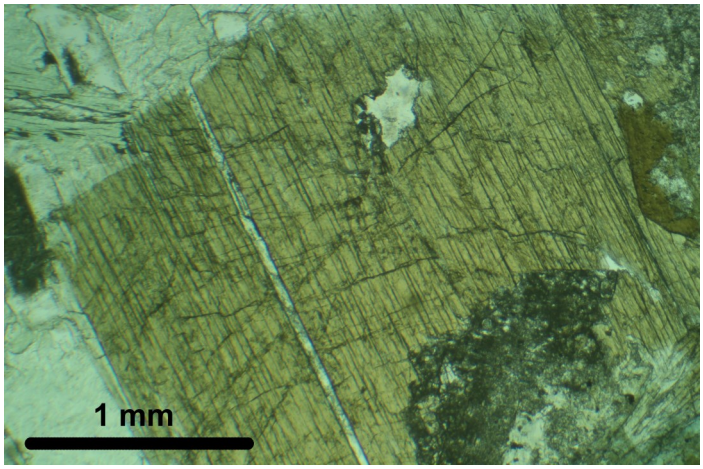


Figure 12: Thin section view of the hornblende lamprophyre specimen shown in Figure 11. This PPL view shows a large brown hornblende phenocryst with a single cleavage and a large area of alteration in the bottom right.

The BGS Keswick 1:50000 sheet (BGS, 1999) shows an elongate intrusion, marked as a lamprophyre, that extends c. 400 m north of the quarry and south of the road for about a kilometre. Two specimens with almost identical locations to the roadside quarry are listed in the Britrocks database (BGS, undated), where they are classified as hornblende-phyric diorites. In a paper that arose out of the BGS mapping programme for the 1:25000 Lorton and Loweswater sheet (BGS, 1990), Fortey et al. (1994) consider that the rock may be "… described informally as a markfieldite or spessartite, although the rock is not considered to be a true lamprophyre ".

Discussion

The three examples range from the "classical" mica lamprophyre exposed in Swindale Beck to the intrusion exposed around Scawgill Bridge, which is not considered by some authors to be a true lamprophyre. Some of the uncertainty around the nature of the three examples arises from alteration; this is particularly the case with the Sale Fell minette, where alteration of the biotite phenocrysts to chlorite renders them much less conspicuous than in the Swindale Beck material.

A further cause of uncertainty probably arises from the lack of obvious phenocrysts, even when this not caused by alteration. A porphyritic texture is generally interpreted (Gill, 2010) to be the result of a two-stage cooling process: a period of slow cooling before final intrusion, which allows growth of the larger phenocryst phases, followed by more rapid cooling during final intrusion, during which the smaller-grained groundmass develops. The rate of cooling in this second stage depends critically on the thickness of the intrusion. Thus, a dyke with a width of c.1 m may cool sufficiently rapidly to develop a fine-grained groundmass with a clear size contrast to the phenocryst phase. A dyke that is ten times as wide cools a hundred times more slowly (Philpotts and Ague, 2009) and thus may crystallise a groundmass that is sufficiently coarse to make the phenocryst phase much less conspicuous.

This effect of dyke width is illustrated by the two dykes in Swindale Beck: they have the same trend and similar mineralogies; however, the thin dyke described in A above is clearly porphyritic, while the much thicker dyke upstream is not conspicuously porphyritic (Woodcock, 2000). In this regard, the intrusion around Scawgill Bridge described in C above, is shown on the BGS 1:50000 Keswick map as being at least 50 m wide and comprises material that is, in general, not conspicuously porphyritic. It may be that the margins of this body, or a thin dyke offshoot from it, may show the porphyritic texture of a true lamprophyre.

Petrogenesis

In his recent textbook on igneous rocks, Gill (2010) comments that "… lamprophyres - though among the most widespread of alkali rocks - are also the least understood in petrogenetic terms". Some progress has been made recently in understanding the origins of lamprophyres. I consider two aspects: the likely nature and origin of lamprophyre source rocks together with mechanisms for partial melting of this protolith.

The geochemistry of lamprophyres is characterised by enrichment in large ion lithophiles (LILs) such as K, Rb, Ba and Sr and in light rare earth elements (LREEs) together with depletion in tantalum and niobium (Brown et al., 2008, Yu et al., 2020). These characteristics are consistent with a subduction-related environment in which the sub-continental lithospheric mantle (SCLM) is enriched by emplacement of magmas produced by hydrous melting in the underlying asthenospheric mantle wedge (Macdonald et al., 1985). Such enriched material may remelt to produce a lamprophyric magma when conditions become suitable; this may be during the same subduction event or subsequently, after storage of the enriched protolith in the SCLM (Pla Cid et al., 2006).

There are basically three ways to melt mantle rocks: by raising the temperature, reducing the pressure or adding water (Philpotts and Ague, 2009). Choi et al. (2020) suggest that "flush" melting, by the addition of water from a subducting slab to the enriched SCLM, produced Late Archean calc-alkaline lamprophyres in the Yilgarn Craton of Western Australia. Melting by adiabatic decompression during regional extension has been suggested as the origin of the Devonian-Carboniferous alkaline lamprophyre province in Scotland (Lundmark et al., 2011). A similar mechanism has been suggested for the Caledonian calc-alkaline lamprophyre province (Vaughan,1996; Brown et al., 2008).

An alternative mechanism for the genesis of Caledonian lamprophyres was proposed by Atherton and Ghani (2002), who applied the "slab breakoff" model of Davies and von Blackenberg (1995). In this model (Figure 13) enriched subcontinental lithosphere is melted by heat conduction from the impinging hot asthenosphere. A modified version of this model was proposed by Miles *et al.* (2016) in which migration of the resulting lamprophyric magmas into the overlying continental crust may have provided a heat source for the generation of crustal melts that contributed to the formation of the associated granites.

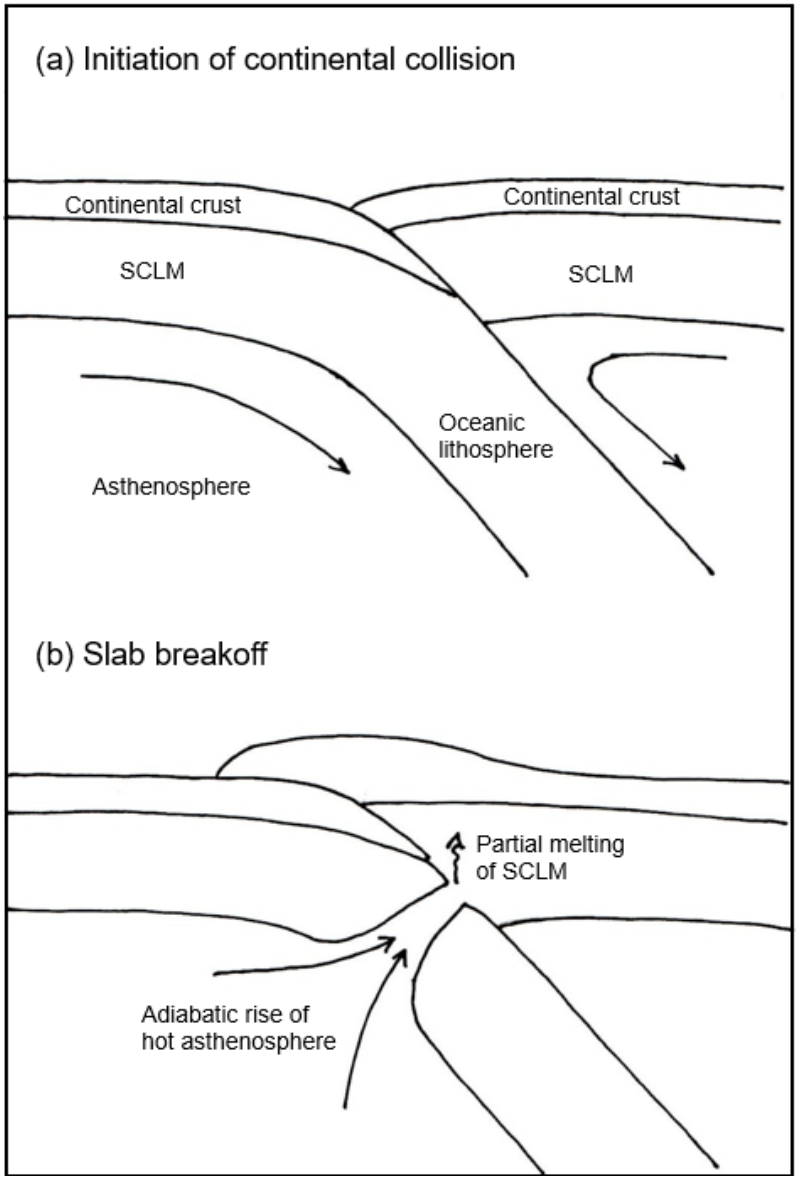


Figure 13: The slab breakoff model of Davies and von Blackenberg (1995). (a) Subduction of dense oceanic lithosphere, together with the attempted subduction of buoyant continental lithosphere, develops extensional forces in the subducting slab. SCLM = Subcontinental lithospheric mantle.

(b) The extensional forces may be sufficient to tear the slab, which detaches and sinks into the asthenosphere. The gap produced is filled by hot upwelling asthenosphere, which impinges on the SCLM and may cause partial melting. If this SCLM has been previously enriched this may produce a lamprophyric magma.

Conclusions

The lamprophyres comprise a fascinating group of rocks; however, their study in hand specimen and thin section can often be frustrating if the primary mineralogy has been significantly altered. There has been significant progress in understanding lamprophyres since the seminal work by Nick Rock and co-workers in the late 1970s, which culminated in the publication of a monograph (Rock 1991). A comprehensive review to update this monograph is, perhaps, overdue.

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