East Fife Coast, Fife

[NO 408 024]–[NO 444 020] and [NO 454 006]–[NO 526 015]

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Introduction

The coastal section between Lundin Links and St Monance in the East Neuk of Fife, which comprises the East Fife Coast GCR site, includes numerous volcanic necks (Figure 4.5). Excellent exposures and a wide variety of volcanic features within a relatively small area make this a valuable site for both research and educational purposes. It is well known internationally, regularly visited by field parties, and is much cited in scientific literature.

In many instances the three-dimensional relationships within the necks and between necks and country rock are clearly seen. Associated strata include bedded and massive, pyroclastic and volcaniclastic deposits; all are cut by minor intrusions and a few necks have a central intrusive plug. The volcanism was commonly phreatic or phreatomagmatic, reflecting the interaction of magma with water, and there are many examples of localized magma-sediment interaction.

In East Fife in general there are more than 100 known volcanic necks, which cut Carboniferous strata ranging from the Pathhead Formation (top Visean) to Middle Coal Measures (Westphalian B). Radiometric ages on associated intrusions span the Late Carboniferous (Stephanian)–Permian boundary, but some may be contemporaneous with earlier volcanic beds in the local Namurian to Westphalian succession. Some necks are associated with the Ardross Fault, an important ENE-trending strike-slip structure that extends for about 8 km, more-or-less axial to the Midland Valley. It possibly exerted control on the location of the volcanism and is thought to be a re-activated Caledonian basement structure.

Both fragmental and crystalline intrusive rocks in a number of the necks contain xenoliths and megacrysts of lower-crustal and upper-mantle material. Their study has provided a major contribution to knowledge of the deep structure of northern Britain and has given an insight into the genesis of the Carboniferous–Permian magmas (see Chapter 1). They have also provided a source of material for numerous detailed studies of individual minerals such as garnets and zircons.

The necks have long attracted the attention of geologists and were first described by Geikie (1880, 1897, 1902) and Wallace (1916). Important work was done by Balsillie (1920a,b, 1923, 1927) and Cumming (1928, 1936), but it is mainly the detailed work of E.H. Francis to which we owe most of our present knowledge (Francis, 1960, 1968a,b, 1970b; Francis and Hopgood, 1970). Comprehensive details of the field relationships of the necks and their interpretation in terms of Silesian volcanic processes were published by Francis in Forsyth and Chisholm (1977). They are featured in several reviews (Upton, 1982; Cameron and Stephenson, 1985; Francis, 1967, 1978a, 1991) and excursion guides (Francis and Hopgood in Upton, 1969; MacGregor, 1996). Detailed studies of the xenoliths and megacrysts include those by Colvine (1968), Chapman (1974, 1976), Chapman and Powell (1976), Macintyre *et al.* (1981), Donaldson (1984), Aspen *et al.* (1990), Hinton and Upton (1991) and Upton *et al.* (1999).

Description

The East Fife Coast GCR site comprises two extensive sections of the East Fife coast. The larger section extends for nearly 10 km from Ruddons Point to St Monance harbour, and the shorter section, west of this, extends for a little under 4 km around Largo Bay from Lundin Links to Viewforth. Of additional geological interest at the site are the local sedimentary sequence, fish and amphibian fossils (Dineley and Metcalfe, 1999), raised beaches, and mineral localities.

A total of 15 or so volcanic necks with associated plugs and minor intrusions, crop out within the site. Most are well exposed in the intertidal zone though exposures vary from time to time. The field relationships of individual necks are described in great detail by Francis (in Forsyth and Chisholm, 1977) and a summary of their main lithological units and structural features is shown here in Table 4.1. The original relationships of these lithologies and structures within the original volcanoes may be conveniently illustrated in a hypothetical cross-section (Figure 4.6).

Lithological components of the necks

Pyroclastic rocks form the principal component of all the necks. The dominant clasts are grey to greenish-grey alkali basalt and basanite, which vary in size from coarse ash to lapilli with rare larger bombs. They are predominantly of the ragged-edged, chilled juvenile type but there are also accessory lapilli and blocks. Other clasts are massive or thinly bedded tuffs and sedimentary rock debris. Fragments of woody material have been recorded in some necks. All are set in an altered greenish-grey matrix of basaltic coarse tuff.

Bedded tuffs appear to be more common than massive tuffs, but the two are intimately associated in the necks and commonly pass laterally into one another. The bedded tuffs are usually medium to thickly bedded and individual beds are moderately sorted. Sedimentary structures include graded bedding and cross-bedding. The massive tuffs are considerably more heterogeneous. They may be either moderately sorted or unsorted and chaotic. The less well-sorted tuffs generally occur towards the centre of necks.

Pyroclastic breccias in which the clasts are predominantly angular and almost exclusively of basalt, are commonly located in the more central portions of the necks. In some cases they grade into marginal basalt-dominated bedded tuff and agglomerate or into coherent basaltic intrusions.

Sediment-derived tuffs are most commonly located at the margins of a neck. Here they either grade outwards into country rock or are bound on both sides by ring-fractures. These tuffs are grey to greenish in colour and are composed mostly of fragments of brecciated country rock, most commonly sandstone, ranging in size up to blocks. In addition, there may be a small but variable population of basaltic clasts and even some basaltic bombs; examples of the latter are seen in the Craigforth Neck. The matrix is generally also derived from the country rock and comprises comminuted lithic fragments and crystals.

(Table 4.1) Lithological units and features of the volcanic necks between Lundin Links and St Monance, East Fife Coast. (Abbreviations: LL = Lundin Links; VF = Viewforth; RP = Ruddons Point; KC = Kincraig; CF = Craigforth; CN = Chapel Ness; EH = Elie Harbour; EN = Elie Ness; WL = Wadeslea; AR = Ardross; CH = Coalyard Hill; NW = Newark; DC = Dovecot; DR = Davie's Rock; SM = St Monance.) Based on Francis in Forsyth and Chisholm, 1977, figs 20–24; Upton *et al.,* 1999.

Lithological units / Necks	LL	VF	RP	KC	CF	CN	EH	EN	WL	AR	CH	NW	DC	DR	SM
Basaltic tuff and agglomerate (bedded)		•	•	•	•		•	•	•	•		•			•
Basaltic tuff and agglomerate (unbedded)	•	•	•	•				•	•	•	•	•	•		•
Basaltic breccia				•			•								
Sediment-derived tuff					•					•	•	•			
Tuffisite breccia			•	•	•	•	•		•	•			•	•	•
Tuffisite dyke(s)		•	•	•		•		•					•		•

Tuffisite intrusion(s)									•	•		•	•		
Basaltic dyke(s)	•				•		•	•	•	•			•		
Basaltic intrusion(s) (not specified)	•		•	•							•			•	•
Olivine basalt and basanite intrusion(s)						•	•							•	
Olivine-dolerite intrusion(s)							•	•							
Sandstone (large xenoliths and rafts)			•	•			•			•	•		•		•
Carboniferous sedimentary rocks	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Bedding: • =collapsed; ■ = centroclinal	■	•	■	•	■		■	•■	■						
Marginal ring-faults or shear zones	•	•		•			•				•				•
Cryptovolcanic structures				•	•								•		
Megacrysts and xenoliths			•					•		•	•				

Tuffisites (intrusive tuffs) were emplaced along radial and concentric fractures within most of the East Fife necks and they are common on the inside of marginal ring-fractures. They also occur as a marginal facies to associated basaltic intrusions. A characteristic feature is a strong flow foliation, especially at the margins. When derived from a mainly sedimentary source, tuffisite commonly veins or acts as the matrix to many of the breccias and sediment-derived tuffs associated with the volcanic necks.

Minor intrusions of basalt, basanite and dolerite are commonplace in and near the volcanic necks. Many are highly irregular. They range from minor dykes and sheets, commonly occupying ring-faults or radial fractures, to central plug-like bodies. The larger intrusions exhibit columnar jointing, indicating slow and uninterrupted cooling. Some basaltic dykes intruding the adjacent, locally carbonaceous, country rock are extremely altered. Their very pale and bleached appearance is due to replacement by carbonates and the rock-type is traditionally referred to as 'white trap'.

Structural features of the necks

Most of the necks have an irregular, but broadly oval, plan and vary in size from a few tens of metres to hundreds of metres across. Their margins are usually inwardly dipping and are commonly ring-faults.

Within the tuff and agglomerate of many necks, there are small areas, usually ill-defined, where the attitude of the bedding and of large rafts of fractured bedded tuff, has been disturbed, re-orientated and even overturned. Some beds appear to have flowed or deformed plastically. Where bedding is relatively undisturbed it is centroclinal, i.e. inclined inwards towards a central focus, with the higher dips close to the neck margins.

Cryptovolcanic ring-structures are noted sporadically among the country rocks near some necks. These are circular or oval areas of variably brecciated strata that vary considerably in size from 3 m to 200 m in diameter. The breccias are composed entirely of angular clasts of sedimentary rock up to several metres across in a variable amount of matrix that consists of tuffisite of mainly sedimentary origin. The degree of fragmentation varies from simply fractured in the smaller structures, through in-situ breccias with increasingly disorientated clasts, to coarse breccias with a higher proportion of matrix and veins of tuffisite in the larger structures. Thin dykes of bleached basalt feature in some. The structures range from small swells and gentle domes to larger vertically sided ring-structures in which blocks become orientated parallel to the contacts.

The individual necks

The necks may be conveniently divided into those associated with the Ardross Fault and those that are not.

Only the necks in the eastern half of the GCR site are associated with the Ardross Fault. They are the Elie Harbour Neck [NT 4930 9955], Elie Ness Neck [NT 498 994], Wadeslea Neck [NT 503 997], Ardross Neck [NO 5045 0020], Coalyard Hill Neck [NO 5120 0085], Newark Neck [NO 516 012], Dovecot Neck [NO 5095 0115], Davie's Rock Neck [NO 5210 0125] and St Monance Neck [NO 5225 0140]. The last three are situated south-east of the Ardross Fault but are still loosely aligned along its trend.

The *Elie Harbour Neck* consists of tuffs, lapillistones and agglomerate, traversed by a few impersistent basaltic dykes. The agglomerate consists of large blocks and bombs of scoriaceous basalt and sedimentary rock, including, in the central part of the neck, a large raft of sediment-derived tuffisite. Geikie (1902) also noted fragments of wood and coal. The Ardross Fault separates the Elie Harbour Neck from the *Elie Ness Neck.* The latter, orientated crudely northeast–south-west, comprises well-bedded, inward-dipping (centroclinal) basaltic tuffs and agglomerates. Sedimentary structures include cross-bedding, graded bedding and slump-bedding, and deformation caused by the impact of volcanic ejecta and contemporaneous collapse (Figure 4.7). The pyroclastic rocks also contain 'breadcrust' bombs of basalt and blocks of sedimentary rock, but it is for its exotic clasts that the neck is perhaps best known. These include various xenolithic nodules and xenocrysts. The latter include pyrope garnet (so-called 'Elie Ruby'), zircon and alkali feldspars. The Elie Ness Neck is separated from the *Wadeslea Neck* by a narrow outcrop of folded sedimentary rocks, and minor tuffisite breccia. The *Ardross Neck,* on the opposite side of the Ardross Fault to the Wadeslea Neck, is comparatively simple and comprises only massive and bedded tuff and agglomerate. A series of *en échelon* dykes of xenolithic basalt, penetrated locally by sediment-derived tuff sites, is present in the northern part. Divorced from the main body of the Ardross Neck, but situated a short distance to the northeast along the line of the Ardross Fault, are two small outcrops of tuffisite. These are important because their orientation, and also that of the materials within them, mirrors that of the fault, strongly suggesting that their emplacement had strong tectonic control.

The *Coalyard Hill Neck* is described by Francis (in Forsyth and Chisholm, 1977) as a composite structure, consisting of outer and inner necks. These are very different in form and litho-logy, but collectively they demonstrate the structure and evolution of a typical Late Carboniferous Midland Valley volcanic neck. The outer neck, which is the older, is only 100 m wide but extends for about 700 m along the north-western side of the Ardross Fault. It is dominated by sediment-derived tuff but there is scattered basaltic material within it. It is cut by tuffisite veins, and flow-banded tuffisite commonly flanks the larger clasts and rafts (Figure 4.8), including some large blocks of crinoidal limestone at the western margin. The inner neck consists of massive, basaltic tuffs and agglomerates with ill-defined masses of basaltic breccia and minor basaltic intrusions. A small intrusion of basanite at the south-western contact contains xenoliths of spinel lherzolite and also rare wehrlite and pyroxenite (Table 4.2). Only a small area of the *Newark Neck* is exposed on the north-western side of the Ardross Fault. It mainly comprises sediment-derived tuffs although locally the matrix carries fragments of juvenile basalt. These tuffs grade imperceptibly into bedded basaltic tuffs and agglomerates forming the central zone of the neck.

The small *Dovecot Neck* provides good examples of neck-margin phenomena such as the localized thrusting, deformation and induration of country rock and intrusions of flow-aligned tuffisite. One large raft of sandstone, penetrated from below by flow-aligned tuffisite, may have formed part of the stoped roof of a cryptovolcanic ring-structure. The *Davie's Rock Neck* is emplaced in the crest of an anticline and consists of a central plug-like mass of nepheline basanite surrounded by tuffisitic breccia. Francis interpreted the exposures as a deep section through another large cryptovolcanic structure. The *St Monance Neck* is the most easterly neck in the GCR site. It consists almost entirely of massive, unbedded lapilli-tuff and agglomerate cut by a series of crosscutting monchiquitic dykes (Figure 4.9). Large clasts of sedimentary rock, some with tuffisite veining, are common towards the margins.

(Table 4.2) Distribution of accidental xenoliths and megacrysts in the East Fife necks (* = fragmental pyrope garnets – the famous, so-called 'Elie Ruby') (additional minor xenocryst phases are listed in the text). (Abbreviations: RP = Ruddons Point; EN = Elie Ness; CH = Coalyard Hill; AR = Ardross.)

Volcanic Neck	RP	EN	CH	AR
Xenoliths				
Hydrated ultramafic rock		•		•
Spinel lherzolite	•		•	
Wehrlite	•		•	
Biotite-amphibole pyroxenite	•		•	
Anorthoclasite	•	•		
Pyroxene granofels and gneiss	•			
Quartzo-feldspathic granofels and gneiss		•		
Garnetiferous quartzo-feldspathic granofels and gneiss			•	
Garnetiferous ultramafic rock		•		
Principal megacrysts and xenocrysts				
High-temperature feldspar — mainly anorthoclase	•	•	•	•
Garnet *		•		
Corundum	•			
Zircon		•		

Necks that are not associated with the Ardross Fault are all situated north-west of the fault. They are the Lundin Links Neck [NO 411 024], Viewforth Neck [NO 431 024], Ruddons Point Neck [NO 454 004], Kincraig Neck [NT 466 998], Craigforth Neck [NT 475 996] and Chapel Ness Neck [NT 4755 9935].

The *Lundin Links Neck* is the most westerly within the GCR site. It is comparatively small and cuts the Middle Coal Measures some 30 m below the Barncraig Coal. The *Viewforth Neck,* farther east around Largo Bay, is composed solely of fragmental deposits. It has steeply dipping, inwardly inclined margins against Passage Formation strata. The *Ruddons Point Neck* forms a rocky promontory between Largo Bay and Shell Bay and is formed of approximately equal proportions of pyroclastic rocks and basaltic intrusions. The main plug is one of the largest in East Fife. The intrusions carry xenocrysts (Table 4.2). On the opposite side of Shell Bay the *Kincraig Neck,* measuring 1.5 km in length, is the largest of the coastal necks in East Fife. It contains most of the elements and features listed in (Figure 4.6) and provides a unique opportunity to determine the three-dimensional relationships between neck materials, intrusions and country rock. The largest intrusion is a flat-based boss or sill-like body of basalt with exceptionally well-developed columnar jointing (Figure 4.10). Both the *Craigforth Neck* and the *Chapel Ness Neck* are comparatively small structures. The latter is unusual in that it mainly comprises an irregular-shaped intrusion of olivine basalt and basanite. Elie Bay to the east contains at least three cryptovolcanic ring-structures.

The Ardross Fault

The surface trace of the Ardross Fault is most readily seen in the shore sections between the Elie Ness, Wadeslea, Ardross and Coalyard Hill necks. The line of the fault is traceable by litho-logical contrasts on either side, and locally by an ill-defined weathered-in zone. The style of the folding in the adjacent country rock is broad and open on one side, and tight, locally isoclinal, on the other; the intensity of folding dies out abruptly away from the fault. The fault shows dextral lateral movement and there is a consistent sense of vertical drag with a downthrow to the north-west (Francis and Hopgood, 1970). Although the fault appears to control the siting of many of the necks, the principal fault movements demonstrably post-date neck emplacement.

The xenolith, cumulate inclusion and megacryst suites

In addition to the dominant clasts of juvenile or 'parental' basaltic material, some tuffs and intrusions in the necks contain sparse, more exotic clasts such as large, accidental crystals and various mafic and ultramafic rocks. Similar material also occurs as megacrysts and xenoliths in associated intrusions (Table 4.2). The Ruddons Point, Elie Ness, Ardross and Coalyard Hill necks are internationally famous in this respect, and this extremely important feature of the Carboniferous-Permian Igneous Province of northern Britain is discussed more fully in Chapter 1.

The majority of exotic inclusions and xenoliths in the Elie Ness and Ardross necks are hydrated ultramafic rocks (Chapman, 1976), including both feldspar-free and albite-bearing pyroxenites. In the Ruddons Point and Coalyard Hill necks the commonest type is a spinel lherzolite but there are also scarce iron-rich wehrlites as well as biotite- and amphibole-rich pyroxenites, rare composite wehrlite-lherzolites, websterites and garnet-bearing pyroxenites (Chapman, 1974). Other rock-types include metamorphic rocks such as granulite-facies mafic gneisses and both garnetiferous and quartzo-feldspathic gneisses. Examples of the latter, with plagioclase porphyroblasts, are recorded from the Coalyard Hill Neck.

Anorthoclase, a high temperature alkali feldspar, is the commonest megacryst phase in the Fife necks (Chapman and Powell, 1976; Aspen *et al.,* 1990). Pinkish-white crystals, some over 10 cm in size, have been found in most necks. Anorthoclase-dominated composite megacrysts grade into anorthoclasites with subordinate zircon, chlorite pseudomorphs after clinopyroxene, corundum and an yttro-niobate rich in the heavy rare-earth elements uranium and thorium (Upton *et al.,* 1999). The Ruddons Point Neck contains the broadest compositional range of anorthoclase megacrysts, with lesser ranges in the Elie Ness, Coalyard Hill and Ardross necks. The Elie Ness Neck is noted for its fresh, orange-brown, fractured, but inclusion-free, pyrope garnets (Colvine, 1968; Donaldson, 1984). They are known locally as 'Elie Rubies' and occur mostly as fragments from 0.25 mm to 25 mm in size. Sub-calcic augite, kaersutite, magnetite, apatite and zircon (the latter rarely up to up to 5 mm in size) have also been recorded at Elie Ness. Orthopyroxene has been recorded at Ruddons Point (Balsillie, 1927), Davie's Rock and Coalyard Hill.

Timing of volcanic activity

The age of the East Fife necks has been the subject of considerable debate. Country rocks range from Dinantian (Asbian–Brigantian) Pathhead Formation strata at, and east of, the Elie Ness Neck, to (Westphalian B: Duckmantian) Middle Coal Measures strata at the Lundin Links Neck. Tuffs interbedded with the local sedimentary succession demonstrate that East Fife had an almost unbroken history of volcanic activity from early Namurian to mid-Westphalian times, so it is possible and indeed likely that the necks span a similar range.

K-Ar whole-rock ages of intrusions within East Fife necks (Forsyth and Chisholm, 1977; Forsyth and Rundle, 1978) show a range from Stephanian to Early Triassic. The youngest (244 ± 6 Ma), was obtained from a minor intrusion within the Lundin Links Neck but is perhaps anomalous due to argon loss. However, the five oldest results, from St Monance, Chapel Ness, Davie's Rock and Largo Law, are indistinguishable within the limits of analytical error within the range 295–288 Ma and hence the best estimate for the time of emplacement is close to the Stephanian–Permian boundary (Forsyth and Rundle, 1978; Wallis, 1989). Other K-Ar whole-rock dates for intrusions from Kincraig (De Souza, 1979) and from the Ruddons Point, Kincraig and Chapel Ness necks by Wallis (1989) all seem to be anomalously young.

K-Ar dating of both inclusions and intrusions associated with the Ruddons Point, Kincraig, Elie Harbour, Elie Ness, Ardross and Coalyard Hill necks was carried out by Macintyre *et al.* (1981). The results suggest that basanites in both of the Elie necks have a probable minimum emplacement age of 276 ± 4 Ma (Early Permian). Anorthoclase megacrysts from the Ruddons Point, Elie Ness, Ardross and Coalyard Hill necks appear to have crystallized by 294 ± 3 Ma (Stephanian). However dating of ultramafic cumulate xenoliths from the Elie Ness and Kincraig necks suggests that the inclusions formed or last equilibrated much earlier, at 315 Ma (Namurian to Westphalian boundary) and at shallow depth. Similar ages have been obtained from megacrysts at Elie Ness; around 318 Ma by U-Pb on zircons (Macintyre *et al.,* 1981) and a plateau age of 311 ± 3 Ma by Ar-Ar on kaersutite (M. Timmerman, pers. comm., 2002).

Interpretation

The location of several volcanic necks within the East Fife Coast GCR site appears to have been controlled by the Ardross Fault. This high-level fault probably resulted from the re-activation of a deep-seated Caledonian structure and is considered to have been active intermittently throughout the Carboniferous and perhaps into the Permian Period (Francis and Hopgood, 1970). The radiometric ages of the necks suggest that they were probably emplaced during Stephanian to Early Permian times. During this time shallow-water environments persisted (Forsyth and Chisholm, 1977) and this had a pronounced effect upon the style of the contemporaneous volcanism.

The present-day outcrop of each neck represents a horizontal slice through the sub-volcanic plumbing of a small- to medium-sized volcano. These volcanoes were the result of violent eruptions and produced mainly fragmental pyroclastic products rather than lavas. There is considerable evidence to suggest that many of these eruptions were steam-driven phreatic and phreatomagmatic explosions, as bodies of ascending magma came into contact with aquifers, wet sediments or bodies of standing water such as shallow seas and lakes. The ash cones that typically form in such conditions have a wide diameter and relatively low height and are termed tuff-rings or maars (Lorenz, 1973, 1986). This type of activity is often compared to Surtseyan-style volcanism of marine areas, as summarized by Kokelaar (1986) and White and Houghton (2000). Phreatomagmatic volcanoes in general range from subaqueous to emergent to subaerial (Godchaux *et al.,* 1992), but the Fife volcanoes most readily fit the transition from emergent to subaerial.

Much of the form and structure of the volcanoes has been preserved due to post-eruptive processes, especially the foundering of sequences within the funnel-shaped conduits that now constitute the necks. Areas of collapsed and centroclinal bedding are thought to be due to the intermittent and progressive inward collapse of unconsolidated fragmental deposits as the magma withdrew to depth. The dominant centroclinal bedding in any one neck is related to the final stages of collapse, generally at the end of the last episode of volcanic activity at that site. The margins of many necks are ring-fractures and it is thought that some of the Fife volcanic sequences may have subsided by up to 500 m, revealing a variety of original structural levels at current erosion levels. However, ring-fracturing may have been an intermittent phenomenon with several generations of subsidence (Lorenz, 1973, 1986; Francis, 1991). The intermittent nature of the volcanicity is indicated by the abundance within the necks of obviously recycled clasts, such as blocks of bedded tuff and volcaniclastic breccia.

The necks are filled by pyroclastic and volcaniclastic rocks that formed sequences of volcanic ejecta in and around the volcanic craters. The presence of bedding, along with fragments of wood, volcanic bombs and clasts of contemporary sedimentary origin, some with interbedded coals, all strongly imply a mainly subaerial origin. The basal facies of subaerial volcanoes such as these usually contain much non-juvenile, country-rock material, commonly as large blocks. Such lithologies are well represented in most of the East Fife necks. Beds of massive tuff within otherwise bedded sequences may be high-concentration base-surge deposits (Chough and Sohn, 1990). Base-surge activity may also have formed some of the hummocky cross-bedding. Other cross-bedding may be due to reworking with the development of slump or debris sheets and lahar-like slurries.

Tuff sequences that are unbedded or with only minor bedded units suggest a more subaqueous origin. This is a common feature in the basal facies of small phreatic to phreato-magmatic volcanoes (Godchaux *et al.,* 1992), where initial activity is accompanied by chaotic deposits and some mobilization, often resulting in slumps and debris flows. The highly degraded state and green colouration of many of the basaltic clasts may reflect the formation of basaltic glass due to quenching by the water, followed by rapid alteration to palagonite and subsequently to chloritic residues. Since there are no known pillow lavas and associated hyaloclastite breccias in the Fife necks at their present levels of exposure, this subaqueous phase was probably short-lived. The phreatomagmatic phase was probably followed by more dominantly magmatic activity in which basaltic pyroclastic eruptions occurred subaerially or in shallow water.

The cryptovolcanic ring-structures are believed to represent incipient neck formation, the breccias forming in country-rock strata above magma bodies that failed to breach the surface to form volcanic cones. Where this explosive brecciation of both country rock and contemporaneous volcanic products was followed by their mobilization through gas/steam fluidization or fluxion processes, bodies of tuffisite were emplaced.

Magmas failing to reach the surface were emplaced as sub-surface intrusions. Most were intruded as dykes, thin sheets and irregular masses, but some formed solid plug-like structures to the main volcanic vents. The Ruddons Point intrusion, for example, is one of the largest in East Fife. The basaltic breccias that are common in the central parts of the necks may be interpreted as either pyroclastic breccias or as masses of intrusive basalt brecciated *in situ* by subsequent intrusions and violent gas and stream-driven eruptions. There is no conclusive proof of subaerial lavas having developed, though these might have been a natural consequence of the later evolution of the volcanoes. Some dykes and plugs may have fed lavas, though no direct evidence for this exists.

The 'exotic' inclusions, xenoliths and megacrysts that occur within the necks and associated intrusions are thought to have been derived from the lower crust and the lithospheric upper mantle. Assemblages from several of the East Fife necks (Table 4.2) have played a leading part in formulating ideas as to the deep structure of the Midland Valley (e.g. Upton *et al.,* 1984) and also in the construction of complex petrogenetic models (e.g. Macintyre *et al.,* 1981; Upton *et al.,* 1999) (see Chapter 1). Chapman (1976) interpreted the various igneous xenoliths from the Elie Ness Neck as within-mantle and within-crust differentiates of alkali basalt magmas. Studies of the pyrope garnet megacrysts (The Rubies') by Colvine (1968) and Donaldson (1984) suggest that the magmas contained significant water and were cooler than had been supposed previously. Aspen *et al.* (1990) considered that the anorthoclase megacrysts represent syenitic (salic alkaline) vein deposits crystallized from magmas in the upper mantle, and Upton *et al.* (1999) concluded that they and the associated anortho-clasites may also occur as pegmatitic veins traversing pyroxenitic wall-rocks.

Conclusions

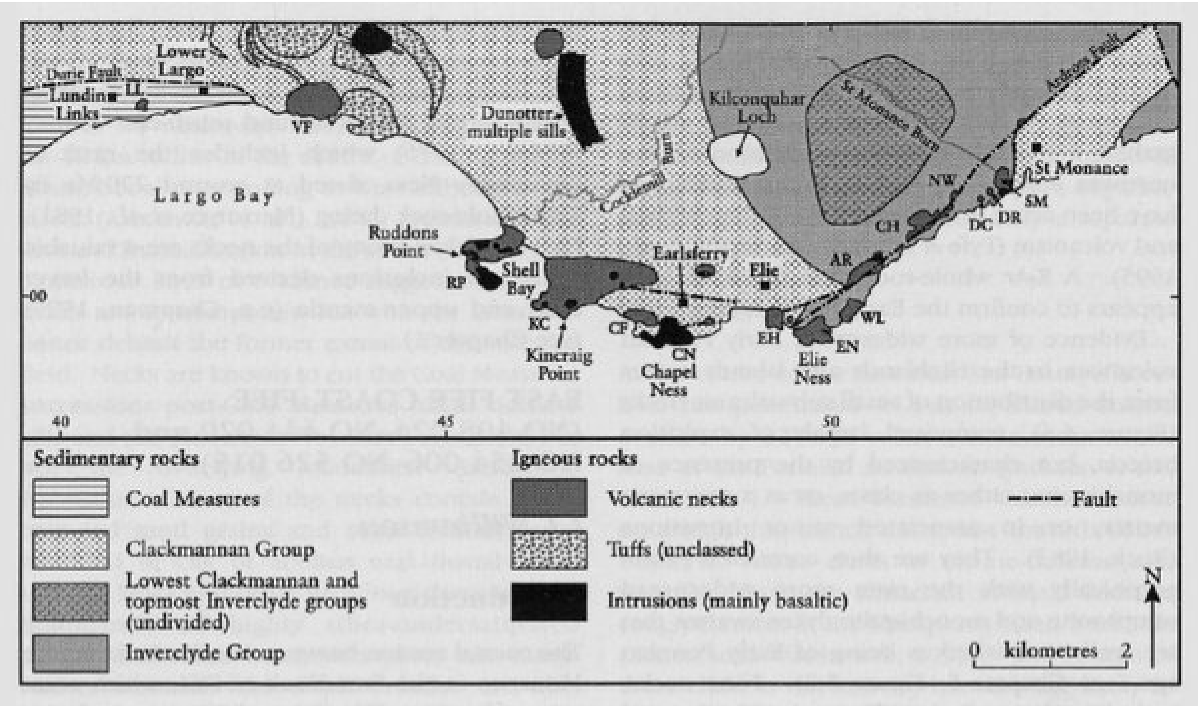
The East Fife Coast GCR site contains no less than 15 volcanic necks, the eroded remains of a series of small Late Carboniferous to Early Permian volcanoes. These exceptional exposures are of international value as they enable reconstructions of the original form of the volcanoes, their mechanisms of emplacement and the environments in which they formed. Exposure is excellent and, as the necks are exposed at different structural levels, three-dimensional relationships are clear. The site is consequently much used for research, and is a popular venue for educational field parties.

The necks are thought to represent the roots of low cinder and ash cones known as tuff-rings or maars, formed during violent (phreatomagmatic) eruptions due to the explosive interaction of magma with groundwater and surface water. The presence of intrusive fragmental rocks (tuffisites) containing much country-rock material, points to the importance of gas-streaming by water vapour generated during the eruptions. Adjacent sedimentary country rocks are commonly disrupted by folding and brecciation. Although there is no evidence that magma was ever erupted as lava, many of the necks contain minor intrusions and larger plugs of basalt, representing magma that solidified relatively close to the surface.

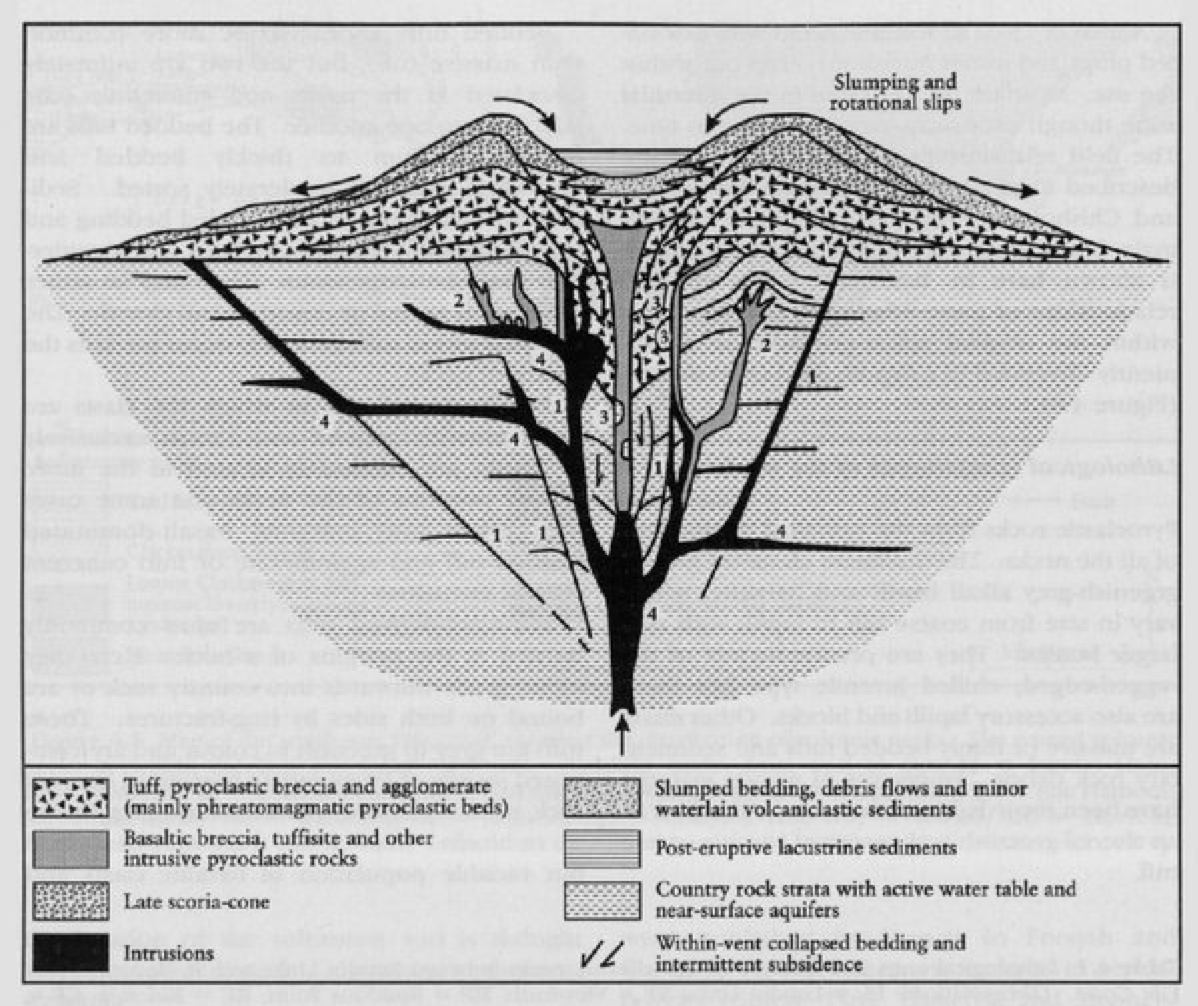
Some of the necks are aligned along the Ardross Fault which, although demonstrably active during and after the volcanism, is thought to be a re-activation of a deeper Caledonian basement structure and probably acted as one of a number of factors controlling the sites of the volcanoes.

Several of the necks contain suites of rocks and crystals (xenoliths and xenocrysts) brought up from great depths by the rising magmas. By studying these assemblages it is possible to investigate the high-pressure–high-temperature processes that operated beneath the volcanoes, in the lower part of the Earth's crust and the underlying upper mantle beneath the Midland Valley. The results have an important bearing upon the origin of the magmas that produced the Carboniferous–Permian Igneous Province of northern Britain.

References



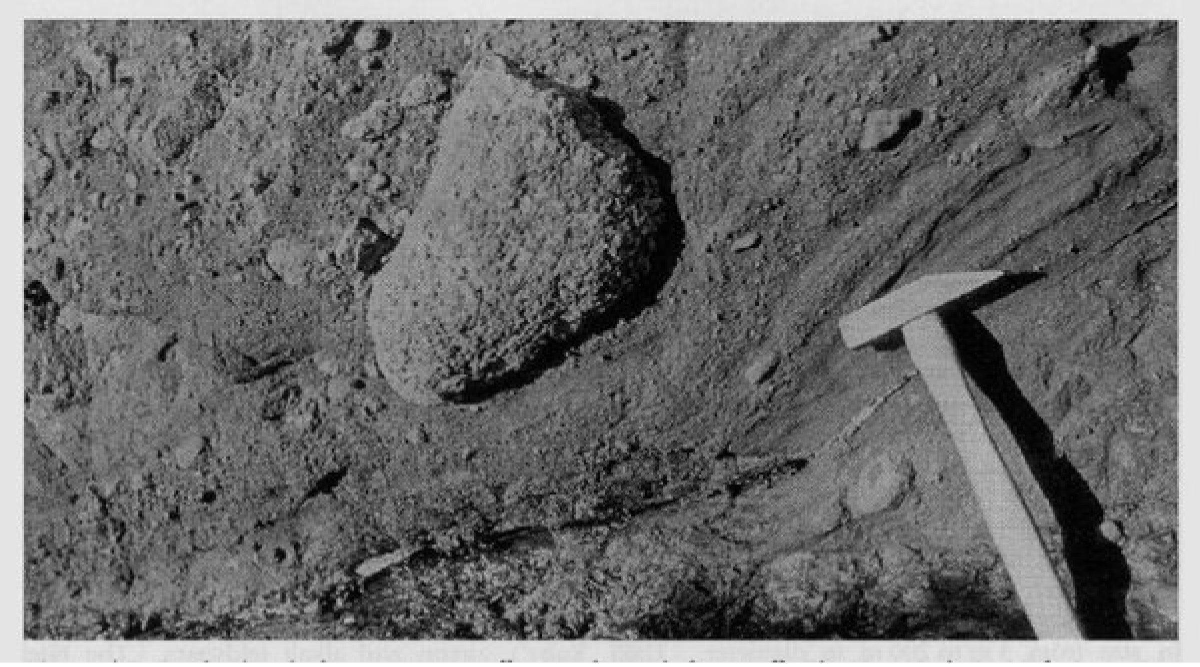
(Figure 4.5) Map of the south-east Fife coast, showing the distribution of volcanic necks. The named volcanic necks lie within the East Fife Coast GCR site. (Volcanic necks, from west to east: LL = Lundin Links; VF = Viewforth; RP = Ruddons Point; KC = Kincraig; CF = Craigforth; CN = Chapel Ness; EH = Elie Harbour; EN = Elie Ness; WL = Wadeslea; AR = Ardross; CH = Coalyard Hill; NW = Newark; DC = Dovecot; DR = Davie's Rock; SM = St Monance.) Based on Geological Survey 1:50 000 Sheet 41, North Berwick (1970).



(Figure 4.6) Schematic cross-section through an evolving tuff-ring, illustrating some of the volcanic processes thought to have been involved in the emplacement of the East Fife volcanic necks. The exposed necks within the GCR site may be interpreted in terms of sub-horizontal sections through this structure. (Features marked on the diagram: 1 = ring-faults with marginal tuffisite and breccia, or basaltic dykes; 2 = tuffisite within country rock — may develop adjacent to sills or dykes; 3 = large foundered bodies of country rock within vent and entrained within breccias and tuffisite; 4 = minor intrusions emplaced along bedding and fault planes.) Based on Forsyth and Chisholm (1977, fig. 17 after Francis, 1970b and Lorenz, 1973); Lorenz (1986); and Godchaux et al. (1992).

Lithological units / Necks	LL	VF	RP	KC	CF	CN	EH	EN	WL	AR	CH	NW	DC	DR	SM
Basaltic tuff and agglomerate (bedded)		●	●	●	●		●	●	●	●		●			●
Basaltic tuff and agglomerate (unbedded)	●	●	●	●				●	●	●	●	●	●		●
Basaltic breccia				●			●								
Sediment-derived tuff					●					●	●	●			
Tuffisite breccia			●	●	●	●	●		●	●			●	●	●
Tuffisite dyke(s)		●	●	●		●		●					●		●
Tuffisite intrusion(s)									●	●		●	●		
Basaltic dyke(s)	●				●		●	●	●	●			●		
Basaltic intrusion(s) (not specified)	●		●	●							●			●	●
Olivine basalt and basanite intrusion(s)						●	●							●	
Olivine-dolerite intrusion(s)							●	●							
Sandstone (large xenoliths and rafts)			●	●			●			●	●		●		●
Carboniferous sedimentary rocks	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Bedding: ●=collapsed;○=centroclinal		●	○	●	○		○	●○	○						
Marginal ring-faults or shear zones	●	●		●			●				●				●
Cryptovolcanic structures				●	●								●		
Megacrysts and xenoliths			●					●		●	●				

(Table 4.1) Lithological units and features of the volcanic necks between Lundin Links and St Monance, East Fife Coast.

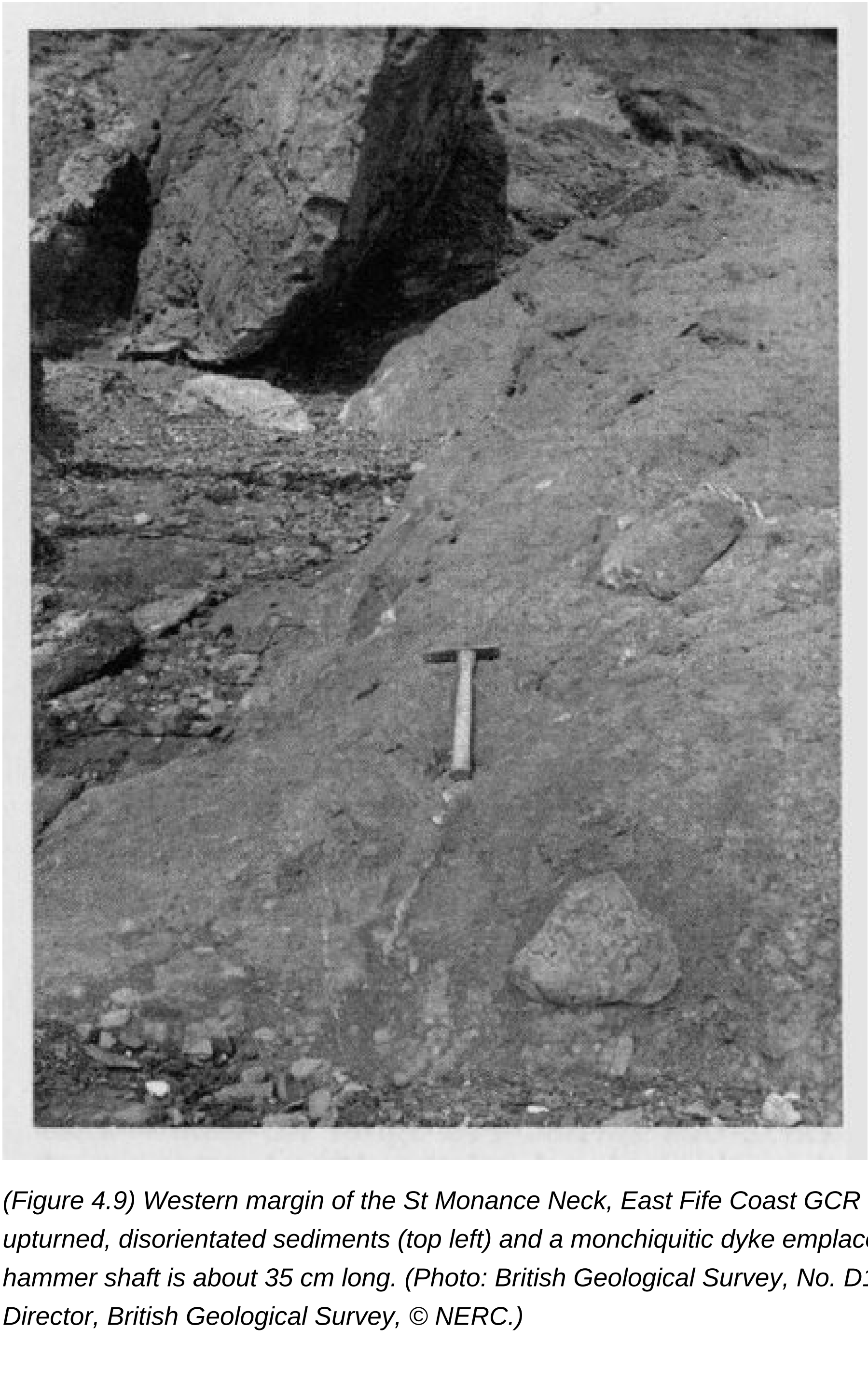


(Figure 4.7) Basaltic bomb showing impact effects in the underlying tuffs, Elie Ness Neck, East Fife Coast GCR site. The hammer head is about 15 cm long. (Photo: British Geological Survey, No. MNS1635, reproduced with the permission of the Director, British Geological Survey, © NERC.)

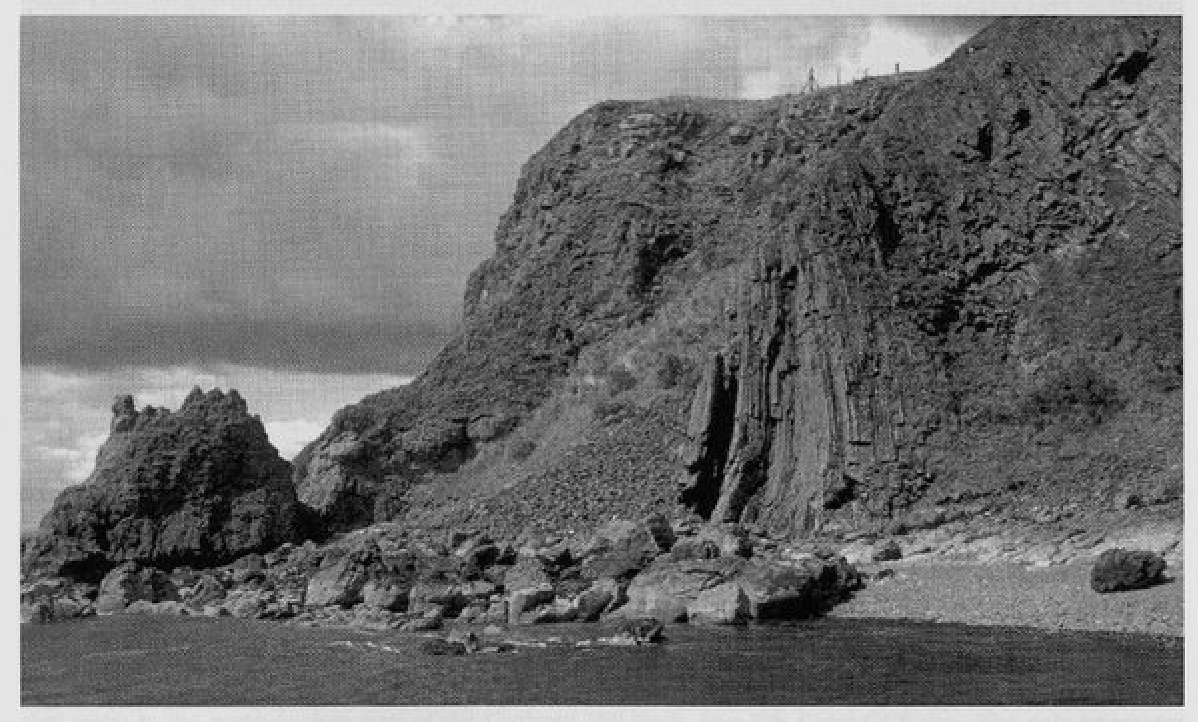
(Figure 4.8) Flow-banding in tuffisite (below hammer) intruded into a large raft of sandstone (on which the hammer rests) in the north-eastern part of the Coalyard Hill Neck, East Fife Coast GCR site. The pale fragments elongated parallel to the edge of the sandstone are of bleached basalt. The hammer shaft is about 35 cm long. (Photo: British Geological Survey, No. D1680, reproduced with the permission of the Director, British Geological Survey, © NERC.)

Volcanic Neck	RP	EN	CH	AR
Xenoliths				
Hydrated ultramafic rock		●		●
Spinel lherzolite	●		●	
Wehrlite	●		●	
Biotite-amphibole pyroxenite	●		●	
Anorthoclasite	●	●		
Pyroxene granofels and gneiss	●			
Quartzo-feldspathic granofels and gneiss		●		
Garnetiferous quartzo-feldspathic granofels and gneiss			●	
Garnetiferous ultramafic rock		●		
Principal megacrysts and xenocrysts				
High-temperature feldspar – mainly anorthoclase	●	●	●	●
Garnet *		●		
Corundum	●			
Zircon		●		

(Table 4.2) Distribution of accidental xenoliths and megacrysts in the East Fife necks.



(Figure 4.9) Western margin of the St Monance Neck, East Fife Coast GCR site, showing tuff and agglomerate (right), upturned, disorientated sediments (top left) and a monchiquitic dyke emplaced along part of the margin (top centre). The hammer shaft is about 35 cm long. (Photo: British Geological Survey, No. D1679, reproduced with the permission of the Director, British Geological Survey, © NERC.)



(Figure 4.10) Curved columnar jointing in basalt intrusion within the Kincraig Neck, East Fife Coast GCR site. (Photo: British Geological Survey, No. D1684, reproduced with the permission of the Director, British Geological Survey, © NERC.)