Petrochemistry and Palaeogeographic Setting of the Ordovician Volcanic Rocks of Smøla, Central Norway

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The Arenig–Llanvirn volcanic rocks of Smøla are distinctly calc–alkaline in their chemistry. All rock-types in the association high-alumina basalt – basaltic andesite – andesite – dacite – rhyolite are represented although the basalts and basaltic andesites are predominant. The volcanites, together with their plutonic associates which include extensive, late, quartz diorites and granodiorites, are indicative of eruption in a mature, evolved island arc developed upon a 'transitional' crust of intermediate (oceanic-to-continental) thickness which gradually thickened throughout Ordovician time. There is little evidence of the precise nature of the immediate substrate to the magmatic arc, but the regional picture favours a construction of the arc upon an obducted and deformed ophiolitic crustal segment. Further consideration of the regional geology, aided by polarity evidence, indicates that the trench, with SE–E subduction, and also the main oceanic tract of Iapetus, was situated to the west of the Smøla arc in Llanvirnian times. This palaeogeographic setting focuses attention on certain problems regarding lithostratigraphic correlation within the now fragmented Caledonian orogen, as well as on the significance and application of the concept of faunal provincialism.

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Introduction

Since the time of the initial researches of Schetelig (1913) and Reusch (1914) the island of Smøla off coastal central Norway has captured the interest of palaeontologists by virtue of the presence of an early Ordovician fauna in limestones. The fossils, mostly gastropods and brachiopods, were described by Holtedahl (1915, 1924) and Strand (1932). More recently, additions to the faunal assemblage have been reported by Bruton & Bockelie (1979).

The limestones, together with conglomerates and other sediments, occur in close association with a suite of predominantly basic volcanic rocks, the petrology of which has been studied by Carstens (1924). Despite this early interest in Smøla the first detailed geological map of the island did not appear until 1975, and represents a compilation by F. Fediuk based on his unpublished investigations from 1969. This provided the impetus for further work; palaeontological, geochronological and in the present case geochemical, a continuation of a study of the petrochemistry of the Lower Palaeozoic basic volcanic and related rocks of the central Norwegian Caledonides initiated in 1971 (Gale & Roberts 1972, 1974). In this paper the results of the investigation of Smøla Ordovician volcanite geochemistry are presented and brief comparisons made with chronostratigraphically equivalent extrusive sequences occurring in other areas of this part of the Caledonian orogenic belt.

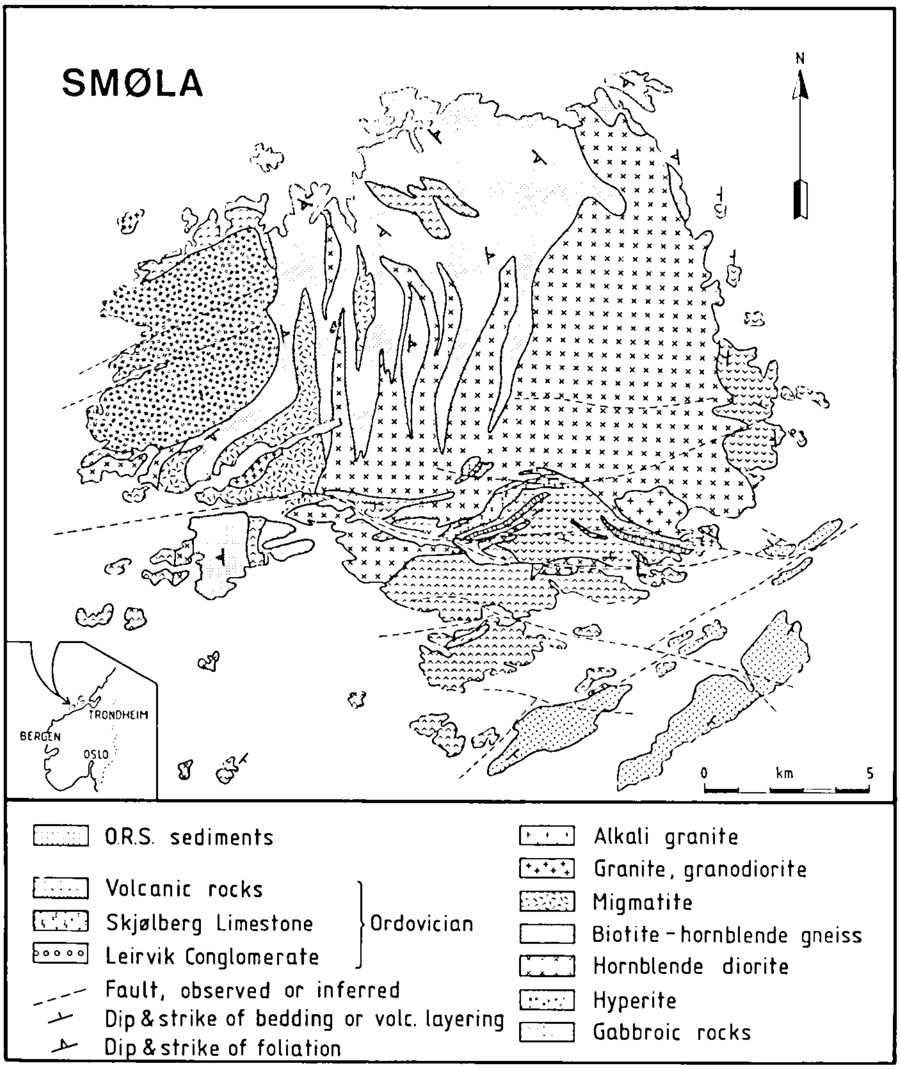

Fig. 1. Simplified geological map of Smøla. The geology is from Fediuk (1975) with minor amendments after Bruton & Bockelie (1979) and the author. S – Skjølberg. L – Leirvik.

Geological setting

Based on the mapping and interpretations of Fediuk (1969, 1975) and Fediuk & Siedlecki (1977) the Ordovician volcano-sedimentary sequence of Smøla may be visualized as constituting an insular outlier in the 'basal gneiss region' of western Norway. The basement to the Lower Palaeozoic rocks was taken, by Fediuk, to be a complex of gneisses, amphibolites and migmatites of assumed Precambrian age, deformed and metamorphosed in Precambrian time, although the actual contact is nowhere seen. An episode of open to tight, locally overturned folding with local faulting followed the Ordovician volcanicity and sedimentation, and this in turn was succeeded by widespread intrusion of quartz diorite and granodiorite. These plutonic rocks, whose thermal–metamorphic aureole products include polycrystalline garnet aggregates in skarn and calc-silicate hornfels (Fediuk & Siedlecki 1977), occur as metre-size angular blocks in Old Red Sandstone basal conglomerates on the islands just southeast of Smøla (Fig. 1) (Peacock 1965, Fediuk & Siedlecki 1977). Rb/Sr dating of the diorite has yielded a whole-rock isochron age of 436 ± 7 m.y. (recalculated to λ Rb^{87} = $1.42 \times 10^{-11} yr^{-1}$) and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70499 ± 0.00006 (Sundvoll & Roberts 1977). An implication from this is that the pre-intrusion deformation can be dated either to upper Llandeilian (Gale et al. 1979) or to uppermost Ashgillian (Ross et al. 1978) time, depending on the time-scale chosen

Aspects of Fediuk's account of the geology and geological history have been disputed by Bruton & Bockelie (1979) in their study of the Ordovician sediments. These authors claim that the volcano–sedimentary outcrop in southern Smøla is delimited by a system of faults, and point to other differences between their own mapping and that of Fediuk. In establishing a formal stratigraphy for the sequence, Bruton & Bockelie considered a conglomerate formation, the Leirvik Conglomerate, to be the oldest unit; Fediuk, on the other hand, believed this conglomerate to be the youngest unit in the area. Another disparity is that whereas Fediuk regarded the volcanites and limestones as being broadly contemporaneous, Bruton & Bockelie considered the effusives to postdate their Skjølberg Limestone Formation (Fig. 1). A third point of contention is that of the character and age of the 'basement' gneisses and associated rocks. Schetelig (1913) interpreted these as products of intense shearing of the later quartz diorites during their emplacement, an opinion followed by Bruton & Bockelie (1979). Fediuk noted a widespread brecciation in both diorites and gneisses which he attributed to forceful emplacement of the former (Fediuk & Siedlecki 1977, p. 18) but his observation that rafts of tightly folded gneisses are present in the diorite was a telling factor in his according an assumed Precambrian age to the gneisses and moderately high grade migmatites.

Comparison of the faunal assemblage occurring in the Skjølberg Limestone with that in the Hølonda Limestone of the Trondheim region led Bruton & Bockelie (1979, p. 29) to ascribe a late Arenig–early Llanvirn age to this carbonate formation; and the andesitic basalts and porphyrites of their overlying igneous 'Phase I' were presumed to be of Llanvirnian age. Investigations by the present author have indicated that this is too simple a picture of the stratigraphy. It is clear from some localities that limestones and basic volcanites are interdigitating and thus more or less coeval, whereas higher up extrusive products are prevalent. The earliest basic lavas could therefore be of late Arenig age.

Mafic plutonic rocks constitute an important element in the geology of Smøla although they have not yet been studied in detail. The largest body, in the west of the island (Fig. 1), is a primary-layered hyperite to norite in a structurally inverted position (Fediuk & Siedlecki 1977). Gravimetric data indicate that this body has a considerable subsurface and offshore extension (Sindre 1977). Amphibolitized gabbro with porphyritic variants and jotunite facies crops out widely in southernmost Smøla and on nearby islands, and contains what have been taken to be elongate rafts of volcanic rocks and rare xenoliths of limestone (Fediuk 1975). Dykes and transgressive sills of a variety of rock-types transect the volcano-sedimentary succession and mafic plutonic bodies. These include porphyritic diabases, diorite porphyrites, microdiorites and aplitic granites (Fediuk 1969). Some of the mafic porphyritic dykes and sills could be consanguineous subvolcanic products, as implied by Bruton & Bockelie's Fig. 8a, but this feeder relationship is nowhere definitive. Finally, mention may be made of the several magnetite–chalcopyrite occurrences on Smøla. These are associated with skarn and volcanites and permitted the establishment of a local mining industry in the 18th century.

The volcanic rocks

FIELD OCCURRENCE

The principal areas of outcrop of the extrusive complex are in the south and southeast (Fig. 1) although a considerably greater strike extent is indicated by occurrences on small islands both to the east and to the southwest of Smøla (Fediuk 1975; also Fig. 1). The volcanic rocks are also recognised in macrorafts and smaller xenoliths apparently engulfed by later plutonic rocks. Basic volcanites, together with subordinate intermediate types, constitute the bulk of the effusive sequence. Fediuk estimated the areal extent of acidic products of the volcanism at ca. 15–20% of the total outcrop, although 10–15% would perhaps be a more reasonable figure. Structural complexity, a deficiency of reliable way-up criteria and discontinuity of outcrop render thickness calculation somewhat conjectural, but a figure between 1000 and 1300 m for the full sequence, excluding the sediments, is considered a modest estimate.

The basic volcanites, principally basalts and basaltic andesites, are dark green to green-black, massive, fine- to medium-grained rocks varying from equigranular to porphyritic. Units of several metres thickness occur in which the lavas have a rubbly or, in places, fragmented or brecciated appearance, moreso within their uppermost portions. These are considered to be flow units. Adjacent to limestone the volcanites are not uncommonly sheared, the contact zones having acted as loci of strain during subsequent tectonic deformation. Calcite veining of millimetre thickness is also pervasive in lavas in juxtaposition with limestone, particularly where the limestone and volcanites interdigitate. Pillow structure has been described from an area near Bekken, ca. 1 km west of Leirvik (Bruton & Bockelie 1979); other than this occurrence, no indubitable examples of this structure have been detected.

Andesitic and intermediate volcanites in general are paler green to pinkish grey-green on fresh surfaces but otherwise display the same textural variation as the darker basalts. With transition into dacitic andesites and dacites, the lithology is usually finer grained, aphyric and of pale, pink-green coloration; plagioclase–phyric units are also present. Pink-white weathering dacitic to rhyolitic volcanites include both lavas and tuffs, the former sometimes showing

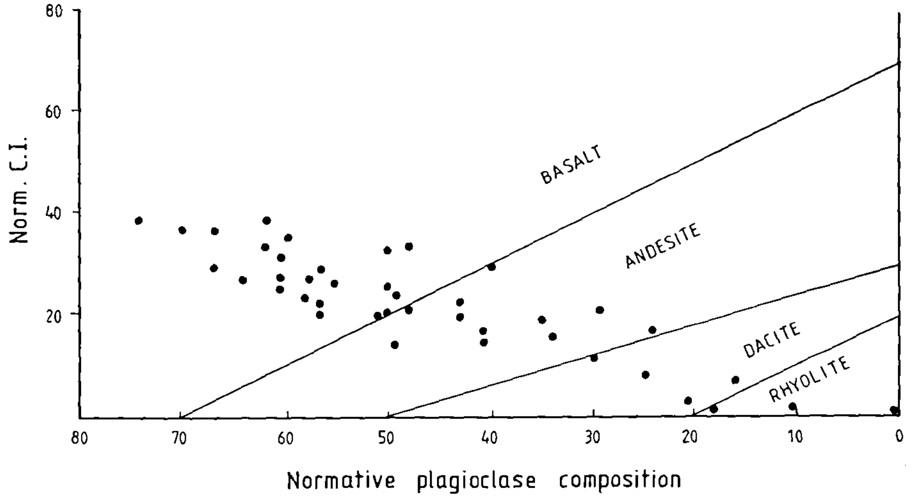

Fig. 2. The Smøla volcanic rocks of the present study plotted on a normative classification diagram (colour index/plagioclase composition). The diagram and dividing lines are after Irvine & Baragar (1971).

flow banding. Carstens (1924) has described crystal tuffs and 'fragmental' tuffs, while Bruton & Bockelie note the local presence of water-lain tuffs within their Skjølberg Formation.

PETROGRAPHY

The volcanic rocks have undergone a maximum grade of metamorphism in lower greenschist facies, and this is reflected in the mineral parageneses even though the primary mineral textures are to a large extent retained. A characteristic mineral assemblage of the basaltic volcanites is that of variably saussuritized or seritized plagioclase and uralitized clinopyroxene with accessory or minor chlorite, Ti-magnetite, epidote and in some cases apatite, leucoxene and calcite.

Some of these basic rocks can be equigranular and aphyric but most are microphyric. Many are distinctly plagioclase- and uralite–phyric with megacrysts measuring 5 mm or more in longest dimension, and ophitic to subophitic textures are present. Some microphyric varieties, including the pillowed basalt, are pilotaxitic. A tectonic foliation is rarely present, although chlorite may show a crude parallelism in some thin-sections.

The modal plagioclase is andesine–labradorite in the range An_{40} to An_{56}; the mean normative composition is An_{57} (Table 1). Metacrysts, as well as groundmass plagioclase, may show a moderate zoning with more sodic rims of andesine to calcic andesine composition. Albitization features have not been detected. The products of uralization vary from quite euhedral, uni-crystal, actinolitic hornblendes pseudomorphous after clinopyroxene and carrying exsolution lamellae and possible pyroxene twinning, to subhedral or euhedral pseudomorphs consisting of a mass of fibrous actinolite which may be partially chloritized. Associated secondary products include leucoxene, calcite and epidote. Relics of the pyroxene are rarely seen, and then as colourless optically positive cores to uralite metacrysts.

Classification of the basic rocks on the basis of plagioclase composition and colour index (Fig. 2) denotes that the majority are basalts but with transitions into the variably defined field of basaltic andesites (here taken as the range 52–55% SiO_2). The intermediate-composition volcanites all fall in the field of andesites on this same figure; three of the 'basalts' also plot in the andesite field, here by virtue of a combination of lower than average CaO and MgO contents and higher than average Na_2O.

The andesites show similar mineral assemblages and textural variations to those of the basic volcanites, although modal plagioclase is here in the range An_{26}–An_{40}, calcic oligoclase to andesine; the mean normative composition is An_{36}. Quartz occurs both as a minor and a secondary constituent in some thin-sections. The dacitic rocks are finer grained, microcrystalline and sometimes show a fluidal texture, but they are also plagioclase-phyric – sodic andesine to calcic oligoclase. Plagioclase and quartz are the main matrix minerals with minor chlorite, epidote and some sphene and opaques.

Chemistry

ANALYTICAL PROCEDURE

Major element analyses from a total of 41 samples have been used in this investigation. Seven of these are taken from Fediuk (1969). SiO_2, Al_2O_3, CaO, MgO and total Fe were determined by classical, standard wet chemical methods and TiO_2, MnO, Na_2O, K_2O and ferrous iron by a method outlined by Langmyhr & Graff (1965) at NGU, Trondheim. Forty of the samples, including the powders of Fediuk's seven samples, were analysed for trace elements on rock powders using a manual Philips 1540 XRF; in the case of V, twelve of the analyses were by emission spectrography. For 28 of the samples, calibration curves were made with synthetic standards, with U.S.G.S. rock standards as contral samples. For the remaining samples international standards were used for calibration. For method, precision and accuracy see Faye & Ødegård (1975).

MAJOR ELEMENT CHEMISTRY

The problems involved in classifying altered volcanic rocks on the basis of their petrochemistry are well known. Secondary alteration, and thus modification of the primary chemistry, may be effected by several processes the most pervasive of which are submarine weathering, burial diagenesis and metamorphism, and regional metamorphism. Devitrification of volcanic rocks rocks involves hydration, but the mobility of the volatiles affords a lesser problem than that arising from the migration and redistribution of several major elements and some of the minor and trace elements, which are processes reflected in common features such as e.g., spilitisation, uralitisation, epidotisation and sericitisation.

Table 1. Chemical compositions of the Smøla volcanites (major elements in wt.% and trace elements in ppm.)

	Basalts and basaltic andesites (n = 27)		Andesites (n = 8)		Dacites (n = 5)	CAB[1]	LKT[2]	OFB[3]
	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$			
SiO_2	49.62	2.04	57.17	1.33	68.09	51.31	52.86	49.91
TiO_2	0.93	0.19	1.13	0.23	0.46	0.88	0.83	1.43
Al_2O_3	18.10	1.33	17.60	0.41	16.27	18.60	16.80	16.20
Fe_2O_3	2.43	0.71[4]	1.84	1.24[4]	0.76	2.91	–	–
FeO	5.02		4.24		1.80	5.80	10.41[5]	10.24[5]
MgO	6.87	1.89	3.30	0.46	1.07	5.95	6.06	7.74
CaO	8.64	1.93	6.36	1.03	2.16	10.30	10.52	11.42
Na_2O	2.99	0.90	4.65	1.11	5.45	2.93	2.08	2.82
K_2O	1.21	0.57	1.34	0.65	2.14	0.74	0.44	0.24
MnO	0.14	0.04	0.12	0.05	0.04	0.15	–	–
P_2O_5	0.18	0.07	0.22	0.05	0.06	0.12	–	–
L.O.I	3.69	2.37	1.64	0.61	1.73	–	–	–
Σ	99.82		99.61		100.03			
norm. plag.	An_{57}		An_{36}		An_{16}	An_{59}		
Zr	120	41	220	61	350	106	52	92
Y	23	4	35	7	34	23	19	30
Sr	557	182	553	56	339	375	207	131
Rb	39	23	35	18	46	23	5	3
Zn	63	34	67	41	43	–	–	–
Cu	38	31	68	40	65	35	62	73
Ni	87	69	18	8	7	50	18	106
Cr	251	232	26	28	13	130	160	310
Ba	301	199	390	150	642	260	60	8
Nb	6.5	3.5	10	6	642	260	60	5
V	222	31	183	45	43	174	265	229

Analysts: major elements – Per-Reidar Graff (NGU)
trace elements – Gjert Faye (NGU)
x Mean value S – standard deviation
1) Calc-alkaline basalt, mean values: major elements from Nockolds & Le Bas (1977), trace elements from Pearce (1973, 1975).
2) Low-K tholeiite of island arc, mean values: from Pearce (1973, 1975).
3) Ocean-floor basalt, mean values: from Pearce (1973, 1975).
4) Calculated from total Fe as Fe_2O_3.
5) Total Fe given as FeO.

Assessing the degree of major element mobility – particularly of the elements Na and Ca but also in some cases K, Mg and Fe – as well as the bulk chemical changes involved is especially difficult. In the present case the preservation of primary feldspars provides a good indication that spilitisation has not occurred on any significant scale. This is also suggested by the mean value for Na_2O (Table 1) in the basalts as well as by a Hughes (1973) plot of alkali variation (Fig. 3). Major/minor oxides–SiO_2 variation (Fig. 4) also indicates that alteration has been minimal in these rocks, and this is especially noticeable when comparisons are made with the metabasaltic sequences occurring further east in the Trondheim region (Gale & Roberts 1974, Loeschke 1976a, b). On an alkali-silica diagram, not reproduced here, the basic and intermediate Smøla volcanites are decidedly subalkaline. With this division established, determination of the character of the rock association can be taken further employing

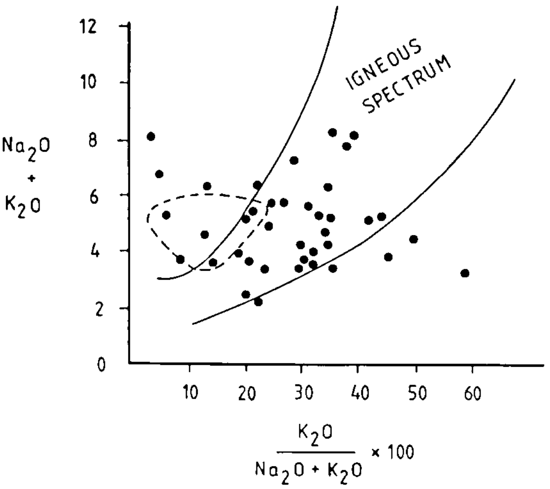

Fig. 3. Variation of (Na_2O + K_2O) *vs.* K_2O/(Na_2O + K_2O) for the Smøla volcanites. The fields for 'average' igneous rocks (igneous spectrum) and spilites (dashed line) are indicated: after Hughes (1973).

the AFM diagram (Fig. 5), which clearly shows that we are dealing with a calc-alkaline variation trend. Confirmation of this is provided by Fig. 6 which highlights the 'high-alumina basalt' (Kuno 1960) affinity of the Smøla basic effusives. The aluminous character is also reflected in the FeO–MgO–Al_2O_3 diagram (Fig. 7a) of Pearce et al. (1977). Use of the FeO/MgO ratio to represent the degree of fractional crystallisation has been employd with much success by Miyashiro (1974, 1975). For the Smøla basaltic lavas variation trends with parameters SiO_2, FeO and TiO_2 are not so well defined because of a restricted range of FeO/MgO ratios but the calc-alkaline kinship is nevertheless discerned when the rhyodacites are included.

Application of a statistical analysis of the eight major element oxides for volcanic rocks has been portrayed graphically by Pearce (1976) in the form of discriminant functions. A plot tailored to discriminate between the various types of volcanic arc basalt (Fig. 7b) corroborates the clear indications of earlier diagrams, i.e. that the Smøla lavas are representative of the calc-alkaline rock series.

TRACE ELEMENTS

The comparable immobility of certain minor and trace elements during alteration and low-grade metamorphic processes has been employed to great effect in recent years in helping to discriminate between magmatic associations generated in different present-day tectonic settings (Cann 1970, Pearce & Cann 1973, Floyd & Winchester 1975) especially in cases where the primary major element chemistry has been severely affected by alteration. The elements concerned are Y, Zr, Ti, Nb, Cr, Ni and the rare earths. The value of these particular elements in magma discrimination is such that even Phanerozoic and older eruptives are capable of meaningful subdivision, as witnessed by studies on, for example, many Norwegian Lower Palaeozoic volcanite sequences (Gale & Roberts 1974, Furnes et al. 1976, Furnes 1980 and references therein).

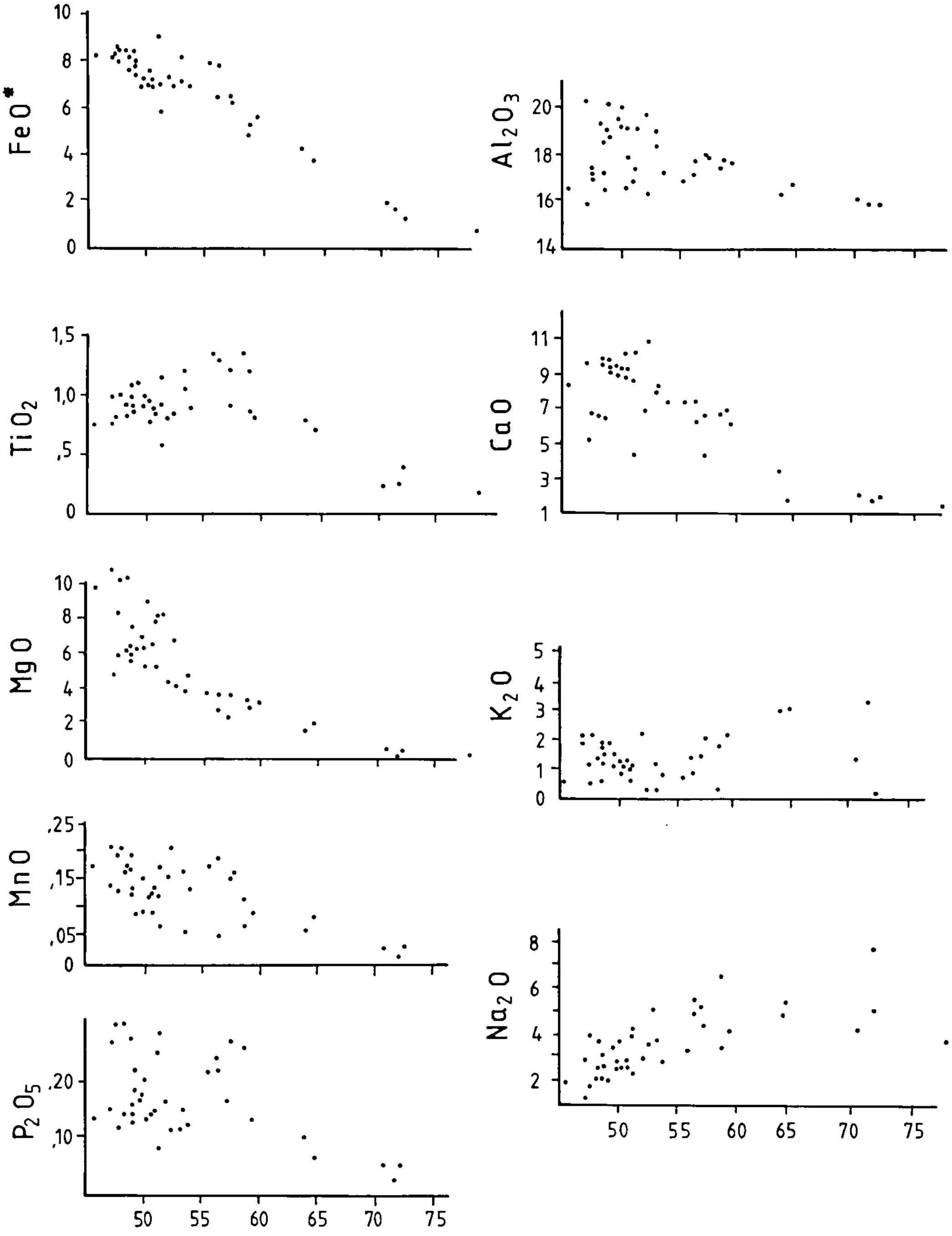

Fig. 4. Variation diagrams of weight per cent major and minor element oxides against SiO_2 for the Smøla volcanic rocks. FeO* = total iron as FeO.

For the Smøla basaltic rocks the minimal alteration involved and the indisputably calc-alkaline classification based on major element data serve to

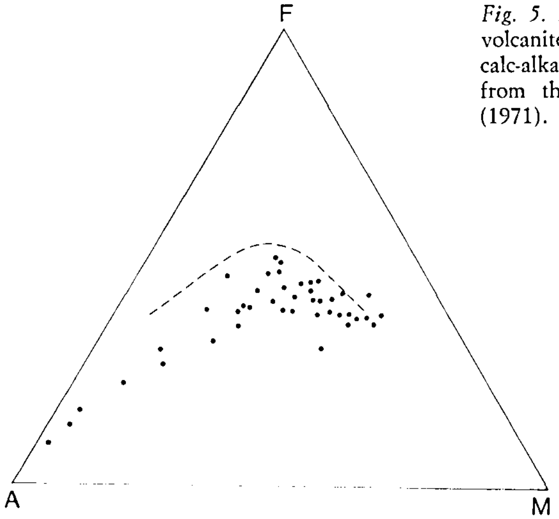

Fig. 5. AFM plot of the analysed Smøla volcanites. The dashed line separates calc-alkaline compositions (below the line) from tholeiitic: after Irvine & Baragar (1971).

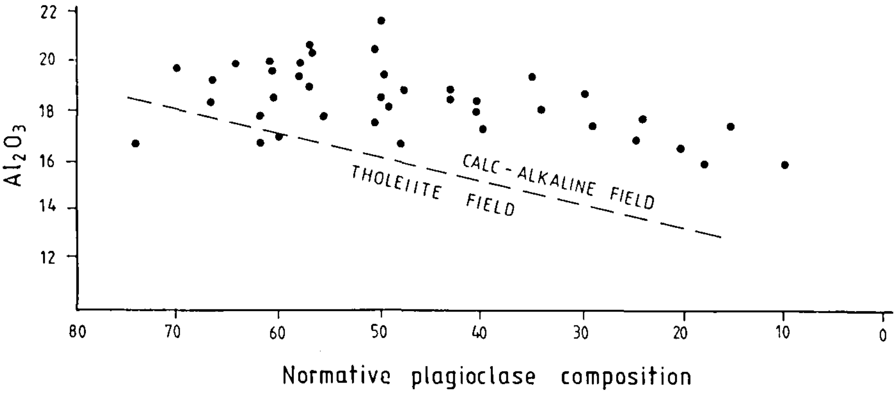

Fig. 6. The Smøla volcanic rocks on a plot of wt.% Al_2O_3 *vs.* normative plagioclase. The dividing line between the calc–alkaline and tholeiite fields is from Irvine & Baragar (1971).

provide a test-case for petrochemical discrimination in Phanerozoic basic volcanic rocks utilizing the incompatible trace elements. As can be seen from the ternary and binary diagrams of Pearce & Cann (Fig. 8a, b), the consistency reported above is maintained, in this case for the elements Zr, Y and Ti, with a grouping that is indubitably calc-alkaline. Comparison of trace element contents (Table 1) with those of the principal volcanic arc and oceanic basalt associations also leaves no doubt of the genetic affiliation of the Smøla volcanic rocks.

In summary, the petrochemical character of these particular Ordovician effusives as evinced by both major and trace element contents and ratios is quite clearly that of a calc-alkaline volcanic association. These are features which have not hitherto been detected on such a scale and consistency in Norwegian Lower Palaeozoic eruptive sequences. Some aspects of the significance of these findings in a regional context are discussed briefly below.

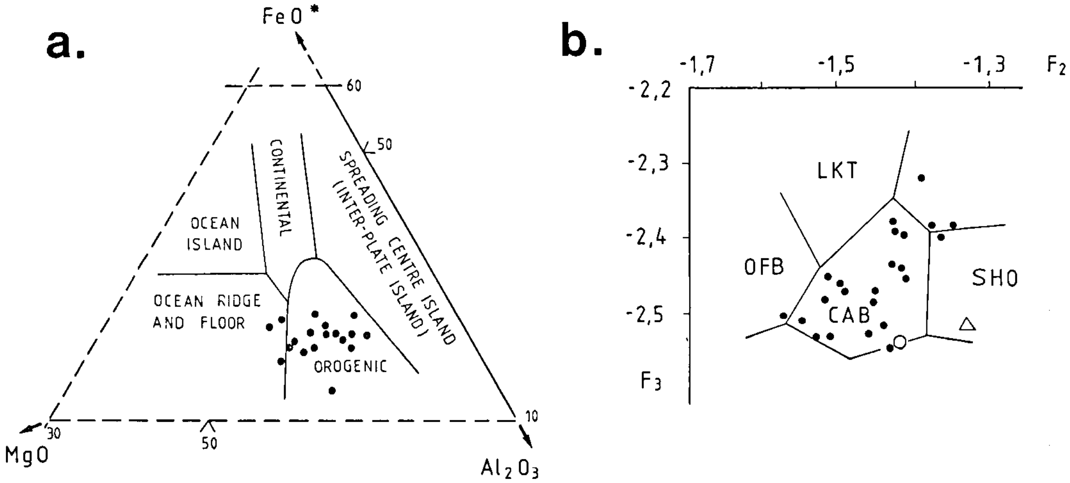

Fig. 7 (a). Part of the MgO-FeO*-Al_2O_3 diagram of Pearce et al. (1977) showing the distribution of screened samples of Smøla volcanites. The samples are those with 50–56 wt.% SiO_2, volatile-free. The 'orogenic' field embraces island arcs and continental margins.
(b). Plot of major element discriminant functions, F_2 *vs.* F_3 (after Pearce (1976)) for the Smøla basalts and basaltic andesites. Only screened samples are used; for selection procedure see Pearce (1976). For comparison purposes the mean values for the Smøla andesites (open circle) and Hølonda andesites (triangle) (Loeschke 1976a) are also plotted. The fields shown are as follows: CAB — calc-alkaline basalts: LKT — low-K tholeiites: OFB — ocean-floor basalts: SHO — shoshonites.

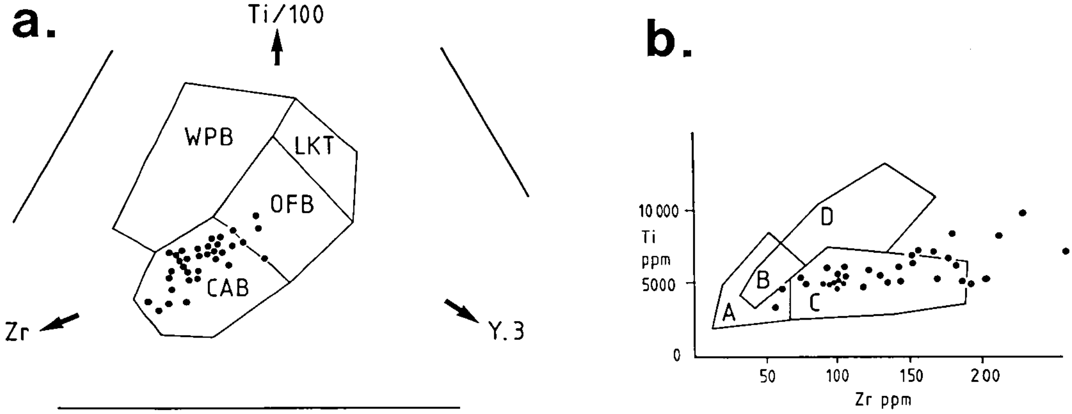

Fig. 8 (a). Smøla basalts and andesites plotted on the Ti–Zr–Y discrimination diagram of Pearce & Cann (1973). CAB — calc-alkaline basalts; OFB — ocean floor basalts; LKT — low-K tholeiites; WPB — within-plate basalts.
(b). Ti vs. Zr variation for the Smøla basalts and andesites; after Pearce & Cann (1973). Fields A+B – low-K tholeiites; C+B – calc-alkali basalts; D+B – ocean floor basalts.

Discussion

Volcanic rocks of the calc-alkaline series ranging from basalts of high-alumina type to andesites, dacites and rhyolites are genetically associated with the island arcs of destructive, intra-oceanic plate margins and subduction-related continental margins. Moreover, of the two principal trends or associations within what is generally termed the orogenic volcanic series, the calc-alkaline rocks are ascribed to the mature or evolved phase of the developing arc system. These distinguish themselves from early or immature arc volcanites represented largely by low-K tholeiites (Ringwood 1974).

The Ordovician volcanic rocks of Smøla thus fall neatly into the category of mature arc effusives. The lithological association, in particular the presence of a shallow-water carbonate reef facies with water-lain volcaniclastics and tuffs interlayered with flows, and also local rudites, provides supporting evidence of the mature arc environment. A hypabyssal, subvolcanic dyke phase is also a characteristic feature of modern island arcs, but more significant here is the granodioritic to dioritic plutonism in Upper Ordovician time which followed the folding and faulting of the volcanosedimentary assemblage. Such a sequence of events, from the volcanostratal construction to plutonic emplacement simultaneous with or post-dating faulting and local folding, is quite typical for many present-day mature island arcs (Donnelly 1964, Baker 1968, Mitchell & Reading 1971). The lithovolcanic association thus helps to confirm the petrochemical data indicating that the Smøla Ordovician rocks are products of, or associated with, a well developed magmatic arc. Based on a chemical discrimination, by Sugimura (1968), of basaltic and andesitic rocks in complex arcs, $(Na_2O + K_2O)/Al_2O_3$ values obtained for the Smøla volcanites should place them slightly on the inner or 'continental' side of the arc.

With this point established it is pertinent to enquire as to the nature of the crust flooring the arc at the time of its construction. Calc-alkaline volcanites are associated with regions of lithosphere subduction, but in two contrasted crustal environments; either intro-oceanic or continental-marginal. The arc may thus have developed on either continental or oceanic crust, although some modern arcs are also based on a thickening, intermediate-type crust. Larger island arcs of a mature type with a predominance of calc-alkaline products over tholeiitic are generally found to have a transitional to continental-type crust some 15–30 km in thickness (Miyashiro 1974). This does not preclude the possibility of initial arc development on oceanic crust which gradually becomes 'continental' as the arc develops. The Smøla geology offers few clues concerning the nature of the fundament to the calc-alkaline magmatic arc. The identity of the present 'basement' is contentious (p. 45), and indeed it is more than likely that the Ordovician sequence is not autochthonous. Comparison with the situation in west Norway and the Trondheim region – and faunal and lithological features encourage such a comparison (Bruton & Bockelie 1979) – allows a consideration that the Smøla arc itself has developed upon a crust thickened as a consequence of tectonic shortening involving ophiolite obduction in Arenig time (Furnes et al. 1979). This involved an eastward translation of slices of the Iapetus Ocean floor on to a continental margin, or even the margin of a microcontinent within Iapetus. Thus, the extrusion of the initial products of the Smøla arc, nowhere exposed, is likely to have commenced upon a transitional to continental 'composite' crust. By analogy with modern arc structures a thickness in the range 25–35 km could be envisaged, and by late Llanvirnian time at the mature arc stage the total crustal thickness may have increased to the region of 35–45 km. It is unlikely to have been much thicker than this as the principal effusive products of the arc are basalts and basaltic andesites, but by the time of diorite-granodiorite plutonism it could have approached 50 km. Comparing the Smøla volcanites with orogenic lavas studied statistically by Ewart (1976), a 'continental' island arc situation seems most reasonable, i.e. an arc with a crust intermediate between that of intra-oceanic arcs and the western American continental margin.

Regional aspects

In their recent review of Lower Palaeozoic volcanism and Scandinavian ophiolite assemblages, Furnes et al. (1979) emphasized the common pattern emerging from studies in different parts of western and central Norway whereby ophiolitic sequences were obducted eastwards, dismembered and in some areas folded and metamorphosed prior to sedimentation and further volcanism initiated in Middle Ordovician time (or earlier) in western Norway and in late Arenig time in the Trondheim region. The actual sequence of Cambro–Ordovician events in a plate tectonic framework is outside the scope of this paper, but in order to place the Smøla arc in a meaningful paleogeographical setting it is essential to consider briefly certain aspects of the stratigraphy, and volcanite successions and geochemistry, of neighbouring districts.

The faunal and lithological similarities between the Smøla Ordovician rocks and those in the Hølonda area of the SW Trondheim region have been stressed by Bruton & Bockelie (1979). These authors, in another publication (1980), consider the Hølonda porphyritic andesites and limestones of the Lower Hovin Group to form part of a volcanic arc system. This, however, is basically a part of the arc/back-arc basinal environment proposed by Gale & Roberts (1974) and supported by Ryan et al. (1980), which demands a southeastward dipping subduction zone. Bruton & Bockelie, on the other hand, appeal to a model involving northwestward subduction to generate the late Arenig–Llanvirn magmatic arc products represented at Hølonda. These two models are mutually incompatible in that, with regard to the positioning of the mature arc, they necessitate quite different palaeogeographic settings within the Iapetus Ocean.

Accepting the faunal and lithological correlations between Smøla and Hølonda, it is important to note the differences in magmatic characteristics. On Smøla we have a wide range of calc-alkaline effusives cut by varied dyke phases with consanguineous gabbros, and intruded by extensive dioritic to granodioritic plutons; at Hølonda the variation is much less, dykes infrequent and plutons absent, but rhyolites and rhyodacites, and tuffs, are more prominent than on Smøla, moreso higher up in the sequence. In the Hølonda district, and westwards towards Løkken, rapid lateral facies changes are

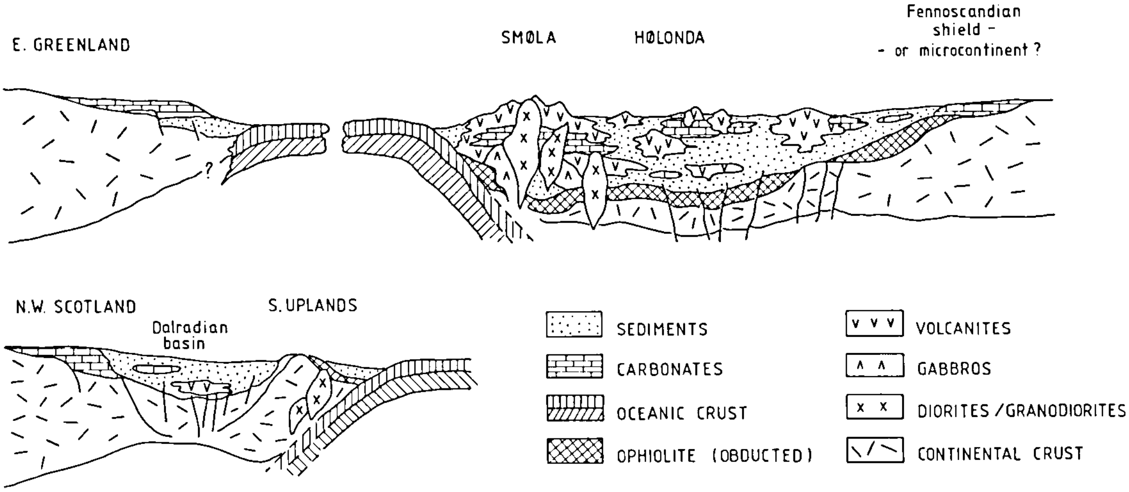

Fig. 9. Schematic, composite reconstruction of the suggested palaeogeographic/plate tectonic situation in Llanvirnian (-Caradocian) time to show the position of the mature Smola arc in relation to the Hølonda area and the Ordovician back-arc basin of the Trondheim region. In this sketch the deepening basin east of Smøla is emphasized at the expense of the slightly earlier, Arenig–early Llanvirn fault troughs of the Hølonda area (cf. Bruton & Bockelie 1980), and the uplifted areas of 'continental' rocks to the east (cf. Ryan et al. 1980). The East Greenland continental margin with shallow-shelf limestones is also indicated. The Iapetus Ocean, between Greenland and Smøla, is purposely foreshortened in this diagram. The smaller sketch (lower left) shows the general situation in the British orthotectonic segment of the orogen on the W–NW side of Iapetus (modified from Phillips et al. (1976)). The diagram is not drawn to scale.

apparent from island-fringing limestones into deep-marine shales and even locally into marginal basin-type basalts (Ryan et al. 1980) and possibly some low-K thoeleiites (Grenne et al. 1979). Northeast from Hølonda the Middle Ordovician rocks are predominantly turbiditic, fairly deep-water sediments (Roberts 1968, 1972) with sediment transport both from east and west, but with an important development of Llanvirnian to ?Llandeilian ocean floor to transitional-type tholeiites indicative of marginal basin spreading (Grenne & Roberts, in manuscript). The overall evidence from this region, for Lower to Middle Ordovician time, thus favours the presence of a well developed evolved arc to the 'west', in the Smøla area, with volcanic arc products diminishing eastwards in a gradually deepening sedimentary basin in which spreading centres opened up and allowed the locally thick accumulation of marginal-basin, ocean floor tholeiitic basalts (Grenne & Roberts, in manus.).

Implicit in this palaeogeographic setting, with the Llanvirnian magmatic arc at its maximum development in the west, is an acceptance of eastward subduction of oceanic crust with the trench situated west of Smøla and the major oceanic tract of Iapetus beyond that (Fig. 9), thus negating the reconstruction of Bruton & Bockelie (1980, fig. 7). This is a situation similar to that envisaged for the Solund–Stavfjord area of West Norway by Furnes et al. (1976). While the above regional volcanosedimentary variations are sufficiently telling in themselves, an additional polarity clue is provided by the chemistry of the andesites from Smøla and Hølonda. Those from Hølonda are consistently richer in K_2O than the Smøla andesites (Gale 1974, Loeschke 1976a), and a discrimination based on their *total* oxide chemistry (Fig. 7b) reveals that the Hølonda porphyritic andesites are rather more shoshonitic in character than their calc-alkaline Smøla counterparts. These features also imply that the Hølonda rocks were situated further away from the subducting oceanic lithosphere than the equivalent andesites of the Smøla arc, in contradiction of Bruton & Bockelie (1980).

Although the Skjølberg Limestone of Smøla has been compared to the Cambro–Ordovician Durness Carbonate of northwest Scotland (Holtedahl 1918, Strand 1932) on grounds of similarity of some of the fauna, no substantive basis exists for the correlation of these two formations as they occupy entirely different geotectonic environments. The Durness has much in common with similar carbonate sequences in western Newfoundland and central East Greenland (Swett & Smit 1972) and developed in a non-volcanic, shallow-marine, shelf environment along the western margin of the Iapetus Ocean. This is in sharp contrast to the magmatic arc setting of the Smøla carbonate (see also Bruton & Bockelie 1979, 1980). Accepting the geochemical data, interpretation, and location of Iapetus as presented here (Fig. 9), it is difficult to envisage a positioning of the Skjølberg/Hølonda rocks in proximity to the margin of the North American plate (cf. Bruton & Bockelie 1980, fig. 7). This in turn has a bearing on the precise significance of the occurrence of fauna from one particular 'province' in rocks within the Caledonian orogenic belt. In the present case for example, a mainly North American fauna has guided an interpretation demanding sedimentation along the North American side of the ocean. This too simple interpretation of faunal provincialism has been questioned by Roberts & Gale (1978) and Ryan et al. (1980) and words of caution raised by Bergstrøm (1980). An attractive alternative hypothesis which should be explored further is that of Neuman's (1972) notion of faunal evolution around volcanic islands and migration to continental margins; this may provide an important key to our understanding of provinciality.

In conclusion, a few words on the Ordovician deformation of the Smøla volcanosedimentary succession are warranted. This deformation pre-dates the Upper Ordovician diorite pluonism, and is also post-Llanvirnian. From an area south of Løkken Ryan et al. (1980) have described a gentle folding at the very top of the Lower Hovin Group, prior to Upper Hovin sedimentation — their post-Llanvirn/pre-mid Caradoc event. Further northeast within the deeper parts of the back-arc basin, this event is recorded by thick accumulations of fan-conglomerates (Roberts 1972). In southwestern Norway a major folding and metamorphism is at least pre-Ashgillian (Sturt & Thon 1978), but could feasibly be as old as Arenig. It is therefore possible that the Ordovician folding on Smøla may equate with at least the youngest phases of this west Norwegian deformation episode, which would be roughly equivalent to the pre-Bala deformation recorded in parts of the paratectonic British Caledonides.

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