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Adinoles revisited: hydrothermal Na(Ca)-metasomatism of pelite screens adjacent to tholeiitic dykes in the Dublin terrane, Ireland

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Abstract

The albitisation of pelitic metasediments to form adinoles adjacent to minor mafic intrusions has in the past been attributed to Na-bearing metasomatizing fluids emanating from the intrusions themselves. The chemistry and mineralogy of adinoles associated with dykes forming a high-intensity swarm in the Tallaght area, County Dublin, Ireland, confirms a metasomatic origin for the adinoles described, with Na and to a lesser extent Ca introduced into the country rocks at the expense of K. We suggest, however, that the source of the metasomatizing fluids was external to the dykes – possibly involving a hydrothermal system driven by an underlying magma reservoir that was parental to the dykes and also contributed volatiles to the hydrothermal system by degassing. Heat flow from the dykes was instrumental in promoting the reaction between muscovite in the country rock pelites and the Na(Ca)-bearing fluids to form albite, temperatures of ~350°C in the country rocks within a metre of the contact being indicated. The mechanism of adinolization proposed is shown to be compatible with recent experimental work on the hydrothermal alteration of greywackes and basalts and also with the likely temperature gradients adjacent to dykes.

KEYWORDS: adinole, metasomatism, pelite, tholeiite, Ireland.

Introduction

THE term adinole (Hausmann, 1828), although of infrequent occurrence in recent literature, was introduced to refer to albitized shales or pelites occurring immediately adjacent to mafic minor intrusions. Subsequently in published work on adinoles it was often inferred that the sodium involved in the formation of the albite had been derived from metasomatic fluids emanating from (Na-rich/spilitic) magmas forming the intrusions. However, the term adinole, as initially defined, precisely describes a specific association of lithologies, with no implied genetic connotation. We therefore propose that the term should remain in use and consequently we use it throughout what follows (with the term adinolization being used to describe the process of adinole formation). Rocks that have been referred to as spilosites (Zincken, 1841) are often found in association with adinoles, and represent partially adinolized argillaceous rocks with albite, chlorite and quartz-'spots' in a sericitic matrix.

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Papers describing adinoles in some detail have been published by Agrell (1939, Dinas Head, Cornwall); Davies (1956, Pen-y-Gader, North Wales) and, more recently, by Dypvik (1979, Sassenfjorden, Spitzbergen). Williams *et al.* (1993) provide extensive new chemical and mineralogical data on the adinoles and related rocks at Dinas Head, Cornwall. All these examples describe an association of albitised pelitic rocks with dolerite intrusions of general sill or sheet form. The dolerites at Dinas Head and Pen-y-Gader are described as albite-dolerites but have very variable Na_2O and K_2O contents with maximum Na_2O contents at both localities of around 5%. Williams *et al.* record a maximum K_2O content of dolerites from Dinas Head of 1.61%, the Pen-y-Gader dolerite having a maximum of around 0.8% K_2O. By contrast, the Sassenfjorden dolerite is characterised as being tholeiitic with average Na_2O ~2.5% and K_2O ~0.8%.

Agrell (1939) concluded that the formation of the Dinas Head adinole represented a 'volume-for-volume replacement of the slate' citing the extreme mechanism:-

$$\text{'sericite}_{(\text{solid})} + \text{albite}_{(\text{solution})} \rightarrow \text{albite}_{(\text{solid})} + \text{sericite}_{(\text{solution})}\text{'}$$

He recognised, however, the problem of lithological variation in the slates making identification of the parent material of the adinoles subject to some uncertainty. He also noted that metasomatic alteration of the slates to form adinoles was preceded by a thermal effect producing spotted slates. Agrell suggested that introduction of Na-Si-rich fluids was responsible for the adinolization and concluded that the composition of the adinole was "controlled by the metasomatic fluids emanating from the igneous rock". Williams *et al.* (1993) were unable to confirm or reject this hypothesis. A recent observation (Floyd *et al*, 1993) that the Dinas Head sill produced soft-sediment deformation on intrusion, and hence was emplaced in sediments that may have incorporated significant sea-water pore-fluids, however, now presents the possibility of an alternative (non-magmatic) *in situ* source of the Na responsible for adinolization.

The Pen-y-Gader adinoles are attributed by Davies (1956) to 'the presence in the igneous body of metasomatizing fluids which autometasomatize the body as well as adinolizing the country rock'. Both Davies and Agrell discuss the Fe^{2+}/Fe^{3+} ratios of adinolized rocks, but produced no clear picture of the redox regime that may have existed during adinole formation.

Dypvik (1979) ascribes addition of Si and Na to black shales at Sassenfjorden to a hydrothermal episode that followed pyrometamorphism resulting from the emplacement of a tholeiitic dolerite intrusion. Albite was formed in two zones: one immediately below the contact zone of the intrusion, but also within another zone 550cm below the intrusion. No suggestion was made as to the source of the metasomatizing fluids.

The presence of an immediately adjacent igneous intrusion may not always be necessary to form adinole-like rocks - perhaps only a source of Na-rich fluid and the right temperature are all that are required. Kish and Cuney (1981) and Ruhlmann *et al.* (1986) attribute veins of albite-uraninite mineralization in Quebec, to metasomatic hydrothermal Na-rich fluids formed during regional metamorphic or magmatic events. The former workers describe veins formed in fractured argillites representing shallow marine sediments in which K predominates over Na. In the vein wall-rocks, there is replacement of K-mica by albite and K is almost completely depleted in wall-rocks high in Na. The wall-rocks show increases in Fe and decreases in Ba and Rb. Kish and Cuney (1981) suggest from fluid inclusion evidence that the temperature and pressure of vein formation was 300–350°C and 2.5 kbar respectively. The fluid inclusions were characterised as aqueous solutions oversaturated with NaCl and containing Ca^{2+} and Mg^{2+}. The gas phase mostly consisted of N_2, CO and CO_2. Oxidizing vein-forming fluids are suggested.

Previous work therefore generally agrees with the concept of a metasomatic origin for adinoles by the introduction of Na into argillaceous or pelitic country rocks. However, although in some examples the source of the metasomatizing Na-fluids was originally identified as the intrusion itself, it seems more likely that the metasomatizing hydrothermal fluids were generated externally to the intrusion by regional metamorphic or magmatic episodes, as has been suggested in the case of some albite-bearing veins. The alternative possibility that saline (Na-rich) solutions were already resident in the argillaceous material as unmodified or modified sea-water pore fluids at the time of igneous intrusion must also be considered in some cases.

This paper re-examines the nature of the processes and controls involved in adinole formation based on examples associated with a tholeiitic dyke swarm emplaced into Ordovician pelitic rocks, in the Tallaght area of SW County Dublin, Ireland.

Geologic setting

The Dublin tectonostratigraphic terrane, within the Leinster Massif of SE Ireland, is divided into two segments by the Leinster Granite Batholith (Max *et al.*, 1990). This terrane is composed of Cambro-Ordovician Ribband Group rocks which, in the

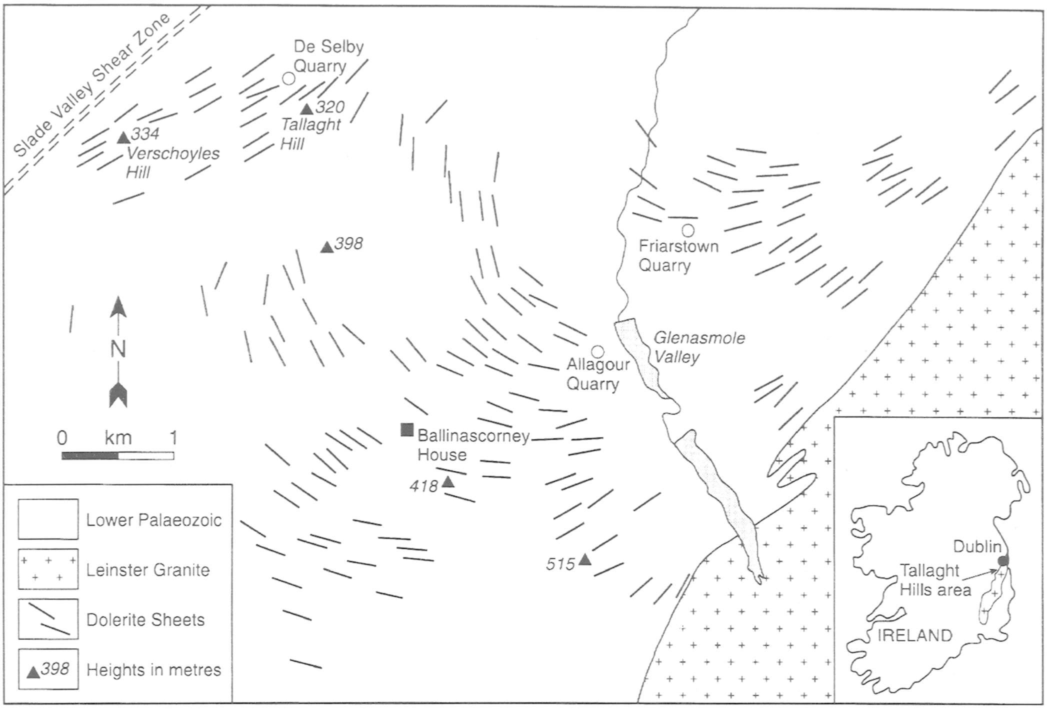

FIG. 1. Map showing the outline geology of the Dublin area and the schematic distribution of the Tallaght dolerite dyke swarm.

section NW of the granite, are intruded by a multiplicity of Caledonian dolerite sheets (Fig. 1). Although emplaced into a folded and lithified sedimentary sequence (Bruck *et al.*, 1974), the dykes preceded a subsequent deformation associated with emplacement of the Leinster granite, dated at 405±2 Ma (O'Conner *et al.*, 1989). The structural, petrological and geochemical features of the Tallaght dyke swarm have already been described (Angus and Brindley 1970; Angus, in press) and need only be summarised here by way of an introduction to the description of the associated adinoles.

The overall configuration of the swarm (shown schematically in Fig. 1) is indicative of a concentric emplacement pattern controlled by fluctuating pressures within a high-level magma chamber (Angus, in press). This contention is supported by the high intrusion intensity in parts of the swarm where multiple injection imparts a sheeted-dyke appearance, and locally the ratio of dyke to country rocks approaches 80%. The sedimentary framework to the intrusions is broadly divisible into two formations dated palaeontologically by Bruck *et al.*, (1974) as Llanvirn to Llandeilo. The Butter Mountain formation occupies a belt adjacent to the NW flank of the the Leinster granite and consists largely of dark blue or grey phyllites and slates. To the west these strata pass conformably upwards into the Aghfarrell Formation also comprising blue or grey phyllites or slates with thin siltstone bands and occasional greywackes.

The most common lithologies in the Tallaght dyke swarm are porphyritic dolerites (Angus and Brindley, 1970). These contain plagioclase phenocrysts ($\sim An_{65}$) up to 1cm in length that are frequently sericitised, while the generally less altered groundmass plagioclase is slightly more sodic (An_{56}). Both phenocrysts and groundmass plagioclase often have clear rims of more albitic composition. Secondary hornblende (replacing augite) is the predominant ferromagnesian mineral. Hydrothermal metamorphism is therefore prevalent in the dykes in which amphibolitization of the primary igneous lithology (augite-plagioclase) is ubiquitous. In the intervening country rock screens, the pelites close to the dolerite intrusions are recrystallized and transformed into adinoles.

Mineralogy of the adinoles and country rocks

Although the intensity of the metasomatic alteration is most noticeable in narrow sedimentary partitions up to one metre wide and wedged between dolerite intrusions, it is in the larger screens 6 to 8 metres across, that the extent of the contact alteration is best displayed. Consequently, two of the larger and better exposed screens, at Allagour quarry and Ballinascorney House reservoir, were serially sampled, and in addition individual samples were collected from narrow, fresh adinole screens in the Friarstown and De Selby quarries. Essentially unaltered slate/greywacke-siltstone samples were obtained from Verschoyles Hill (Saggart) and De Selby in the north-west of the area, as well as from the large screens mentioned previously. The sampling locations are shown on Fig. 1 and specified in Table 1.

Typically the adinoles are white-weathering rocks with a dark green-grey chert-like appearance when fresh. The mineral assemblage is representative of the chlorite-schist facies and comprises quartz, albitic plagioclase, chlorite, sericite, leucoxene dust and zoisite. The chlorite aggregates appear to pseudomorph embryo porphyroblasts of some higher grade ferromagnesian silicate (biotite or cordierite) and together with rare garnet porphyroblasts indicate that the lower grade adinole assemblages have retrogressed from a higher temperature hornfels facies mineralogy. Transformed representatives of phyllites, slates, siltstones and greywackes can sometimes be distinguished, but the geochemical study has centred chiefly on the phyllites and slates of which suitably homogeneous samples were more readily available. In the incompletely transformed siltstones, the fine-scale sedimentary layering is emphasised by selective adinolization. The layers are alternatively rich in chlorite and sericite, although each mineral is common to both, and forms tiny flakes set in a fine-grained mosaic of quartz and albite.

X-ray diffraction studies of the Ballinascorney House Weir sedimentary screen show that progressive changes in bulk mineralogy occur towards the dyke contacts (Fig. 2). Albite is clearly enriched in the adinolized samples at the expense of muscovite (sericite) and quartz. The country rock is noticeably depleted in both the latter minerals as the contact is approached, and muscovite appears to be totally destroyed immediately adjacent to the dyke contact. Chlorite is present in much the same amounts in all

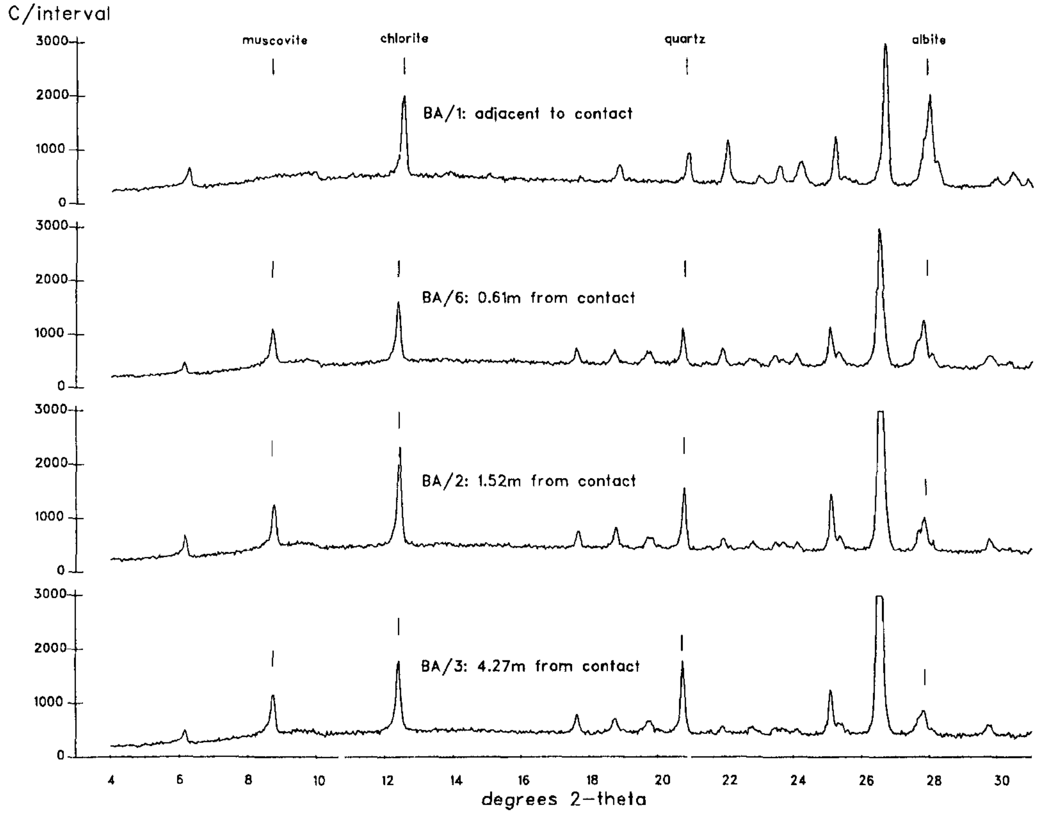

FIG. 2. XRD patterns showing change in bulk country-rock mineralogy towards a dyke contact.

TABLE 1. Chemistry of Tallaght adinoles and country rocks

	Allagour Quarry			Ballinascorney House Weir							Individual samples[2]			
Sample[1]	AL/1	AL/2	AL/3	BA/1	BA/2	BA/3	BA/4	BA/5	BA/6	BA/7	DES/A	DES/C	FQ/A	VE/C
metres[3]	0.0	0.61	6.71	0.0	1.52	4.27	4.57	6.40	7.01	7.62				
code[4]	A	A/C	C	A	A/C	C	C	C	A/C	A	A	C	A	C
%														
SiO_2	56.51	62.13	59.99	62.63	64.27	62.48	58.78	71.16	57.21	64.98	55.03	55.18	59.84	59.79
TiO_2	1.31	0.86	0.85	0.80	0.83	0.86	0.92	0.70	0.94	0.85	1.03	1.02	0.81	0.93
Al_2O_3	18.72	17.82	19.31	17.31	16.87	18.50	20.91	12.98	21.23	16.48	21.52	23.08	18.36	19.71
Fe_2O_3	2.24	1.10	1.16	1.01	1.24	1.45	1.50	0.97	1.23	0.90	1.31	2.12	1.06	1.19
FeO	5.58	5.17	5.82	4.95	5.64	5.63	4.92	4.74	5.68	5.64	5.19	4.26	5.32	6.37
MnO	0.11	0.12	0.14	0.13	0.39	0.21	0.20	0.18	0.20	0.17	0.07	0.03	0.04	0.11
MgO	3.00	2.38	2.48	1.97	1.78	1.85	1.55	1.41	1.88	1.83	2.70	1.94	2.69	2.55
CaO	1.39	0.46	0.29	3.52	0.34	0.30	0.40	0.97	0.83	1.37	1.38	0.24	2.82	0.12
Na_2O	6.94	1.98	1.50	4.90	1.38	1.08	1.99	2.54	2.22	4.46	4.16	0.35	5.49	1.26
K_2O	0.26	3.65	4.05	0.41	3.47	4.12	4.55	1.41	4.34	0.93	3.59	6.81	0.88	3.21
P_2O_5	0.15	0.11	0.12	0.12	0.11	0.11	0.10	0.12	0.11	0.12	0.14	0.12	0.08	0.12
H_2O+	3.22	3.86	4.12	2.14	3.39	3.95	3.86	2.57	4.02	2.60	3.64	4.43	2.59	4.42
S	0.48	0.42	–	–	0.01	–	–	–	0.04	0.04	0.04	0.52	–	0.02
Total	99.91	100.06	99.83	99.89	99.72	100.54	99.68	99.75	99.93	100.37	99.80	100.10	99.98	99.80
ppm														
V	117	110	–	106	110	115	133	83	121	–	164	181	140	137
Cr	130	84	–	89	82	91	103	63	99	–	122	122	96	114
Ni	43	27	–	44	28	37	27	30	52	–	55	45	46	38
Cu	82	69	–	12	23	17	47	15	6	–	7	63	3	12
Zn	82	82	–	67	104	83	85	61	85	–	97	106	38	88
Ga	21	26	–	26	23	27	22	16	31	–	32	34	28	32
Rb	8	134	–	18	136	154	179	51	151	–	142	250	33	146
Sr	214	68	–	338	62	68	105	134	104	–	133	19	220	43
Y	35	22	–	27	19	18	27	27	28	–	37	23	33	32
Zr	225	163	–	150	164	149	146	191	152	–	138	134	144	142
Nb	26	18	–	18	20	19	19	17	23	–	20	22	18	19
Ba	64	778	–	129	537	625	786	312	763	–	579	781	251	455
La	30	22	–	24	5	8	26	18	25	–	29	4	31	26
Ce	92	59	–	80	24	48	40	47	68	–	75	10	93	74
Pb	16	13	–	20	10	10	15	17	21	–	5	9	7	8

Serial samples[1] were collected from the two locations as follows: (a) Seven samples (BA/1-7) were taken at the the Ballinascorney House Weir locality (Sheet 24) in a NW-SE traverse of a 7.6m wide sedimentary screen separating two dolerite dykes. (b) Three samples (AL/1-3) were collected from a sedimentary screen adjacent to a dolerite dyke at Allagour Quarry, 535m N55°E of Slievenabawnage summit (Sheet 24).

Individual samples[2] of adinole and country rocks were taken from De Selby Quarry, (DES) 270m N30°W of Tallaght Hill summit (Sheet 21); Friarstown Quarry (FQ) 240m N of Friarstown House, Sheet 24, and Slade of Saggart (VE), 400m N50°W of Verschoyles Hill summit (Sheet 21).

The Sheet numbers are 6" maps of County Dublin.

[3] distance from contact with dyke; [4] Codes: A = adinole; C = country rock; A/C = adinolized country rock.

parts of the country rock screen and appears to be relatively unaffected by the adinolization process The main mineralogical transformation observed to have taken place in the Tallaght country rock screens as a result of adinolization, and the implied chemical changes that must have been involved, can therefore be summarised as follows:-

$$\begin{array}{lll} \text{muscovite} & + \text{ quartz} & \rightarrow \text{albite} \end{array}$$

$$KAlSi_3O_{10}(OH)_2 + 6SiO_2 + 3Na^+_{(fluid)} \rightarrow 3NaAlSi_3O_8 + 2H^+_{(fluid)} + K^+_{(fluid)}$$

From this it is obvious that Na must have been introduced at the expense of K, which appears to have left a system that was clearly not a closed one.

Chemistry

Samples were analysed for major and trace elements by X-ray fluorescence spectrometry. The Norrish and Hutton (1969) fusion technique was used for major elements, and pressed powder pellets with calculated mass absorption coefficient correction for matrix effects were used for trace elements. Na_2O was measured by flame photometry. Classical methods were used for the determination of FeO and H_2O^+ (Riley, 1958 *a,b*). Representative chemical analyses of country rocks and adinoles are presented in Table 1.

TABLE 2. Comparison of Tallaght country rocks with average shale

Sample	Average Tallaght country rock[1]	Average ML Arenig black shale[2]	Average Shale[3]
%			
SiO_2	59.15	61.98	58.41
TiO_2	0.94	0.58	0.92
Al_2O_3	20.43	15.29	15.11
Fe_2O_3	7.61	4.71	6.75
MnO	0.12	–	0.11
MgO	2.11	4.26	2.49
CaO	0.22	1.27	3.09
Na_2O	0.90	1.15	1.29
K_2O	4.71	4.99	3.20
P_2O_5	0.12	–	0.16
S	0.18	–	0.24
ppm			
V	144	178	130
Cr	109	103	90
Ni	40	38	68
Cu	31	35	45
Zn	92	100	95
Ga	28	17	19
Rb	183	148	140
Sr	43	109	300
Y	24	16	26
Zr	142	144	160
Nb	20	8	11
Ba	620	603	580
Pb	9	11	20

[1] Mean of BA/3; DES/C; VE/C

[2] Mid-Late Arenig black shale – Fyffe & Pickerill (1993)

[3] Turekian & Wedepohl (1961) – *Geol. Soc. Amer. Bull.* **72**, 175–92.

[t] total Fe as Fe_2O_3

Composition of country rocks

An average composition for unaltered Tallaght country rock has been calculated from samples BA/3, DES/C and VE/C, all of which were selected on the basis of their low Na_2O contents. The average Tallaght parent material is tabulated in Table 2 together with the average shale calculated by Turekian and Wedepohl (1961) and an average Lower-Middle Arenig black shale recorded by Fyffe and Pickerill (1993). The Tallaght average is in reasonable agreement with both of the average shales, except in respect of CaO and Sr which are much lower than the Turekian and Wedepohl average. The Tallaght average Al_2O_3 is higher than that of the average shales.

Before the chemical effects of adinolization can be assessed, it is necessary to explore the implications of any lithological variations present in the country-rock screens for the bulk rock chemistry of the adinole parent materials. The mineralogy of the pelitic parent materials is essentially sericite + chlorite + quartz, the quartz content being the main variable. The chemical effects of lithological variation is clearly demonstrated in Fig. 3 where SiO_2, Al_2O_3, TiO_2 and K_2O concentrations are plotted against distance across the Ballinascorney House Weir country rock screen. The profile for SiO_2 mirror images those shown for the other three components reflecting the predictable reciprocal relationship between quartz and the clay mineral components. Al_2O_3 and TiO_2, which may be regarded as immobile components

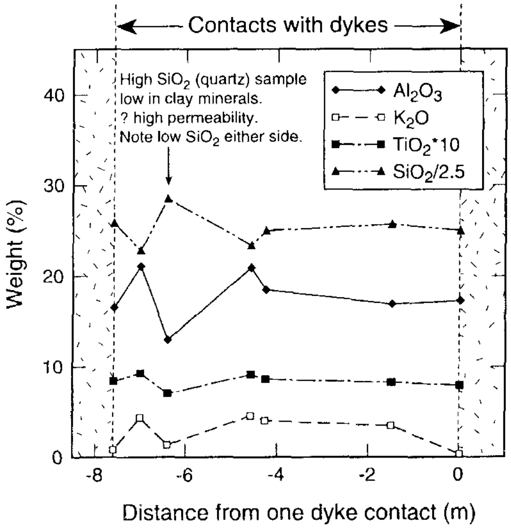

FIG. 3. Plot showing variation of SiO_2, Al_2O_3, TiO_2, K_2O across Ballinascorney House weir country-rock screen.

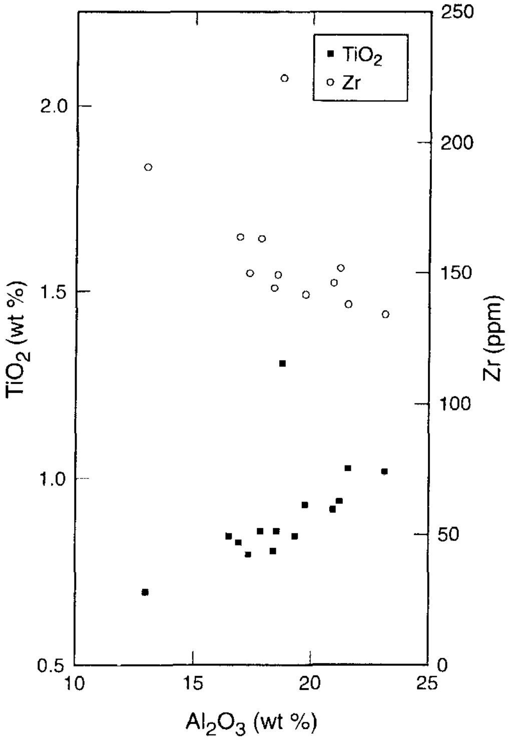

FIG. 4. Plot of Al_2O_3 *vs* TiO_2 and Zr *vs* Al_2O_3 for all country-rock samples.

within the system under consideration, give profiles of identical shape. The profile for K_2O, although mobilized in the adinolization process (see later), does echo the profiles for Al_2O_3 and TiO_2, in the central parts of the screen, reflecting lithology as the dominant control of K content away from strongly adinolized zones. These profiles demonstrate significant variation in lithology across the screen, with one sample in particular (BA/5, SiO_2 = 71.16%) having a higher quartz content. Caution is thus required in identifying the chemical effects of adinolization.

Plots of Al_2O_3 *vs* TiO_2 and also Zr *vs* Al_2O_3 (Fig. 4) for all the country rock samples show strong positive and negative linear correlations respectively, confirming the relative immobility of these components. One sample (Al/1) plots in an anomalous position on these diagrams, indicating an atypical composition which has comparatively high values for both TiO_2 and Zr, possibly related to an atypical original heavy mineral suite in this sample.

Chemical effects of adinolization

Na, K and Ca. The most obvious chemical changes resulting from the metasomatism are in the Na, Ca and K concentrations. In Fig. 5 element concentrations across the Ballinascorney House Weir sedimentary screen are plotted against distance from immediately adjacent dolerite intrusions. [Note that Figs. 5–8 are plotted using cation percentages/ratios. Equivalent plots using oxide weight percents produce the same relationships]. Na and Ca are enriched toward the dolerite-sediment junctions, with significant additions evident from about 1m out from the contacts, whereas the behaviour of K is antipathetic to that of Na and Ca. This variation is virtually identical to that shown by the Allagour Quarry screen (see Table 1). Na_2O and CaO reach maxima of about 6.94% and 3.52% respectively in the adinoles and K_2O is reduced from an average of about 4.7% in the unaffected country rock to as little as 0.26% in the adinoles. Other major element variations are rather irregular and of little obvious significance except perhaps in reflecting heterogeneity in the original sedimentary material. Overall, the amounts of Na, Ca and Mg added during adinolization appear to be similar to the amounts of K and H_2O removed.

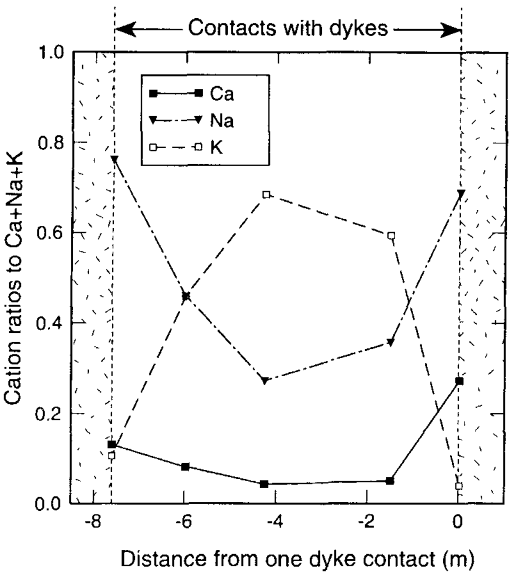

FIG. 5. Plot of Na, K and Ca as cation ratios to (Ca+Na+K) *vs* distance across the Ballinascorney House Weir sedimentary screen. (the mean of samples BA/4, 5,6 have been used to eliminate effects due to lithological variation seen in Fig. 3).

These relationships are further confirmed by plotting an 'isocon' diagram (Grant, 1986) for BA/3 (as parent material) against BA/1 (adinole), which also suggests that replacement has been on a more or less constant mass basis. Overall, using this

TABLE 3. Chemical comparison of adinoles, country rocks & intrusive rocks from Tallaght, Pen-y-Gader, Sassenfjorden and Dinas Head

	Adinoles and country rocks							
	Tallaght		Sassenfjorden[1]		Pen-y-Gader[2]		Dinas Head[3,4]	
%	max	min	max	min	max	min	max	min
Na_2O	6.94	0.35	9.8	0.4	10.8	0.82	8.89^3 11.10^4	0.51^3 0.35^4
CaO	3.52	0.12	0.7	0.4	1.3	0.66	2.48^3 6.07^4	0.60^3 0.08^4
	min	max	min	max	min	max	min	max
K_2O	0.26	6.81	0.8	3.9	0.21	4.5	0.25^3 0.08^4	4.57^3 4.60^4

	Intrusives											
	Tallaght			Sassenfjorden[1]			Pen-y-Gader[2]			Dinas Head[3,4]		
%	max	av.(13)	min	max	av.(4)	min	max	av.(6).	min	max	av.(2, 5)	min
Na_2O	3.61	2.92	2.33	3.3	2.65	2.1	5.3	3.98	2.3	3.61^3 4.70^4	3.70^3 3.57^4	3.79^3 1.55^4
CaO	11.38	8.86	7.20	10.3	9.48	8.8	11.0	6.35	3.2	7.60^3 7.18^4	5.88^3 4.45^4	4.15^3 0.78^4
K_2O	1.72	0.71	0.17	0.9	0.75	0.6	0.80	0.24	0.04	0.48^3 1.61^4	0.47^3 1.11^4	0.46^3 0.47^4

[1] Sassenfjordern data from Dypvik (1979);
[2] Pen-y-Gader data from Davies (1956);
[3] Dinas Head data from Agrell (1939);
[4] Dinas Head data from Williams *et al.* (1993)

approach, it is clear that Na, Ca, (Sr, La and Ce) have been added, and K (Rb, Ba, and Zn) removed, as a result of the adinolization process. Dilution/concentration effects due to the addition/removal of these components are therefore regarded as minimal and unlikely to influence the interpretation of the data.

The profile shown by Ca is noticeably more assymetrical than those for the other components shown in Fig. 5. This is possibly a reflection of the irregular distribution of epidote, but may be a function of a higher temperature gradient existing on one side of the country rock screen compared to the other.

The metasomatic addition of Na and removal of K is commonly regarded as the most diagnostic feature of any adinolization process. This is evident from the geochemical data on the Dinas Head adinoles in Cornwall (Agrell, 1939; Williams *et al.*, 1993) and the Llyn-y-Gader spilosites and adinoles associated with the Pen-y-Gader dolerite sill in North Wales (Davies, 1956) (Table 3). [A few of the rocks at Dinas Head identified as adinoles on the basis of field characteristics by Williams *et al.*, (1993) do not conform to this general pattern and are relatively high in K (up to 4.6% K_2O) and low in Na (minimum ~0.4% Na_2O), i.e. they have levels of these elements comparable with little altered slate]. Other examples such as the desmoisites from Zvornik in West Serbia (Djordjevic and Karamata, 1972) and the metasomatized black shales from Sassenfjorden, Spitzbergen (Dypvik, 1979), further confirm the ubiquitous additions of Na. In these examples of adinoles associated with sills, maximum concentrations of Na_2O are generally greater than in the Tallaght adinoles, reaching 10.8% and 11.1% in the Pen-y-Gader and Dinas Head samples respectively and 9.8% in the Sassenfjorden examples (Table 3). The level of enrichment in (non-carbonate) Ca accompanying adinolization of the Tallaght rocks is not generally observed in the other examples. Many adinoles from Dinas Head (Williams *et al.*, 1993), for example, show high levels of Na_2O but very low

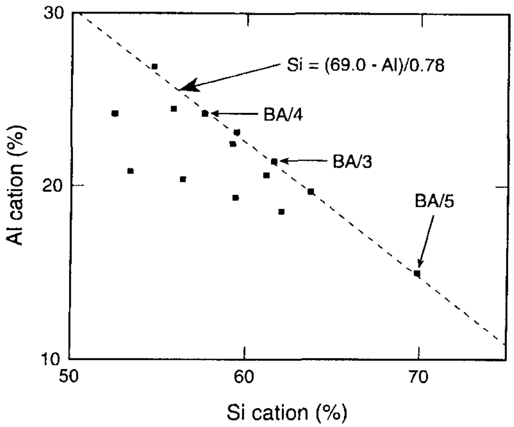

FIG. 6. Plot of Si *vs* Al as cation % for all Tallaght country rocks and adinoles. The dotted line represents the relationship between Si and Al for three samples from the central (unaffected) part of a country rock screen. Samples (to the left of the line) departing from the linear relationship have elevated Na content.

levels of CaO (e.g. 9.17% and 0.08% respectively). The data reported for the Dinas Head adinoles, however, shows that some adinoles do have a high CaO content, but this component has an obvious correlation with CO_2 content and appears to be linked to an elevated carbonate content. Whether carbonate was introduced into the adinoles at Dinas Head as an integral part of the adinolization process is unclear.

The higher levels of Na fixed as a result of adinolization of country rocks adjacent to sills compared to the Tallaght (dyke) examples may be due to (a) the greater heat flux in the case of sills and/or (b) the relative impermeability of the sills resulting in 'ponding' of the hydrothermal fluids below sills (see below). The greater importance of Ca in the Tallaght examples suggests metasomatizing fluids of a different composition and/or situation in a different position within a major hydrothermal fluid system.

SiO_2. Si and Al show a strong linear inverse relationship (Fig. 6) in the Tallaght country rocks and adinoles, which reflects the reciprocal relationship between quartz and clay components of these rocks. However, these plots also indicate that samples with elevated Na content depart from the linear relationship and, assuming that Al is immobile, have a lower Si content than that predicted from the Al content. A further test of this observation was achieved by calculating the linear relationship between Si and Al using three samples from the centre part of a country rock screen (BA/3, BA/4 and BA/5), and using this relationship to calculate the difference between the predicted and actual Si contents of all the Tallaght country rocks. This difference is plotted against Na content in Fig. 7, which shows a strong positive linear relationship ($r^2 = 0.91$) between Si removed (predicted Si − actual Si) and the extent of adinolization as expressed by the Na content. From this evidence, Si appears to be mobilised and lost from the system to some degree during the adinolization.

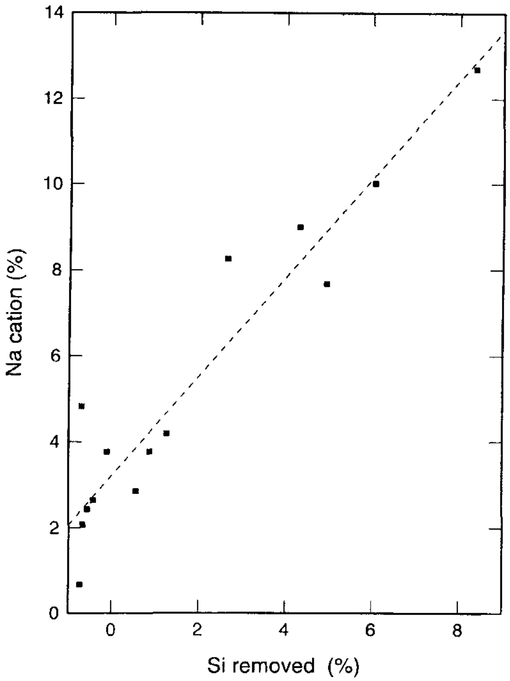

FIG. 7. Si removed (= Si predicted from Al content (see line and equation Fig.6) minus actual Si) plotted against Na content for all Tallaght country rocks and adinoles. Si appears to be increasingly removed as adinolization intensifies.

Applying a similar approach to the Pen-y-Gader adinoles (Davies, 1956) suggests that beneath the sill at that locality SiO_2 increases with increasing Na content, and Dypvik (1979) concluded that addition of SiO_2 took place beneath the dolerite intrusion at Sassenfjorden. Agrell (1939) also calculated that addition of SiO_2 was involved in the adinolization process at Dinas Head (although the location of the samples with respect to the individual components of the intrusive complex is unknown, and one sample indicated a loss of SiO_2). These examples, all point to the addition of Si to pelitic rocks beneath sills during adinolization. There is little information as to the fate of Si above sills, but the chemistry of the roof sediments above the Pen-y-Gader sill, suggest, if anything, that SiO_2 decreases towards the upper sill contact, i.e. Si may have been removed from this zone, but the possibility of lithological control renders this very uncertain.

We suggest the possibility that in the latter instances the sills have acted as impermeable roof traps for rising metasomatic fluids containing Si dissolved during adinolization of underlying pelites, whereas adjacent to the Tallaght dykes (and above sills?) the hydrothermal fluids have not been similarly restrained and consequently Si has been removed (upwards) from the local system. This proposed ability of sills to act as barriers to vertical movement and hence dispersal of hydrothermal metasomatizing fluids rising beneath such intrusions may also account for the occurrence of more intense adinolization beneath sills as opposed to adjacent to dykes as already discussed.

H_2O^+. It is clear (Table 1) that adinolized samples have less H_2O^+ ($\sim$2–3.5%) than unaffected parent country rocks which contain $\sim$4–4.5% H_2O^+, and there is an obvious negative correlation (r = –0.71) between Na_2O and H_2O^+ for the Tallaght country rocks and adinoles. This indicates that adinolization has been accompanied by dehydration, presumably mainly reflecting the replacement of the hydrous phase, muscovite/illite, by the anhydrous phase, albite. There is no evidence that hydrous fluids displaced from the adinolized parts of the country-rock screens have migrated only locally to hydrate further the otherwise unaffected outer parts of the country rock screens. It is therefore presumed that any hydrous fluid generated by local dehydration adjacent to the dykes has ultimately left the immediate system, possibly carrying with it K, Si and other elements mobilised during adinolization. Dehydration of adinolised pelites is also evident from the chemical data from all the other examples cited (e.g. Agrell, 1936; Davies, 1956; Williams *et al.*, 1993).

Trace elements. Calculation of inter-element correlation coefficients for all the Tallaght adinoles and country rocks reveal certain relationships. As might be expected from the coherent geochemical behaviour of Sr with CaO (r = 0.95), and Rb and Ba with K_2O (r = 0.99 and 0.92 respectively), these particular trace-elements display similar trends to the major elements they substitute for. Both Rb and Ba exhibit depletion up to 0.75m from the contacts, from which point Sr increases rapidly towards the dyke contacts. Similar trends in these trace elements were recorded by Dypvik (1979) in Triassic black shales metasomatized by a dolerite sill at Sassenfjorden in Spitzbergen, although the degree of Sr enrichment is less marked than at Tallaght, in conformity with the lesser enrichment in Ca.

Y, La and Ce also show positive correlations with Na_2O (r = 0.69; 0.71 and 0.81 respectively), suggesting introduction of these components during adinolization. Zn shows a negative correlation with Na_2O (r = –0.54) and a positive correlation with K_2O (r = 0.71) indicating removal of this element from the adinoles. Cr, Ni and V correlate positively with Al_2O_3 and negatively with SiO_2 suggesting their association with clay minerals and relative immobility. Cr, Cu and Nb positively correlate with Fe_2O_3 (r = 0.73; 0.71 and 0.80 respectively).

Redox effects. With reference to the Cornish adinoles, Dewey (1915) argued that the state of oxidation of the iron, in both dolerites and country rocks, controlled the degree of adinolization; sedimentary material poor in ferric iron was more readily altered and only those dolerites with Fe_2O_3/FeO greater than 0.33 were capable of adinolizing adjacent slates. Agrell's work (1939) on the Dinas Head adinoles tended to support this conclusion that slates with iron mostly in the ferrous state reacted more readily. Davies (1956) showed that the tendency to form adinoles decreased as Fe_2O_3/FeO ratio of the dolerites became lower, but with the added qualification that "higher Fe_2O_3/FeO ratios must be looked upon as the consequence of the presence in the igneous body of metasomatizing fluids .... not the cause of the activity". Thus in the Pen-y-Gader dolerite Fe_2O_3/FeO = 0.3 and the associated metasomatism is quite intense, whereas in the two associated sills of Twr Du and Mynydd Moel, which do not give rise to extensive adinoles, the ratios are 0.23 and 0.19 respectively. In the Tallaght dolerites the average Fe_2O_3/FeO = 0.24 and correspondingly the extent and intensity of adinolization is limited. These early works therefore confuse the cause or effect aspects of redox regimes.

The distribution of Fe^{2+} and Fe^{3+} (relative to total Fe) across one of the Tallaght country rock screens is shown in Fig. 8. Both Fe^{3+} and Fe^{2+} produces smooth curves with little scatter, and clearly show that Fe^{3+} decreases and Fe^{2+} increases as the contacts with the dykes are approached. A possible interpretation of this is that organic matter in the country rock screens close to the dyke contacts was oxidised as a result of heating from the dyke and this caused a corresponding reduction of Fe^{3+} to Fe^{2+}. i.e.:-

$$2Fe_2O_3 + C_{(organic?)} \rightarrow 4FeO + 2CO_2\ _{(fluid?)}$$

By contrast, it is interesting to note that there is some evidence in the Dinas Head adinoles analysed by Williams *et al.*, (1993) for an oxidation of iron towards the contact with underlying dolerite, this process presumably being promoted by different controls than those operating in the Tallaght case.

Dyke chemistry. The Tallaght dykes are tholeiitic on the basis of alkali/silica and Nb/Y ratios and normative compositions which include significant hyperthene and sometimes quartz. Variations in primary bulk chemistry of the dyke lithologies are

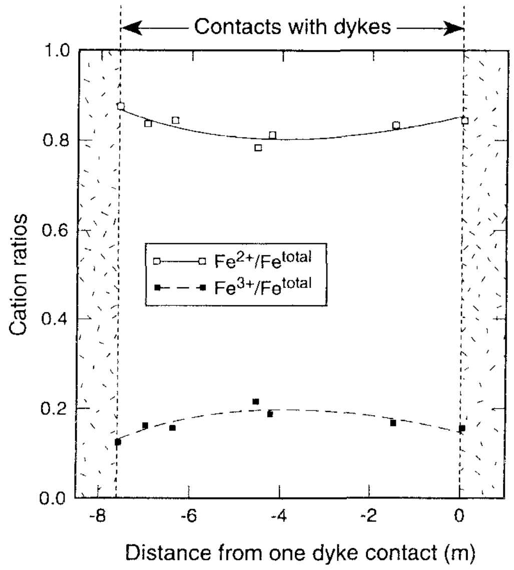

FIG. 8. Fe^{2+} and Fe^{3+} variation across the Ballinascorney House Weir sedimentary screen demonstrating reduction of Fe towards contacts with dykes.

influenced by the locally porphyritic nature of the dolerites which vary between aphyric and highly feldspar-phyric. Changes in dyke chemistry at the margins, such as indicated in the case of one dyke by the data in Table 4, (lower Ca and Na, higher K) are complicated by processes such as flow differentiation, and cannot therefore be interpreted with any certainty as due to reactions with hydrothermal fluids, although this cannot be ruled out. The changes are small, but could nevertheless be in accordance with removal of Na and Ca and the introduction of K predicted from the complimentary chemical changes involved in adinolization. On the other hand, the average dyke composition suggests a somewhat elevated Na content overall, and this might be due to introduction of minor amounts of Na from metasomatizing fluids responsible for adinolization of the wall-rock pelites. In the light of the pervasive and ubiquitous hydrous alteration of the dyke mineralogy we consider the latter scenario to be more likely, i.e. the dyke lithology has received minor amounts of Na rather than donated it. This is compatible with the observed occurrence of clear albite rims around altered Ca-plagioclase cores in the Tallaght dolerites, and contrasts with the observation by Willams *et al.* that the Dinas Head dolerite contains primary (?) plagioclase of An_{10} composition.

TABLE 4. Chemistry of Allagour quarry dyke (~ 6.1m wide)

Sample	NSA3	NSA4	mean(13)
distance in from contact	0.0 m	0.46 m	
%			
SiO_2	49.97	49.85	49.51
TiO_2	2.36	2.25	2.01
Al_2O_3	14.22	14.23	14.25
Fe_2O_3	2.63	2.59	2.31
FeO	10.41	9.72	9.36
MnO	0.20	0.20	0.20
MgO	6.42	5.97	6.70
CaO	7.40	9.26	8.86
Na_2O	2.33	2.69	2.92
K_2O	0.72	0.54	0.71
P_2O_5	0.24	0.22	0.19
S	0.16	0.13	0.13
H_2O+	3.48	2.55	2.99
Total	100.54	100.20	100.13
ppm			
V	374	354	328
Cr	86	94	176
Ni	38	39	50
Cu	74	64	69
Zn	152	113	136
Ga	24	24	21
Rb	29	22	23
Sr	158	155	167
Y	42	43	40?
Zr	167	158	147
Nb	10	7	8
Ba	78	53	112
Pb	9	9	8

Comparison of the Tallaght dyke chemistry with that of the igneous material from Sassenfjorden, Pen-y-Gader and Dinas Head (Table 3), demonstrates considerable variation in Na_2O, CaO and K_2O at each of these localities. The Pen-y-Gader and Dinas Head dolerites, however, have higher average Na_2O (4–5%) than the Tallaght or Sassenfjorden dolerites (~2.8%) and much more variable CaO contents. The original major-element chemistry of all these intrusive rocks is obscured by the effects of subsequent alteration and it is not possible on the data available to establish their primary affinities. We think it is most likely that the differences in Na_2O, CaO and K_2O seen are most likely to reflect the different extents of hydrothemal alteration to which the intrusions at the various localities have been subjected.

Discussion

Evidence from the majority of cases recorded in the literature indicates at least two major prerequisites for adinole formation: pelitic host rocks and high-level basic (tholeiitic) intrusions as a heat source. Identifying the origin of the Na-rich hydrothermal fluids which effect adinolization and the general conditions favourable to this process requires a new approach, since it now questionable that the intrusions themselves have acted as the main sources of Na-bearing metasomatizing fluids.

The role of parent material mineralogy

The dependence of adinole formation on clay-rich country rock is substantiated by a virtual absence of Na metasomatic enrichment in other associated lithologies. Thus in West Serbia, Djordjevic and Karamata (1972) noted that "if the diabases lie in sandstones, cherts or limestones, or if they were injected into unconsolidated sandy, siliceous or carbonate sedimentary material, only a weak chloritization immediately at the contact, or recrystallization of carbonates near the contact is found. Very often no alteration at all is observed". Similarly with the Talnakh intrusion (Arkhipova and Natorkhin, 1969) in the north-west of the Siberian platform; the principal 'branch' intrudes Permo-Carboniferous sandstone, siltstone and mudstone, altering the latter pelites to adinole, whereas the north-western 'branch' lies mainly in Devonian gypsiferous dolomites and marls which show no evidence of Na-metasomatism. However, it is interesting that older dolerites enclosed in this Devonian succession "have been changed to spilosite and albitite". Butler (1961) also recorded Na enrichment (with K-depletion) in Moine arkoses in contact with the Glenmore dolerite plug, emphasising that this "and several of the other examples of metamorphism of quartzo-feldspathic rocks show a trend to soda-enrichment similar to but much less marked than that of adinolization".

It cannot be fortuitous that extensive adinole formation is restricted to pelitic rocks. Obviously, the chemistry and mineralogy of such rocks is as important as the availability of suitable hydrothermal fluids. Fixation of Na in albitic plagioclase clearly requires sources of Si and Al which are readily available in pelitic rocks. The limited Na enrichment recorded in arkoses, could be equated with paucity in the requisite (Al-bearing) mineral constituents suitable for fixation of sodium, as well as limited availability of sodium.

Recent experimental work on the hydrothermal alteration of basalt and greywacke by NaCl solutions (Rosenbauer *et al.*,1983; 1988) has provided a basis for understanding these controls. Rosenbauer *et al.* (1983) demonstrated that illite, dolomite and quartz comprising 67% of the greywacke reacted in experiments at 350°C and 500 bars with pure 4 *m* NaCl to produce albite and smectite, the rock gaining Na and losing Ca and K to solution. Reaction of the greywacke (Bischoff *et al.*, 1981) with natural brine resulted in less Na_2O being introduced (about one tenth of that introduced using 4 *m* NaCl) and only limited reaction occurred with seawater (0.55 *m* NaCl). Only minimal reaction occurred at 200°C but significant reaction was found at 350°C. Similar experiments using MORB-type basalt and 4 *m* NaCl produced minimal albitization (Rosenbauer *et al.*, 1983). Subsequent experiments (Rosenbauer *et al.*, 1988) were successful in producing complete alteration of a MORB-type basalt in the presence of quartz by 3.4 *m* NaCl at 350°C and 400 bars to produce albite + actinolite + smectite. Reaction of the basalt/quartz mixture with synthetic 'natural brine' and basalt with 3.4 *m* NaCl and 'natural brine' did not produce significant albitization, and it was concluded that excess silica, a high Na/Ca ratio and absence of Mg in the fluids were important for the albitization of basalt. Although such experiments using static solutions are unlikely to fully represent the effect of a natural situation in which fluxing of reactant fluids is likely to occur, this experimental work suggests that (a) reaction with *unmodified seawater* is unlikely to produce albitization of a sedimentary country rock even if the parent material mineralogy is suitable (i.e. muscovite/illite + quartz present)' Na-rich (Mg-poor?) hydrothermal fluids being implicated; (b) temperatures of above 200°C and probably around 350°C are needed for significant reaction to occur; (c) dyke rocks could have been saturated with Na-bearing hydrothermal fluids without any significant albitization because excess silica (solid or in solution) appears to be necessary for this reaction to occur.

Source of the metasomatizing fluids

Magmatic fluids. Analytical data on fluids from geothermal systems and from fluid inclusions in hydrothermal minerals indicate that Na^+, Ca^{2+}, K^+ and Mg^{2+} are the dominant cations and Cl^-, HCO_3 and SO_4^{2-} the dominant anions (Holland, 1967). This would appear to be the starting point for adinolization.

Giggenbach (1988), on the basis of high temperature gases released from basaltic magmas, suggests that fluids emanating from basic magmatic bodies at depth are likely to consist mainly of water vapour containing CO_2 (20–40%); SO_2/H_2S (5–10%); HCl (1–2%). Initially these fluids remain close to equilibrium with the rock.

Absorption of these gases into deeply circulating groundwater, results in highly reactive solutions capable of virtually complete cation leaching of the country rock and the production of chloride and sulphate laden waters (Na/K brines). Giggenbach (1984, 1988) identified four subsequent major hydrothermal environments (Fig. 9*b*) in which different alteration processes affecting country rocks operate :-

1. K metasomatism and silicification in major upflow zones
2. H metasomatism by CO_2 attack on Ca-Al silicates leading to calcite formation and Al-enriched argillic (to clay) to phyllic (to micas) alteration. This mainly occurs in parts of the hydrothermal system subject to rapid cooling or dilution adjacent to major upflow zones. Na, Ca, and some Mg are liberated (Hemley and Jones, 1964)
3. Na, Mg, Ca metasomatism (propylitic alteration) associated with descending and heating solutions affecting rock over the meteoric recharge zones at the periphery of a hydrothermal system
4. Isochemical recrystallization and hydration over close to stagnant parts of a hydrothermal system.

Application of Giggenbach's (1988) model for magmatically driven hydrothermal systems (Fig. 9) to the Tallaght dyke-swarm situation suggests the following possible scenario. A magma body at depth (~8km?) was not only the source of the material injected at relatively high level as dykes, but also degassed hydrous fluids containing CO_2, SO_2, and HCl. Absorption of these fluids into deep circulating ground water, initiated a hydrothermal system as described above, ultimately producing Na, Ca (Mg) brines in the descending/reheating zones peripheral to the hydrothermal system. It is in this latter part of the hydrothermal cycle that adinolization could have occurred.

The emplacement of the dykes will have established local temperature gradients and, therefore, locally perturbed the simplified thermal regime indicated by Giggenbach (1984,1988), which takes no account of the thermal effects of higher level intrusions from the main magmatic body. Hence, temperatures of the order of 300–350°C are envisaged adjacent to the dykes, but at significantly shallower depths than indicated by the geothermal gradients indicated for the Giggenbach model.

Barton *et al.* (1991) point out that contact metasomatic effects are concentrated in the upper crust, being controlled by marked chemical and physical contrasts between intrusion and country rock, the availability of external fluids (e.g. seawater) and relatively high permeabilities. At depth, they argue, such factors do not pertain and metasomatism is less extreme. Metasomatism in and around mafic intrusions is regarded by Barton *et al.*, (1991) as largely due to circulation of *external* fluids with only minor metasomatic effects directly due to magmatic fluids. Consequently, metasomatism is limited around

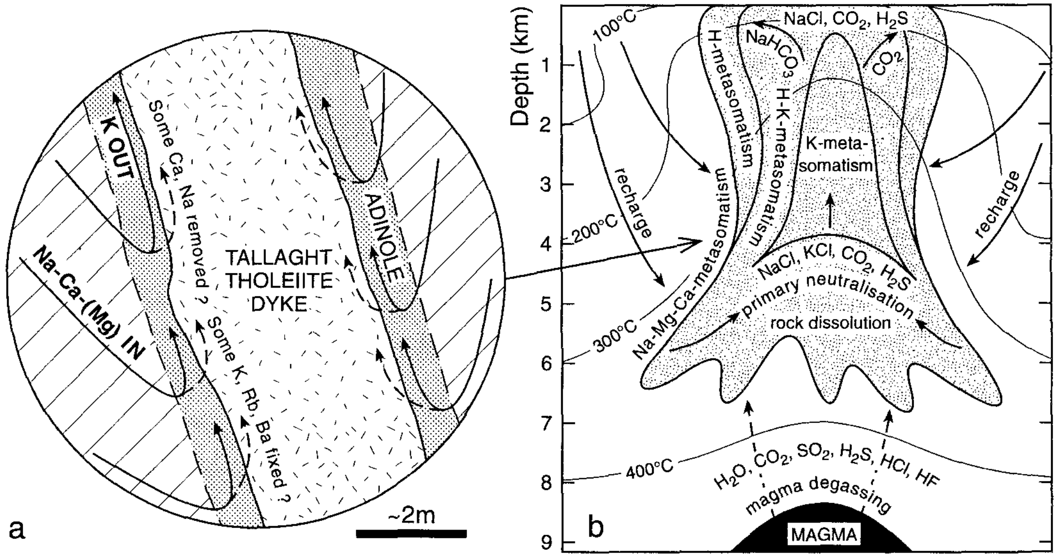

FIG. 9. Schematic diagram showing (*a*) hydrothermal circulation and metasomatism of Tallaght dykes and (*b*) Giggenbach's (1984, 1988) model for fluid composition and circulation within magmatically driven hydrothermal systems. Note that no depth implication for the Tallaght dykes is implied (see text).

most mafic intrusions in terrestrial as opposed to marine environments, this largely being a function of the availability of seawater in the latter situation in which shallow Mg-metasomatism, then deeper Na and Na(Ca) metasomatism occurs (Barton *et al.*, 1991).

In view of the likelihood of increased H_2O solubility in basic magmas at depth, more pronounced metasomatic activity than that associated with some higher level dolerite bodies might initially be expected around deep-seated gabbroic intrusions. In addition, the presence of a plutonic intrusion itself will, of course, establish an overlying hydrothermal system that will have different chemical characteristics at different levels in the country rocks (Giggenbach, 1984,1988). However, degassing mafic intrusions driving such systems upwards would inevitably be out of reach of any descending (Na-Ca) hydrothermal fluids (which would re-enter the hydrothermal system above the intrusion contact zone) and would therefore not be subjected to significant metasomatic effects from this source.

To what extent metamorphic water arising from dehydration of the pelitic rocks, or the circulation of heated meteoric ground water will have contributed to the magmatically driven hydrothermal system, or subsequently modified its effects, is difficult to assess in the absence of stable isotope data. The loss of water from adinolized pelites by dehydration, however, points to a potential contribution to the hydrothermal fluids from this source.

Saline groundwaters. Evidence from studies of deep groundwaters in crystalline rocks e.g. in the Canadian Shield and elsewhere (see Fritz and Frape (Eds.), 1987) suggests that highly saline Ca-Na-Cl brines may commonly occur in terrains not affected by active magmatic hydrothermal systems. Although the potential origins of the water component are various, both allochthonous (sedimentary basin brines; modified seawater) and autochthonous (leaching of fluid inclusions; water-rock interaction) sources of the salinity in the brines have been suggested.

There are therefore different mechanisms by which saline groundwaters or brines may be formed. However, the obvious genetic association of the Tallaght adinoles with a magmatic source at depth strongly suggests that the origin and composition of the metasomatizing fluids were related to hydrothermal fluid circulation and reaction as envisaged by the Giggenbach (1984, 1988) model outlined above.

Heat flow and convection adjacent to dykes

We suggest that the width of the adinolization zones ($\sim$1 m average) may indicate the extent of the effective thermal regime rather than the limit of the hydrothermal system adjacent to intrusive contact. Delaney (1987) presented calculated time-distance temperature profiles for heat transfer during emplacement of mafic dykes. He assumed a normal geothermal gradient and modelled temperature profiles for a 2 m thick dyke at an initial temperature of 1150°C emplaced at 2 km depth in country rock at 50°C. The profiles produced show that temperatures of 350°C and above are indeed likely to be attained in the wall-rocks within about 1m of the contact with the dyke, the exact distance depending on the water content of the magma and whether latent heat generation is allowed for or not. Buchan and Schwarz (1987), on the basis of remanent magnetism measurements, studied maximum temperature profiles across dyke contacts, and for a 1.25 m wide dyke (initial magma temperature 1150°C) emplaced in country rock at an ambient temperature of 150°C showed that the maximum temperature reached in the wall rock at 1 m from the contact was about 400°C. Both these approaches, therefore, indicate that maximum temperatures in excess of about 350°C may be expected in country rocks within 1m of contacts with dykes 1–2 m thick. Since the Tallaght dykes usually exceed the dimensions considered above and, in addition, may have been emplaced in a terrain with a higher geothermal gradient, it is not unreasonable to assume that the adinolized zones ($\sim$1m thick) were elevated to temperatures of at least 350°C. As Delaney (1987) points out, however, groundwater flow influences the cooling behaviour of dykes and hydrothermal circulation can be a dominant heat transfer mechanism. But, the time required for steady hydrothermal circulation to be achieved increases with decreasing permeability, and most individual dykes cool too quickly for hydrothermal circulation to be established. The emplacement of the Tallaght dykes in intense swarms, in a region of high heat flow driving a major hydrothermal system associated with an underlying plutonic magma body may nevertheless have allowed local hydrothermal circulation to develop alongside the dykes (Fig. 9*a*).

This conforms with the theoretical treatment of natural convection adjacent to a hot vertical surface in a permeable medium (Parmentier, 1979) and its application to natural convection of vaporizing ground water adjacent to the contact of an intrusion early in its cooling history (Parmentier and Schedl, 1981). In this situation liquid water moves horizontally towards the contact where it is heated and vaporized and then moves vertically upwards along the contact. Heat and chemical transfer in this upwards direction is enhanced and would therefore limit the extent of lateral transfer into the country rock. This might also explain the fate of the displaced K, Rb, Ba. Although in some situations e.g. Pen-y-Gader (Davies, 1956), K, Rb and Ba are redistributed to the outer, lower temperature regions, in many instances these elements, and perhaps some Na etc. as well, are removed, possibly in a meteoric, hydrothermal system. The 'adinoles' with elevated levels of K and low levels of Na recorded by Williams *et al.* (1993) may have formed by localised K-enrichment, but seem more likely to represent lithologies that have retained parent material (slate) levels of these elements, possibly during isochemical recrystallization to produce a rock superficially resembling an adinole. As in the adinolized contact zones of the Rosbeg dolerites in Donegal (Pitcher and Berger, 1972), there is no real evidence in the Tallaght adinoles for outward displacement and concentration of K, Rb or Ba nor of significant absorption of these elements into the magma. However, hotter, less dense water rising along the contact could remove K etc., as well as heat conducted out of the intrusions. Subsequently, in the later stages of cooling, such hydrothermal systems could have encroached on the solidified dykes and resulted in the lower temperature degradation of their mineralogy.

Conclusions

We suggest that the Tallaght dyke swarm represents an intense shallow intrusive system closely associated with an underlying volume of basic magma that had degassed magmatic volatiles and established an overlying major hydrothermal system of the sort envisaged by Giggenbach (1988). Heat-flow from the dykes possibly superimposed local hydrothermal convection onto the upper regions of this much larger system, in the lower parts of which the interaction of acid hydrothermal fluids with country rocks resulted in the formation of cation-rich brines. Circulation, modification and ultimately descent of metasomatizing hydrothermal fluids eventually produced Na-Ca (Mg)-rich fluids in the vicinity of the dykes. The heat flow from the dykes produced temperatures in excess of 350°C within ~1m of the dyke contacts and promoted the reaction between the fluids and the country-rock pelites resulting in the conversion of muscovite (+ quartz?) to albite in the adinoles. Local fluid circulation patterns - towards (and into?) the dyke contacts and then upwards - continually replenished the supply of metasomatizing constituents to the wall-rock and removed other constituents such as K (and Si?). As the intrusions cooled, the local hydrothermal circulation was reduced and below the adinolization temperature threshold (~350°C?), retrograde hydration reactions occurred in the dykes.

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