# Compositional evolution of tephra deposits in a syn-rift basin: monitoring the growth of the proto-Icelandic mantle plume

**Brian Bell**

**Department of Geographical & Earth Sciences,**
**University of Glasgow,**
**Glasgow G12 8QQ, UK**

**Abstract:** Magmas produced by decompression-induced melting of mantle plumes are responsible for the large-scale sequences of volcanic rocks referred to as continental flood basalts (CFBs). Monitoring the geochemical evolution of such plumes is fraught with problems of deriving a detailed chronology of all associated volcanic events, from which the compositional fingerprints can be obtained. Due to their terrestrial environment of eruption, CFBs do not appear to faithfully record all magma compositions involved. An alternative approach, presented here, is to monitor the geochemical cycle through detailed analysis of tephra that has accumulated within a related rift basin and from which compositional data can be obtained. The proto-Icelandic plume developed during the Early Palaeogene (~62 Ma) and continued producing voluminous quantities of pyroclastic and effusive products until it retracted into a rift zone, leading to the commencement of ocean floor spreading at ~55 Ma. The entire geochemical cycle, from initiation to retraction, is faithfully recorded in tephra preserved within the early Palaeogene Shetland, Faroe and Moray groups of the Faroe-Shetland Basin, indicating early alkaline compositions through small degrees of melting, a peak involving tholeiitic basalt magmas at which time effusive volcanism was intense, diminishing in the early Eocene to further production of alkaline magma compositions.

## Introduction

The geochemical evolution of magmas produced by decompression-induced melting of a mantle plume is a compositional monitor of the plume's evolution. Such plumes are construed to be responsible for rapidly erupted terrestrial lava sequences, commonly referred to as continental flood basalts (CFBs), which develop prior to rifting of continental lithosphere and the initiation of ocean floor spreading. However, terrestrial deposits, whether sedimentary or volcanic, typically do not preserve a faithful record of *all* events. Reasons for this are numerous, including the obvious possibilities of non-deposition and erosion. Within the marine environment, there is much greater scope for a more complete geological history being preserved within the various strata that accumulate. This is particularly true where pyroclastic materials are widely dispersed due to wind transport in the Earth's upper atmosphere, leading to a significant volcanic contribution to clastic units within sedimentary basins.

Such complete records are not easily accessed unless either the sedimentary basins that received such volcanic products are subsequently uplifted, or where there are sufficient well penetrations to permit a detailed sample set be acquired. This study follows the latter route, made possible by more than 140 commercial wells which have been drilled in the Faroe-Shetland Basin (FSB) of the NE Atlantic Ocean, where rifting has occurred since Triassic times.

## Geological Setting

Palaeogene volcanic activity associated with the impact of the proto-Icelandic plume in the NE Atlantic took the form of the eruption of magmas to produce terrestrial flood lava sequences (a.k.a. CFBs) and associated basinal hyaloclastite deltas, together with tephra (ash) deposits interbedded with the lavas and the hyaloclastites and within clastic sedimentary units within the rift-related basins between NW Europe and Greenland.

Rifting in the FSB commenced in Triassic times, but only very few of the released commercial wells within the basin reach these strata. More commonly, the wells penetrate the Palaeogene interval and stop where typically shale-prone Cretaceous strata are encountered. However, there is no substantive evidence to suggest that there was any volcanic activity associated with the impact of the plume prior to *c.* 65 Ma. Certainly, no tephra have been identified within these undoubtedly Cretaceous strata. Consequently, the initial stages of the plume-related volcanic activity are, potentially, preserved within the tephra component of the earliest Palaeogene strata.

The Palaeocene stratigraphic development of the FSB is summarised in Fig. 1, through to the Early Eocene, after which tephra deposits are not found and it is generally considered that volcanism was restricted to subaqueous effusion of pillow basalts at the newly-developed mid-Atlantic ocean floor spreading axis. The emergence of Iceland above sea-level at *c.* 15 Ma marked a return to pyroclastic effusive activity, along with the dominant flood lava sequences, but is not considered here, where the early activity of the plume, prior to ocean floor spreading commenced, is the main focus.

Early Palaeogene tephra was dispersed SE over Europe, with some of the best-preserved deposits within the mo clay basin in NW Denmark providing high-quality compositional data (Pedersen et al. 1975; Morton and Evans 1988; Larsen et al. 2003). Closer to the Palaeogene rift zone, a tephra chronology has been developed for the North Sea Basin, including some compositional data (Jacques and Thouvenin 1975; Knox and Morton 1983, 1988; Morton and Knox 1988, 1990; Jolley and Morton 1992). Onshore equivalents to the North Sea Basin sequences crop out along the SE coast of England, including the Woolwich, Reading, Upnor and Harwich formations (Knox et al. 1990).

Some preliminary findings from the FBS have been reported (Morton et al. 1988; Waagstein and Heilmann-Clausen 1995), but no detailed analysis has been undertaken until the present. Pyroclastic deposits have also been identified interbedded with the Early Palaeogene lava sequences of East Greenland (Heister et al. 2001), the Faroe Plateau Lava Group on the Faroe Islands (Rasmussen and Noe-Nygaard 1970), the Inner Hebrides of Scotland (Emeleus et al. 1996; Bell et al. 1996; Bell and Williamson 2002) and the Antrim Plateau of NE Ireland (Mitchell et al. 1999).

Within the FSB (Fig. 1), the earliest Palaeogene strata belong to the Sullom Formation of the Shetland Group and comprise sandstones within a mudstone-dominated sequence, deposited in shelf, slope and basin environments. The overlying Vaila Formation of the Faroe Group is a thicker and more heterogeneous sequence, involving silty mudstones and siltstones, interbedded with thick sandstone units. A variety of facies is represented, from outer shelf to basin, with slump and mass flow being commonly recognised deposition mechanisms. The Lamba Formation forms the upper part of the Faroe Group and comprises a sequence of volcaniclastic siltstones and sandstones, the Kettla Member (equivalent to the Balmoral Tuffite/Andrew Tuff of the Glamis Member of the North Sea Basin), possibly of turbidite association, overlain by a mudstone-dominated sequence of deepwater association that forms the bulk of the formation. Some sandstone units are interbeddded with the mudstones, especially within the basinal sections. The Moray Group comprises shallow marine (coastal plain) sandstones, the Colsay and Hildasay sandstone members, interbedded with impure sandstones, siltstones and mudstones of the predominantly shallow marine Flett Formation (equivalent to the Sele and Dornoch formations of the North Sea Basin). It was during Flett Formation time that hyaloclastite deltas prograded into the FSB, fed by subaerial lavas from the west. The overlying Balder Formation comprises impure silty and sandy mudstones, interbedded with various volcaniclastic units of mud through to sand grade material. Depositional environments ranged from paralic and littoral to shelfal.

## Sample preservation, alteration effects and sampling strategy

The samples analysed in the present study are predominantly of glassy material, in the form of tephra shards derived from explosive pyroclastic eruptions during the Early Palaeogene evolution of the NE Atlantic. The tephra was dispersed into the atmosphere and accumulated as a distinctive component of the FSB fill. Reworking of older material, up-sequence, appears to be minimal, enabling the compositional data to be interpreted as a chronological record of the plume’s compositional evolution.

As with the samples analysed by Larsen et al. (2003) from the mo clay succession of the Fur Formation exposed in the cliffs at Limfjorden, NW Denmark, problems were encountered during geochemical analysis. The tephra component of the FSB strata occurs as sedimentary grains, commonly with well-preserved shapes involving bubble walls, indicating both their volcanic origin and the fact that they have suffered very little, if any, mechanical abrasion prior to deposition, and that subsequent reworking was minimal. Significantly, where the tephra occurs within mud facies, or occurs in contact with lithograins of mudstone, alteration is significant. These grains are typically hydrated and there is abundant evidence of chemical leaching, thus the primary composition of the grain is lost. The grains are not isotropic and colour zonation patterns are obvious indicators of post-depositional alteration. Where the grains occur in arenaceous facies, or occur within a carbonate cement, alteration is commonly negligible, the grains are isotropic, and loss-on-ignition (LOI) values are low (typically < 4 wt.%), indicating that post-depositional hydration during burial has been minimal.

Hydration-driven alteration has typically affected certain elements more than others. Least affected are $TiO_2$ and $P_2O_5$, two of the so-called immobile elements, together with $K_2O$ and $Al_2O_3$. Most affected are $Na_2O$, CaO and MgO. Data for FeO and $SiO_2$ are equivocal. Similar observations are reported by Larsen et al. (2003). The trace-elements selected for analysis are those considered to be both the least mobile and also those which provide the most robust and useful geochemical signal as to the nature of the magma.

Repeat and multiple analyses of individual grains, of grains from the same sample (or sample depth within a well), and by using both electron probe micro-analysis (EPMA) and bulk-sample analysis using X-ray fluorescence spectrometry (XRFS), have enabled the construction of the best possible data base, given the nature and preservation state of the tephra. In excess of 2000 analyses were obtained from 50 samples from 12 wells. The entire Early Palaeogene stratigraphic interval was sampled, although certain wells yielded samples from restricted portions of the interval. Data for both the entire range of major-elements, together with selected (deemed useful) trace-elements were collected from each sample. Ba, Rb and Sr data were also obtained, although their validity due to proven mobility during hydration-driven alteration is widely recognised. Yttrium mobility has been discussed by Morton and Knox (1990) and Larsen et al. (2003), but was not recognised as a significant process in the samples analysed in the present study. The entire dataset is summarised in Table 1. All samples are of basaltic composition. This may be a sampling bias, or could be attributed to the poorer preservation potential of more evolved compositions (but see Fisher and Schmincke 1984 and Larsen et al. 2003). However, as this study is concerned with the nature of the least evolved magmas derived from the proto-Icelandic plume and not with subsequent fractionation events, this bias is not deemed detrimental.

EPMA was undertaken using a Cameca SX 50® using internally calibrated operating conditions. XRFS analyses were performed for both major- and trace-elements on fused glass discs and pressed powder pellets, respectively. Sodium data were cross-checked by atomic absorption spectrometry. The REE were analysed by inductively-coupled plasma mass spectrometry (ICP-MS).

In presenting these data, the primary aim is to monitor and model the geochemical evolution of the proto-Icelandic plume. Additionally, the data are used to explore possible sources of the tephra within the context of NE Atlantic volcanism.

This report presents a summary of the full data-set and preliminary conclusions. Further data acquisition is on-going, prior to publication of these results and presentation of a detailed model for the entire FSB – NE Atlantic region. Well numbers and depths have been omitted from the tables in this report, prior to obtaining company agreements to disclose these data.

## Major- and trace-element data

Summary major- and trace-element data are depicted in Figs. 2 & 3. Compositional variation in terms of silica content is relatively limited and Mg# has been chosen as a usable fractionation index. The major-element data plot in a relatively tight cluster, indicating basaltic compositions, both tholeiitic and alkaline. Plotting well outside this cluster is the tephra from the Post Balder Formation interval, which is of a more evolved (Mg# ~0.28) and thoroughly alkaline character (*ne* normative). Of the more robust major-elements, $TiO_2$ ranges from 4.72 wt.% in the early alkaline Sullom Formation tephra, down to 0.90 wt.% in the tholeiitic post Balder Formation tephra. $P_2O_5$ follows a similar relationship, with values of 0.73 wt.% and 0.13 wt.%, respectively. The distinctly different composition of the alkaline post Balder Formation tephra is also evident from its trace-element signature, with elevated values of Y (92 ppm), Nb (485 ppm) Zr (1985 ppm), Rb (264 ppm) and a very low Cr content (9 ppm). These data are complemented by an elevated P/Ti ratio (0.34) and similarly high values of Zr/P (0.55) and $TiO_2/FeO^T$ (0.31).

Consideration of the more robust (immobile) major- and trace-elements, Fig. 4 illustrates the stratigraphic variations in P/Ti, La/Y, Zr/Y, Ti/Zr and Zr/P, where some clear and coherent trends, with time, are evident. Correlations between bulk composition and these ratios are evident. The tholeiitic tephras (top Sullom; Vaila 1, Vaila 2, Vaila 3, Kettla, Flett Unit 1, Flett Unit 2, Flett Top, Balder and early Post Balder) have consistent either uniform values of these ratios or, in the case of Ti/Zr, a relatively smooth trend, with the ratio decreasing, up-section. The absolute differences in these parameters can be attributed to original magma compositions and are the product of the melting event. The uniformity of values for each stratigraphic level is compelling evidence that the data set is monitoring magma composition, with time.

Low values of Zr/Nb and high absolute concentrations of Zr and Nb are clear indicators of alkaline basaltic melts, as reported for the base Sullom Formation and post Balder Formation tephras (Table 1; Fig. 4). Similarly, high values of Zr/Y (>15) are indicative of these early- and late-stage magmas, plotting well away from the smooth positive correlation trend between $TiO_2$ and Zr/Y (Fig. 5).

REE analyses comprise data for La, Ce and Yb, with Y as a proxy for the heavy REE. In a plot of $TiO_2$ vs. La/Yb (Fig. 6), the two alkaline suites are easily discriminated by their high La/Yb ratios (i.e. equivalent to steep REE patterns). The remaining tholeiitic suites have similar, but not identical values of La/Yb and show no obvious correlation with $TiO_2$ (cf. Fig. 4). Within the tholeiitic suites, the Sullom Formation and the Kettla Member have the lowest values, implying higher degrees of melting, whereas the Vaila 1, 2 and 3 and Faroes units 1 and 2 suites have values > 3.1, implying smaller amounts of melting.

## Isotopes

One sample from each suite was analysed for Sr and Nd isotopic compositional data. Two samples from three suites were analysed to confirm intra-suite isotopic homogeneity and duplicate analyses of three samples were made to confirm reproducibility of the technique. The data are summarised in Table 2 and Fig. 7. There is a strong negative correlation between the two isotope datasets, as well as positive and negative correlations between Zr/Nb for $Sr_{58Ma}$ and $Nd_{58Ma}$, respectively. The three correlations are not linear, with a marked kink approximately mid-way between the two end members (the early and late alkaline tephras of the Base Sullom Formation and the post Balder Formation sequences). The trends do not impinge of the field(s) that define the isotopic characteristics of present-day basaltic lavas on Iceland.

## Magma compositions with time

The eleven suites which are recognised, from the Early Palaeocene Sullom Formation though to the Early Eocene post Balder Formation strata, provide a continuum of tephra compositional data spanning the period from the impact of the proto-Icelandic plume, through to the stage when ocean floor spreading had been established within the rift zone between the Faroe Islands and East Greenland. In the following section, the compositional characteristics of each suite are summarised and possible correlations with well-characterised volcanic rocks throughout the NE Atlantic region are discussed.

### *Base Sullom Formation alkaline tephra*

The base Sullom Formation tephra are distinctly alkaline and *ne* normative. Within a few of the grains, plagioclase ($An_{55}$) and alkali feldspar ($Or_{93}Ab_{07}$) occur as scattered microphenocrysts. Distinctive trace-element characteristics are readily recognised: low Zr/Nb ~5 and Ti/Zr ~60; high Zr/Y ~17 and Zr/P ~0.15; and a distinctive high value of La/Yb ~30. On a primitive mantle –normalised multi-element plot, the relative enrichment, compared to younger tholeiitic basalt tephra, of the light REE (La and Ce), Nb, Zr and Y are evident, as is the relative enrichment in Ti. These tephra also have a high value of $Sr_{58Ma}$ and a low value of $Nd_{58Ma}$, and are unlike present-day Iceland basalts. Importantly, they contrast with the 'overlying' top Sullom Formation tephra, which are very different in all aspects of composition (see below). Within the trace-element ratio stratigraphic profiles, these tephra differ markedly from the overlying suites and clearly are of a different geochemical affinity. Only in the post-Balder Formation strata is there a return to such relatively extreme compositions.

The base Sullom Formation is of Danian age, within the T10 interval of Ebdon et al. (1995) (Fig. 1). It has a biostratigraphic age within the range of Nannoplankton Zones 1 to 3 (Martini 1971) and an estimated age of 63 – 62 Ma (Chron 28n – 29n). This stratigraphic age places these alkaline tephra as preceding the first phase of volcanic activity identified within the North Sea Basin by Knox and Morton (1988) and Knox (1997), which occurred during Nannoplankton Zones 5 and 6, between 60 and 58 Ma. The earliest volcanic activity within the Hebridean Igneous Province has been dated at ~60.5Ma from both the Mull and Eigg lava fields by Chambers and Pringle (2001). A similar age, 60 to 61 Ma, is recognised for the oldest volcanic units in central west Greenland by Storey et al. (1998). Consequently, volcanic rocks of base Sullom Formation age have not been unequivocally recognised elsewhere within the NE Atlantic.

Some circumstantial evidence has been presented which suggests that late Cretaceous volcanic activity (Ritchie et al. 1999) and sill emplacement (Fitch et al. 1988) may have occurred. However, careful scrutiny of these isotopic data indicates that late Cretaceous events are highly unlikely and that younger ages are more probable, well within the Palaeocene.

### *Sullom Formation tholeiitic basalt tephra*

The Sullom Formation tholeiitic (basalt) tephra contrast in most aspects of composition with the Base Sullom Formation alkaline tephra. With respect to bulk major- and trace-element characteristics, this tholeiitic tephra is relatively depleted in the alkalies, Ti, P, the REE (especially the LREE), Sr, Ba, Y, Zr and Hf. Indeed, of all the tholeiitic tephras (Table 1; Fig. 8), the Sullom Formation material has amongst the lowest Rb, Ba, La and Ce contents. On plots of trace-element data against stratigraphic age (Fig. 4), there are also marked differences, with lower values of Zr/P, Zr/Y, La/Y and P/Ti, and relatively higher values of Ti/Zr and Zr/Nb, in comparison to the early alkaline tephra. These changes in trace-element ratios, up-sequence, are clear indications of larger degrees of melting within the source plume material, relatively diluting the highly incompatible elements, for example Nb and the LREE, by comparison with the more compatible elements, P, Zr and Y. Such marked contrasts are less evident in subsequent tephra types, which are tholeiitic and therefore more akin to the Sullom Formation tholeiitic basalt tephra.

In tandem with their relatively high Zr/Nb value (11.67), this first appearance of tholeiitic tephra has a relatively high value of $Sr_{58Ma}$ (0.70401) and a low value of $Nd_{58Ma}$ (0.51280), more akin to present-day Iceland basalts than the subjacent alkaline tephra.

### *Vaila Formation tephras*

These three discrete basaltic tephra units, from: close to the base of the formation ($V_1$); the middle part of the formation ($V_2$): and, the very top of the formation ($V_3$); are in many respects similar, especially in terms of their major-element compositions, being distinctly tholeiitic and with moderately high Ti contents. Values of Zr/Y, Zr/P, P/Ti and La/Y are all relatively constant between the three tephras. Futhermore, they have elevated values of Zr/Nb, ranging from 11 to 13.33, coupled with a trend of decreasing Ti/Zr with decreasing stratigraphic age (Fig. 4). There is also a straightforward correlation with respect to initial Sr and Nd values (Fig. 7) where, as Zr/Nb increases, there is a decrease in the initial Sr value and an increase in the initial Nd value. The higher value of Zr/Nb, relative to that of the subjacent Sullom Formation tholeiitic tephra, implies a greater degree of melting, which is in agreement with the trend of decreasing Ti/Zr for the three tephras, $V_1$, $V_2$ and $V_3$.

Morton et al. (1988) identified a single ash layer from an offshore British Geological Survey (BGS) borehole (82/12), west of the Shetland Islands (Fig. X). Morton et al. (1988) discussed in detail the likely age of the 'tuff' and concluded that an early Selandian age is most likely. Thus, this unit is of comparable age to the $V_1$ tephra described in this study. The relatively few geochemical data presented by Morton et al. (1988), characterising the borehole 82/12 tuff as having a high Ti content and of tholeiitic character fits with this interpretation, but by no means proves a robust correlation.

*The Kettla Member tephra*

The Kettla Member has long been recognised as being of volcanic origin, or of volcanic derivation. Certain facies appear to comprise volcaniclastic strata, whereas elsewhere there are materials which are more akin to primary tephra deposits, or at least are little modified by the sedimentary environment (Knox et al. 1997). Samples were assessed in terms of their textures for evidence of significant sedimentary reworking, for example, rounding of grains, significant mechanical breakage of grains and alteration through hydration. Only materials that are devoid of these characteristics were analysed. Due to the significance of this long-recognised unit, which also forms a significant seismic marker throughout the FSB, it will be initially treated in isolation.

The Kettla Member tephra is tholeiitic basalt in composition, with a high Ti content and an overall enriched trace-element pattern (Fig. 8), similar in many respects to the subjacent $V_3$ tephra. However, it differs in that it continues the downward trend (with decreasing stratigraphic age) of Ti/Zr (which continues downwards with the overlying two tephra units). However, it differs in that it has a relatively low Zr/Nb value (10.57). Values of $Sr_{58Ma}$ and $Nd_{58Ma}$ fall nearly mid-way between the two end-points of the relatively smooth trend depicted in Fig. 7.

The Kettla Member falls within Nannoplankton Zone 6 and is equivalent to the Balmoral Tuffite/Andrew Tuff of the Glamis Member of the North Sea Basin. Knox and Morton's (1988) Phase 1 within the North Sea Basin comprises graded tephra layers, each a few centimetres thick. Jolley and Morton (1992) correlate a sequence of tuffaceous sandstones with a tholeiitic MORB-like composition within a cored BGS borehole (82/15) in the Inner Moray Firth Basin of the North Sea to the same volcanic event(s).

Disseminated grains of tephra within the Thanet Formation of Kent, SE England, appear to be of comparable age (Knox 1979; Knox and Morton 1988). In Denmark, bentonitic ash layers have been described by Heilmann-Clausen et al. (1985) from the Holmehus Formation.

This Phase 1 event also has a time correlation with the voluminous lavas sequences of the Hebridean Igneous Province, where the Skye and Mull lava fields were erupted and the various sub-volcanic intrusive centres, Rum, Skye, Mull, Ardnamurchan were emplaced during the interval 60.5 to 58.5 Ma (Chambers and

Pringle 2001; Bell and Williamson 2002). Jolley and Morton (1992) suggested, on the basis of similarities in geochemistry, that the borehole 82/15 tholeiitic tuffaceous sandstones were derived from airfall ashes equivalent (possibly even co-magmatic) to the Preshal More lavas of the Skye Lava Field, and which Bell and Williamson (1994) concluded were erupted from a Cuillin volcano which developed slightly later than the bulk of the Skye Lava Field.

### *Flett Formation tephra units 1 & 2*

These two tephra units occur within the Thanetian Flett Formation, equivalent to the Sele Formation of the North Sea Basin (Nannoplankton Zone 9) and the negative ash series in Denmark (Larsen et al. 2003). Regional stratigraphic relationships indicate chronostratigraphic equivalence with the Faroes Lower and Middle formations. In terms of their major-element compositions, both tephra units are of tholeiitic basalt composition with high Ti and P contents, ~3.3 wt.% $TiO_2$ and ~0.3 wt.% $P_2O_5$, respectively. They have similar Zr/Nb and La/Yb ratios, ~8.65 and ~3.2, respectively, but different Ti/Zr and P/Ti ratios (see Table 1), suggesting a common mantle parentage, but differing due to the effects of zircon, apatite and Fe-Ti oxide fractionation. Values of $Sr_{58Ma}$ and $Nd_{58Ma}$ that correlate with Zr/Nb suggest that fractionation may have been concurrent with contamination by crustal material, the so-called AFC process. Representative primitive mantle –normalised multi-element plots for typical Lower and Middle formation lavas are depicted in Fig. 8, together with typical tholeiitic basalt tephras from the Danish negative ash series, along with both sets of Flett Formation tephra data. Comparison of bulk-sample characteristics indicate temporal and compositional equivalence between: (i) the Flett Formation Unit 1 tephra, the Faroes Lower Formation and the East Greenland Nansen Fjord Formation; and, (ii) the Flett Formation Unit 2 tephra, the Faroes Middle Formation and the East Greenland Milne Land Formation (Waagstein 1988; Larsen et al. 1999). Furthermore, certain of the Danish negative ashes, which are of the same age, offer good compositional matches to both units 1 and 2 tephra and a genetic link appears justifiable (Larsen et al. 2003).

### *Balder Formation tephra*

Balder Formation tephra appear to have a very consistent composition, typified by low Ti and P contents ($TiO_2$: 1.1 wt.%; $P_2O_5$: 0.14 wt.%), a Zr/Nb ratio of 12-13, a low Zr/Y value (~1.7), and low concentrations of the LREE (La/Yb ~3.25).

Likely time (Nannoplankton Zone 10) and compositional equivalents are the North Sea Basin Phase 2b (Knox and Morton 1988), certain layers within the positive ash series of Denmark (Larsen et al. 12003), and MORB-like flows within the Upper Formation of the Faroe Islands (Waagstein 1988; Larsen et al. 1999).

### *Post Balder Formation tholeiitic tephra*

Within the post Balder Formation strata of the Stronsay Group, tholeiitic basalt tephra occur low in the sequence, typically within sandy units. These tephra are typically aphyric, although rare pseudomorphs of serpentine after olivine occur in a few shards. They have a similar major-element composition to that of the Balder tephra, but a different trace-element signature: Zr/Nb ~15; Ti/Zr ~120; and, Zr/Y ~2.8 (Table 1). On the $TiO_2$ vs. Zr/Nb plot (Fig. 5) these tephra plot as an 'end-member' of the relatively straight-line variation identified for the complete suite of tephra compositions. Similarly, they define one end-member on the Zr/Nb vs. $Nd_{58Ma}$, Zr/Nb vs. $Sr_{58Ma}$ and $Sr_{58Ma}$ vs. $Nd_{58Ma}$ plots, having a signature, in terms of isotopic composition, similar to that of present-day Icelandic basalt lavas.

### *Post Balder Formation alkaline tephra*

The alkaline post Balder Formation tephra is *ne* normative and is only matched in terms of composition by the tephra identified from the base of the Sullom Formation (see above). Plagioclase ($An_{40}$) and alkali feldspar ($Or_{95}Ab_{05}$) occur as uncommon scattered microphenocrysts. Distinctive trace-element characteristics are: low Zr/Nb ~4 and Ti/Zr ~5; high Zr/Y ~22 and Zr/P ~0.55; and a distinctive high value of La/Yb ~39. On a primitive mantle –normalised multi-element plot, the relative enrichment, compared to older tholeiitic basalt tephra, of the light REE (La and Ce), Nb, Zr and Y are evident, as is the relative depletion in Ti. These tephra also have a high value of $Sr_{58Ma}$ and a low value of $Nd_{58Ma}$, distinctly different from present-day Iceland basalts.

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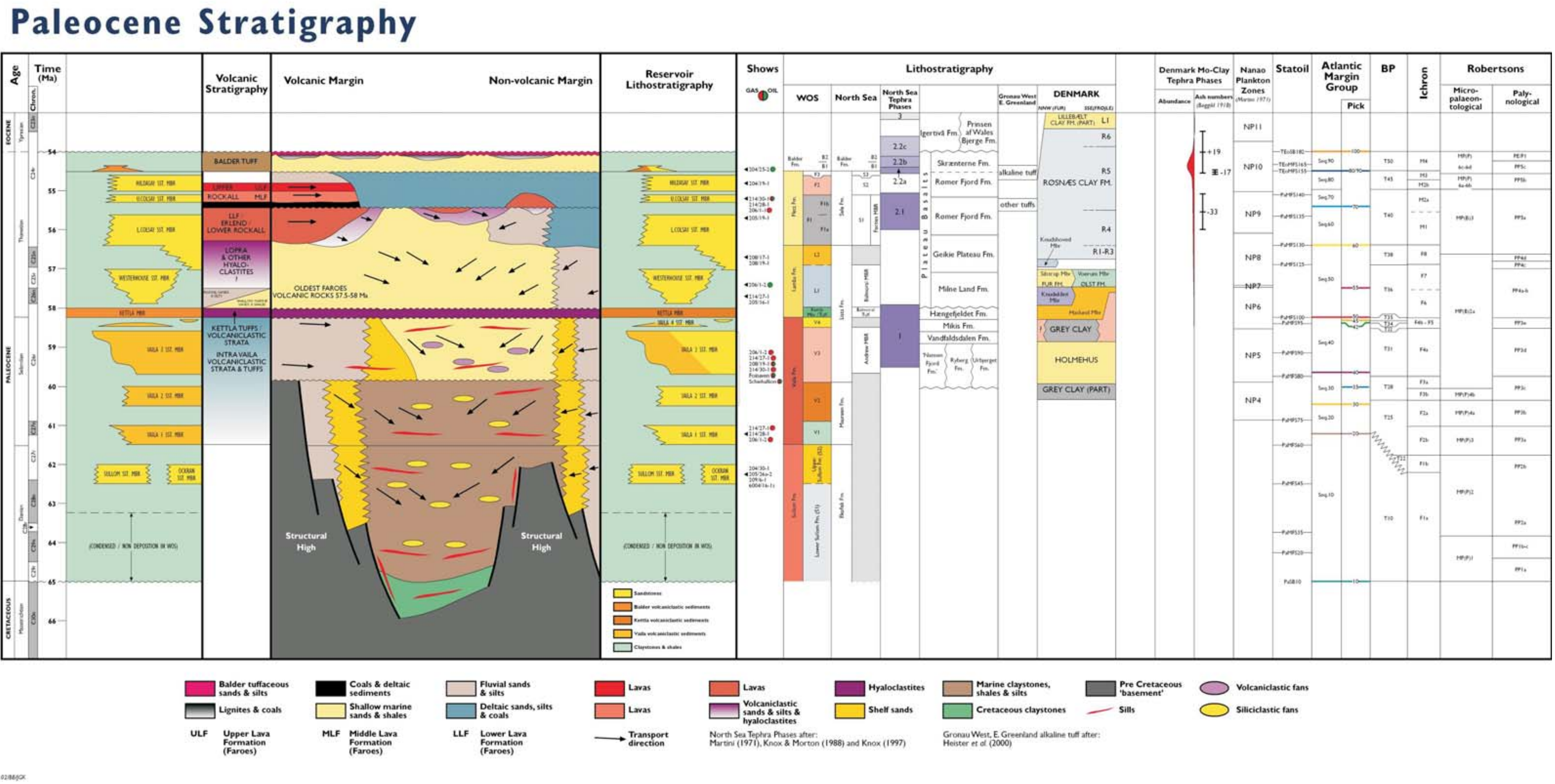
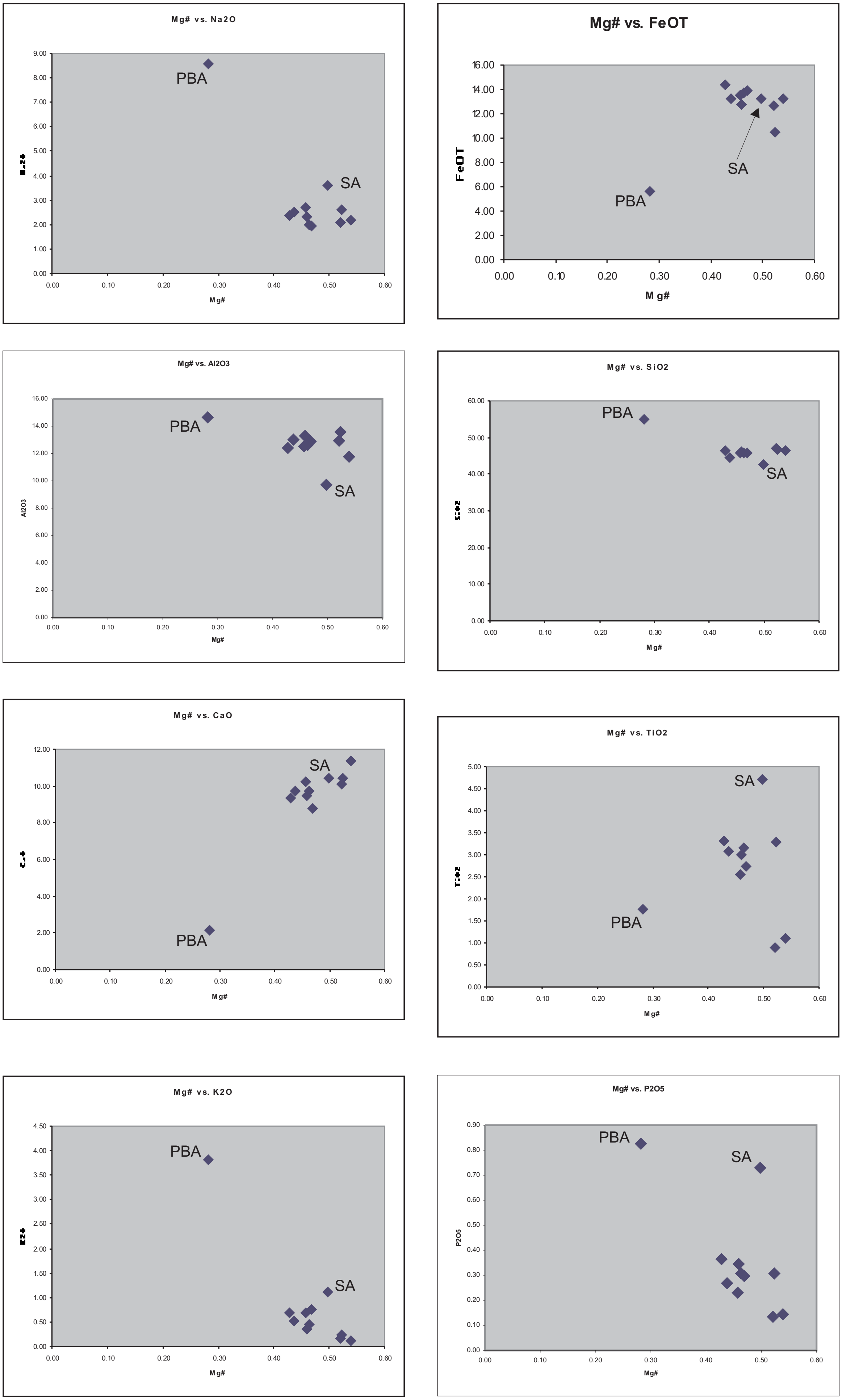
Figure 1


Paleocene Stratigraphy
Age
Time (Ma)
Chron.
EOCENE
PALEOCENE
CRETACEOUS
Volcanic Stratigraphy
Volcanic Margin
Non-volcanic Margin
Reservoir Lithostratigraphy
Shows
GAS OIL
Lithostratigraphy
WOS
North Sea
North Sea Tephra Phases
Gronau West E. Greenland
DENMARK
Denmark Mo-Clay Tephra Phases
Abundance
Ash numbers (Bøggild 1918)
Nanao Plankton Zones (Martini 1971)
Statoil
Atlantic Margin Group
Pick
BP
Ichron
Robertsons
Micro-palaeon-tological
Paly-nological
BALDER TUFF
UPPER ULF
ROCKALL MLF
LLF ERLEND / LOWER ROCKALL
LOPRA & OTHER HYALO-CLASTITES
KETTLA TUFFS / VOLCANICLASTIC STRATA
INTRA VAILA VOLCANICLASTIC STRATA & TUFFS
OLDEST FAROES VOLCANIC ROCKS 57.5-58 Ma
Structural High
Structural High
HILDASAY SST. MBR
U.COLSAY SST. MBR
L.COLSAY SST. MBR
WESTERHOUSE SST. MBR
KETTLA MBR
VAILA 4 SST. MBR
VAILA 3 SST. MBR
VAILA 2 SST. MBR
VAILA 1 SST. MBR
SULLOM SST. MBR
OCKRAN SST. MBR
(CONDENSED / NON DEPOSITION IN WOS)
Sandstones
Balder volcaniclastic sediments
Kettla volcaniclastic sediments
Vaila volcaniclastic sediments
Claystones & shales
Plateau Basalts
Igertivâ Fm.
Prinsen af Wales Bjerge Fm.
Skrænterne Fm.
Rømer Fjord Fm.
Rømer Fjord Fm.
Geikie Plateau Fm.
Milne Land Fm.
Hængefjeldet Fm.
Mikis Fm.
Vandfaldsdalen Fm.
Nansen Fjord Fm.
Ryberg Fm.
Urbjerget Fm.
alkaline tuff
other tuffs
LILLEBÆLT CLAY FM. (PART)
RØSNÆS CLAY FM.
GREY CLAY
HOLMEHUS
GREY CLAY (PART)
2.2c
2.2b
2.2a
2.1
1
NP11
NP10
NP9
NP8
NP7
NP6
NP5
NP4
Balder tuffaceous sands & silts
Lignites & coals
Coals & deltaic sediments
Shallow marine sands & shales
Fluvial sands & silts
Deltaic sands, silts & coals
Lavas
Lavas
Lavas
Volcaniclastic sands & silts & hyaloclastites
Hyaloclastites
Shelf sands
Marine claystones, shales & silts
Cretaceous claystones
Pre Cretaceous 'basement'
Sills
Volcaniclastic fans
Siliciclastic fans
ULF Upper Lava Formation (Faroes)
MLF Middle Lava Formation (Faroes)
LLF Lower Lava Formation (Faroes)
Transport direction
North Sea Tephra Phases after: Martini (1971), Knox & Morton (1988) and Knox (1997)
Gronau West, E. Greenland alkaline tuff after: Heister et al. (2000)
4054/9.02/BB/JGK

SA = Sullom (Formation) Alkaline Tuff/tephra
PBA = Post Balder (Formation) Alkaline Tuff/tephra

Figure 2



# Figure 3

SA = Sullom (Formation) Alkaline Tuff/tephra
PBA = Post Balder (Formation) Alkaline Tuff/tephra

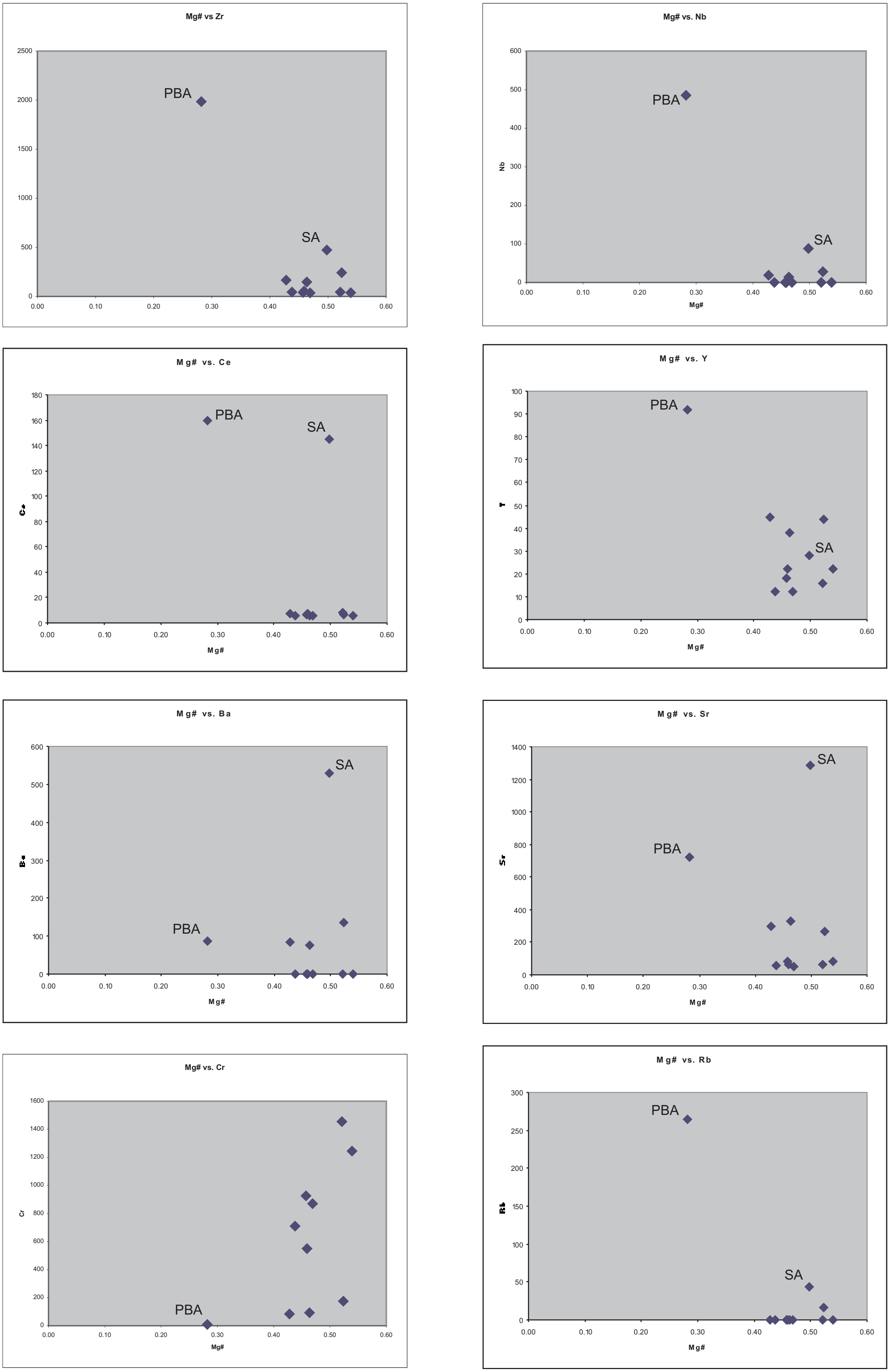


Figure 4

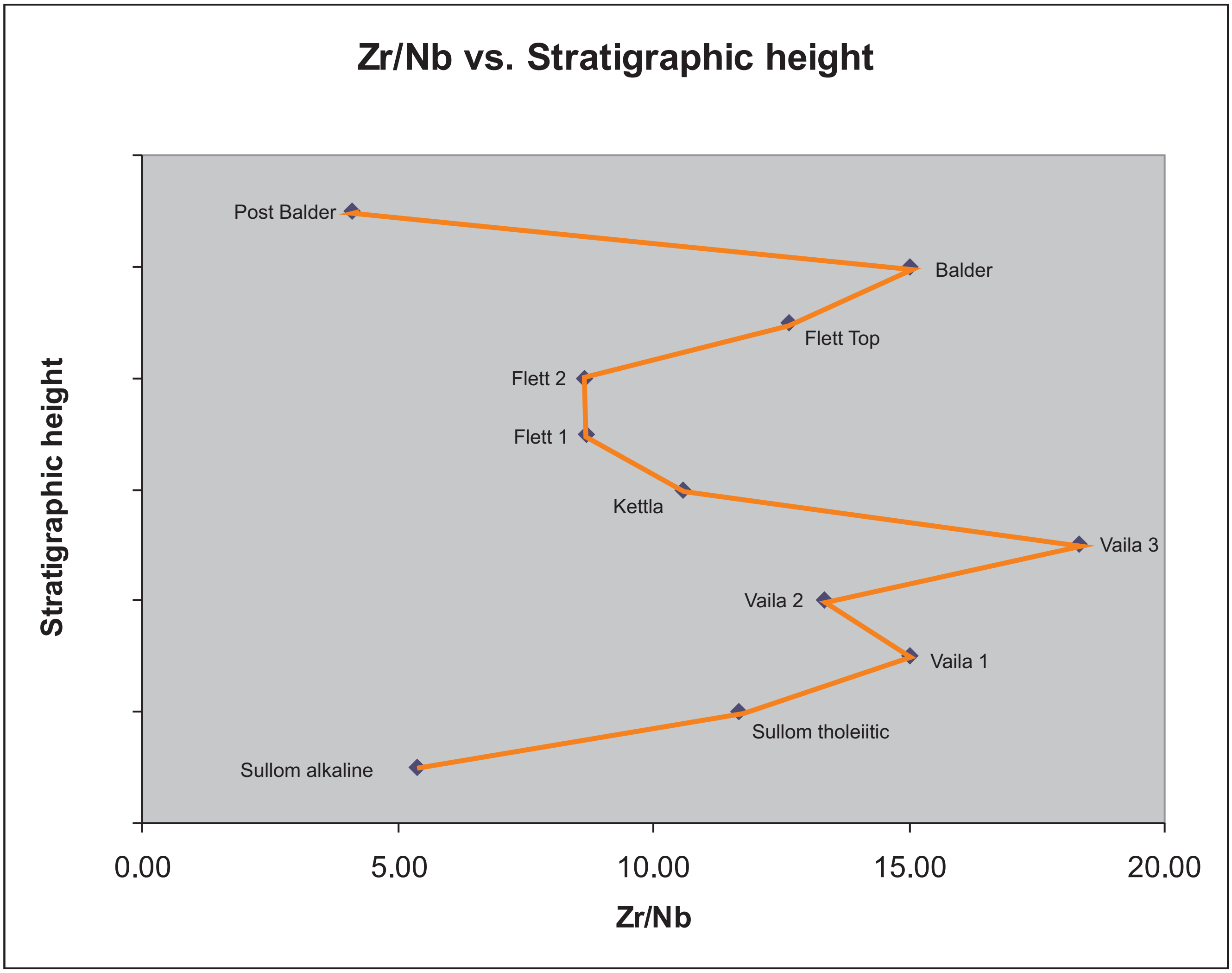
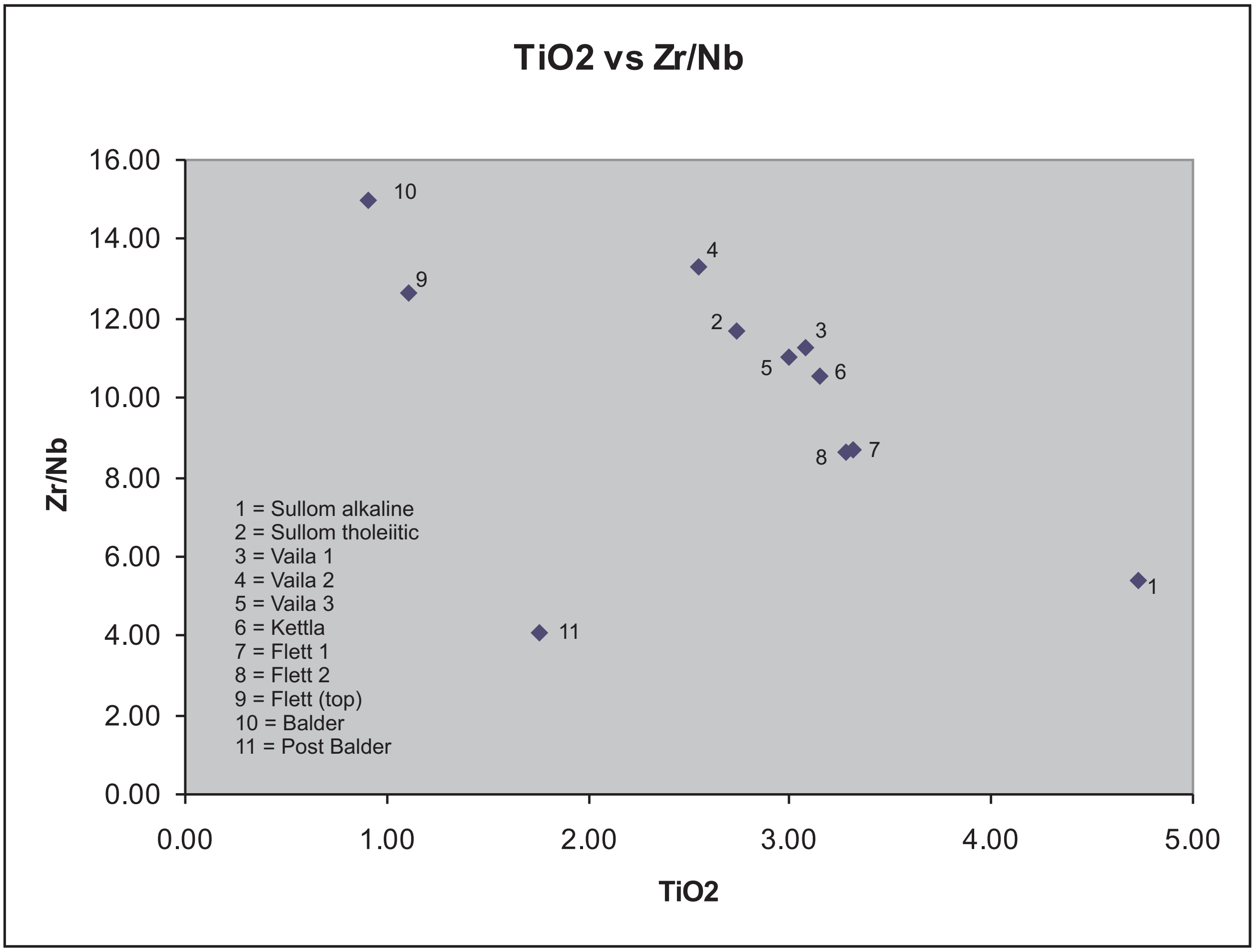
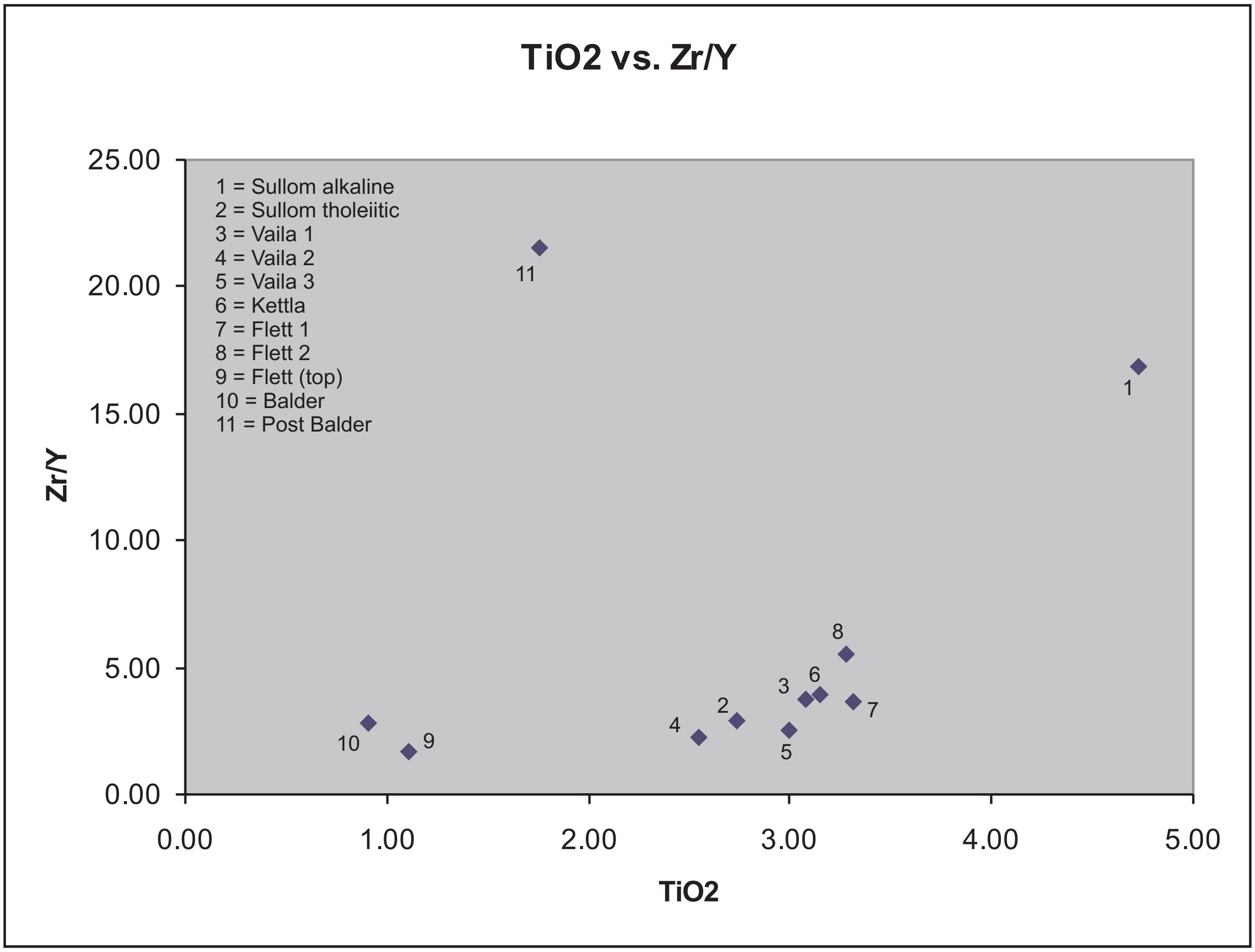
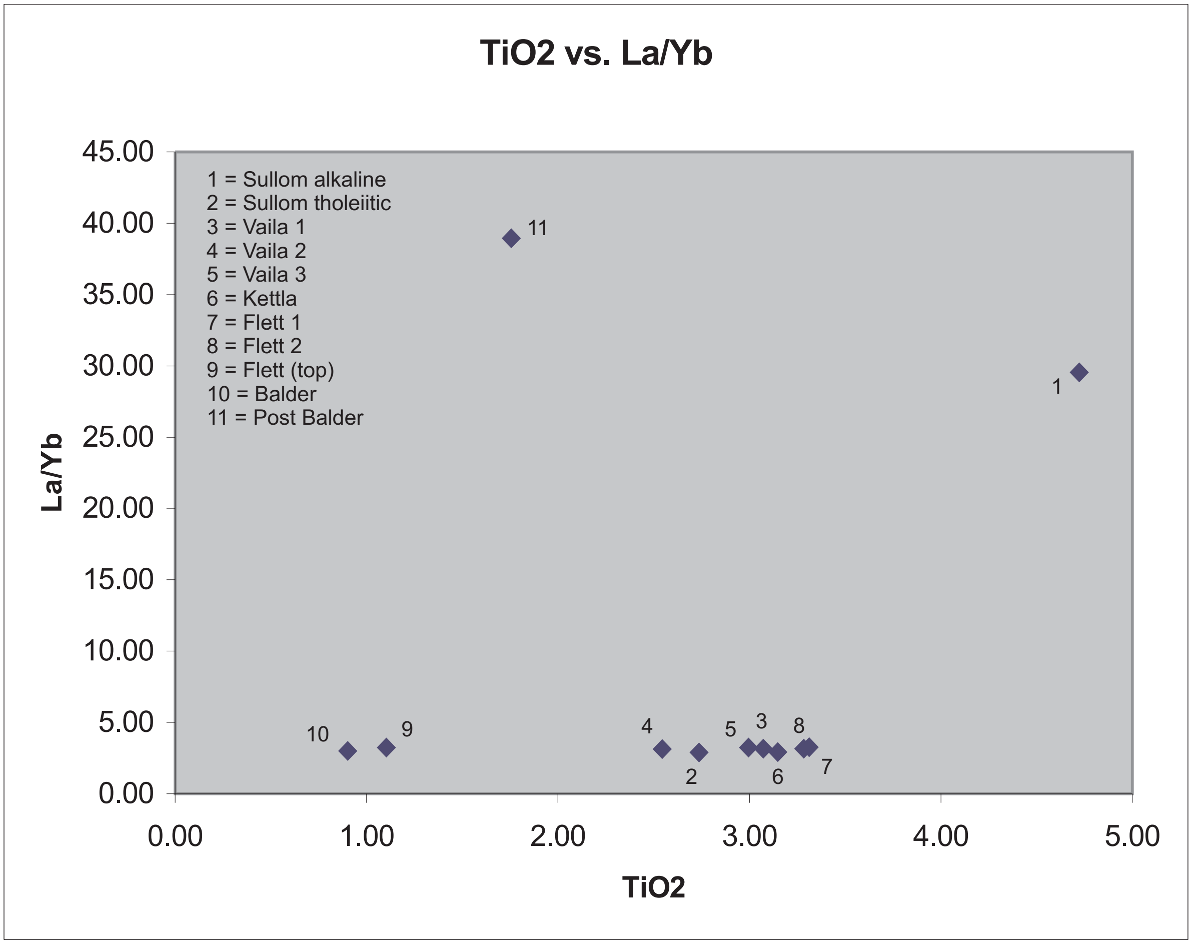

Zr/Nb vs. Stratigraphic height
Stratigraphic height
Post Balder
Balder
Flett Top
Flett 2
Flett 1
Kettla
Vaila 3
Vaila 2
Vaila 1
Sullom tholeiitic
Sullom alkaline
0.00
5.00
10.00
15.00
20.00
Zr/Nb

Figure 5

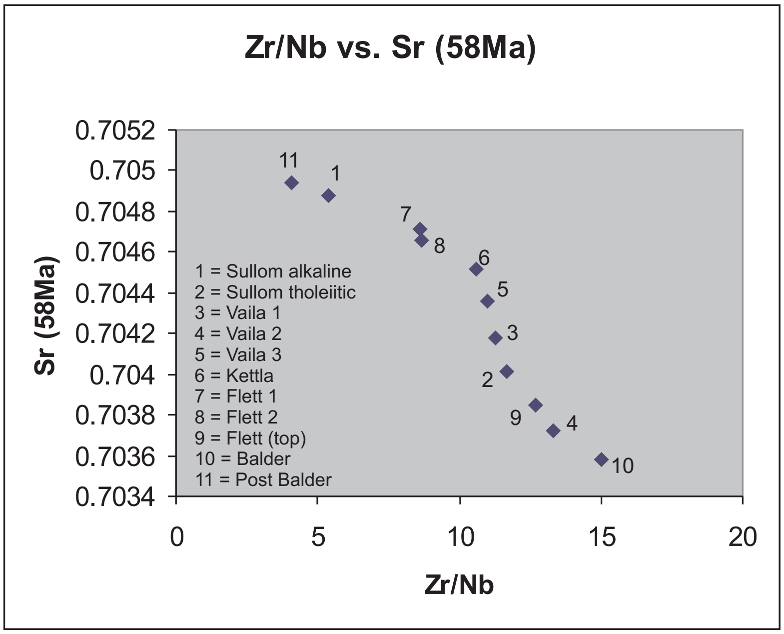

TiO2 vs Zr/Nb
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Zr/Nb
0.00
1.00
2.00
3.00
4.00
5.00
TiO2
10
9
4
2
3
5
6
8
7
1
11
1 = Sullom alkaline
2 = Sullom tholeiitic
3 = Vaila 1
4 = Vaila 2
5 = Vaila 3
6 = Kettla
7 = Flett 1
8 = Flett 2
9 = Flett (top)
10 = Balder
11 = Post Balder

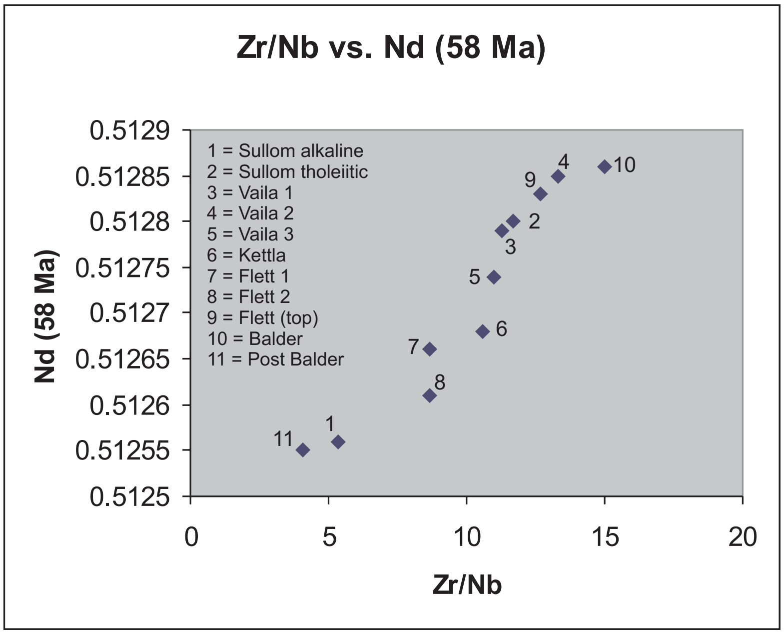

TiO2 vs. Zr/Y
25.00
20.00
15.00
10.00
5.00
0.00
Zr/Y
0.00
1.00
2.00
3.00
4.00
5.00
TiO2
1 = Sullom alkaline
2 = Sullom tholeiitic
3 = Vaila 1
4 = Vaila 2
5 = Vaila 3
6 = Kettla
7 = Flett 1
8 = Flett 2
9 = Flett (top)
10 = Balder
11 = Post Balder
11
1
8
3
6
2
7
4
5
10
9

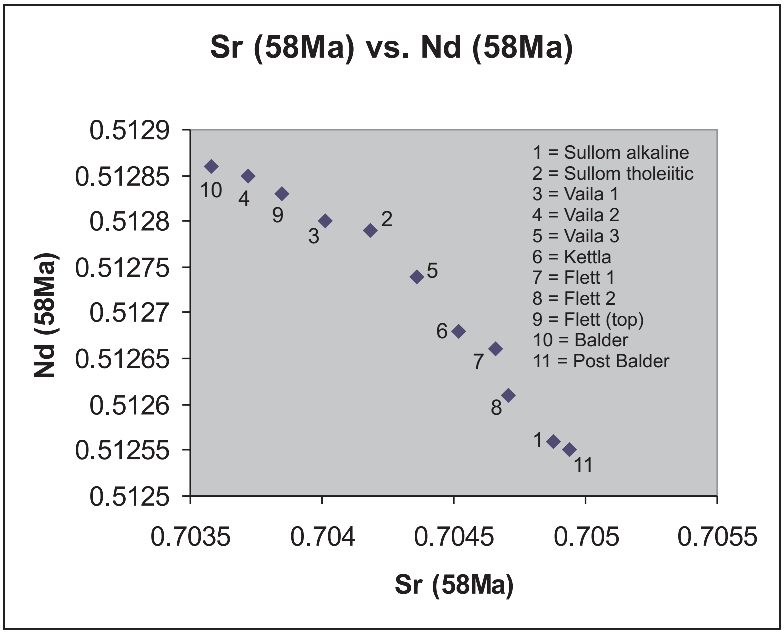
# Figure 6


TiO2 vs. La/Yb
La/Yb
TiO2
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0.00
1.00
2.00
3.00
4.00
5.00
1 = Sullom alkaline
2 = Sullom tholeiitic
3 = Vaila 1
4 = Vaila 2
5 = Vaila 3
6 = Kettla
7 = Flett 1
8 = Flett 2
9 = Flett (top)
10 = Balder
11 = Post Balder
11
1
10
9
4
2
5
3
6
8
7

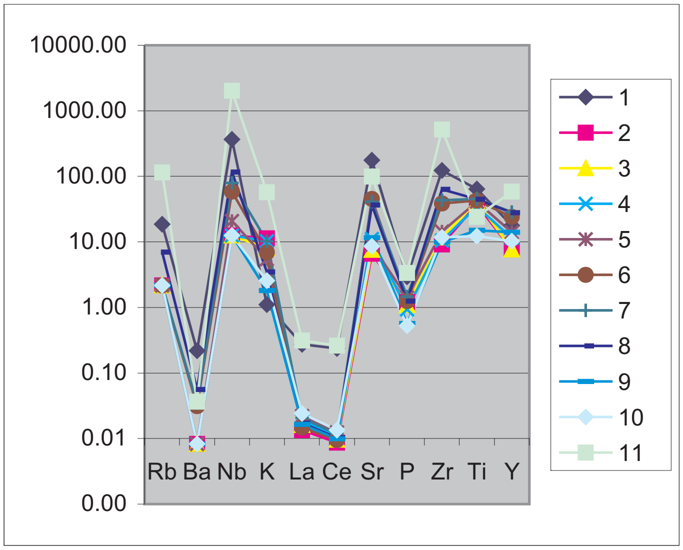
# Figure 7

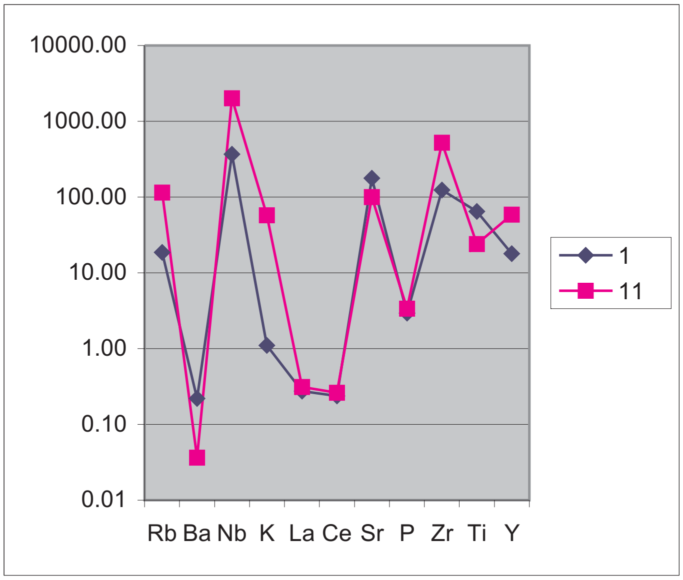

Zr/Nb vs. Sr (58Ma)
Sr (58Ma)
0.7052
0.705
0.7048
0.7046
0.7044
0.7042
0.704
0.7038
0.7036
0.7034
0
5
10
15
20
Zr/Nb
1 = Sullom alkaline
2 = Sullom tholeiitic
3 = Vaila 1
4 = Vaila 2
5 = Vaila 3
6 = Kettla
7 = Flett 1
8 = Flett 2
9 = Flett (top)
10 = Balder
11 = Post Balder
11
1
7
8
6
5
3
2
9
4
10


Zr/Nb vs. Nd (58 Ma)
Nd (58 Ma)
0.5129
0.51285
0.5128
0.51275
0.5127
0.51265
0.5126
0.51255
0.5125
0
5
10
15
20
Zr/Nb
1 = Sullom alkaline
2 = Sullom tholeiitic
3 = Vaila 1
4 = Vaila 2
5 = Vaila 3
6 = Kettla
7 = Flett 1
8 = Flett 2
9 = Flett (top)
10 = Balder
11 = Post Balder
4
10
9
2
3
5
6
7
8
1
11

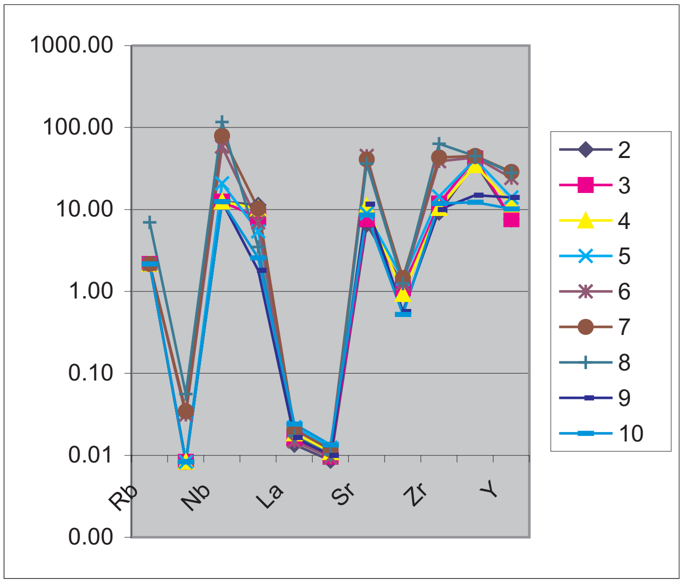

Sr (58Ma) vs. Nd (58Ma)
Nd (58Ma)
0.5129
0.51285
0.5128
0.51275
0.5127
0.51265
0.5126
0.51255
0.5125
0.7035
0.704
0.7045
0.705
0.7055
Sr (58Ma)
1 = Sullom alkaline
2 = Sullom tholeiitic
3 = Vaila 1
4 = Vaila 2
5 = Vaila 3
6 = Kettla
7 = Flett 1
8 = Flett 2
9 = Flett (top)
10 = Balder
11 = Post Balder
10
4
9
3
2
5
6
7
8
1
11

# Figure 8





1 = Sullom alkaline
2 = Sullom tholeiitic
3 = Vaila 1
4 = Vaila 2
5 = Vaila 3
6 = Kettla
7 = Flett 1
8 = Flett 2
9 = Flett (top)
10 = Balder
11 = Post Balder



## Table 1: Summary of Tephra Compositional data

| | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Well** | | | | | | | | | | | | |
| **Depth** | | | | | | | | | | | | |
| **Sample reference** | S1: Alkaline | *No equivalent* | S2: Tholeiitic | *No equivalent* | V1: Tholeiitic | *BGS 82/12* | V2: Ttholeiitic | *No equivalent* | V3: Tholeiitic | *No equivalent* | Kettla | *BGS 82/15* |
| **Number of analyses** | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| **Normalised Data** | | | | | | | | | | | | |
| **$SiO_2$** | 42.58 | | 45.78 | | 44.59 | 48.11 | 45.91 | | 46.23 | | 45.89 | 49.68 |
| **$TiO_2$** | 4.72 | | 2.74 | | 3.07 | 2.95 | 2.54 | | 3.00 | | 3.15 | 1.12 |
| **$Al_2O_3$** | 9.72 | | 12.87 | | 13.02 | 13.12 | 12.53 | | 13.30 | | 12.62 | 13.28 |
| **$Fe_2O_3$** | 0.00 | | 0.00 | | 0.00 | | 0.00 | | 0.00 | | 0.00 | 0.00 |
| **FeO** | 0.00 | | 0.00 | | 0.00 | | 0.00 | | 0.00 | | 0.00 | 0.00 |
| **MnO** | 0.14 | | 0.22 | | 0.18 | 0.14 | 0.21 | | 0.17 | | 0.16 | 0.12 |
| **MgO** | 6.51 | | 6.06 | | 5.09 | 7.28 | 5.63 | | 5.34 | | 5.86 | 10.36 |
| **CaO** | 10.42 | | 8.77 | | 9.72 | 12.02 | 10.24 | | 9.48 | | 9.74 | 1.33 |
| **$Na_2O$** | 3.59 | | 1.94 | | 2.51 | 2.58 | 2.72 | | 2.31 | | 1.98 | 3.07 |
| **$K_2O$** | 1.10 | | 0.75 | | 0.53 | 0.46 | 0.68 | | 0.36 | | 0.46 | 0.75 |
| **$P_2O_5$** | 0.73 | | 0.30 | | 0.27 | 0.02 | 0.23 | | 0.35 | | 0.31 | 0.10 |
| **LOI** | 6.25 | | 6.25 | | 5.84 | | 5.48 | | 6.20 | | 5.56 | 6.26 |
| **Total** | 99.02 | | 99.54 | | 98.02 | 97.74 | 99.68 | | 99.46 | | 99.44 | 99.81 |
| | | | | | | | | | | | | |
| **$FeO^T$** | 13.27 | | 13.86 | | 13.21 | | 13.51 | | 12.72 | | 13.71 | 13.74 |
| **Mg #** | 0.50 | | 0.47 | | 0.44 | | 0.46 | | 0.46 | | 0.46 | 0.60 |
| **$TiO_2/FeO^T$** | 0.36 | | 0.20 | | 0.23 | | 0.19 | | 0.24 | | 0.23 | 0.08 |
| **TA ($Na_2O$ + $K_2O$)** | 4.69 | | 2.69 | | 3.03 | | 3.40 | | 2.68 | | 2.44 | 3.82 |
| | | | | | | | | | | | | |
| **CIPW Norm** | | | | | | | | | | | | |
| **qz** | | | | | | | | | | | | |
| **or** | | | | | | | | | | | | |
| **ab** | | | | | | | | | | | | |
| **an** | | | | | | | | | | | | |
| **ne** | | | | | | | | | | | | |
| **di** | | | | | | | | | | | | |
| **hy** | | | | | | | | | | | | |
| **ol** | | | | | | | | | | | | |
| **mt** | | | | | | | | | | | | |
| **il** | | | | | | | | | | | | |
| **ap** | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| **V** | 49 | | 195 | | 210 | | 362 | | 370 | | 345 | 244 |
| **Cr** | <5 | | 870 | | 710 | | 925 | | 550 | | 92 | 350 |
| **Ni** | <5 | | 545 | | 650 | | 485 | | 390 | | 48 | 99 |
| **Sr** | 1285 | | 48 | | 55 | | 80 | | 65 | | 328 | 121 |
| **Rb** | 43 | | <5 | | <5 | | <5 | | <5 | | <5 | 8 |
| **Ba** | 530 | | <5 | | <5 | | <5 | | <5 | | 75 | 119 |
| **Zr** | 472 | | 35 | | 45 | | 40 | | 55 | | 148 | 72 |
| **Nb** | 88 | | 3 | | 4 | | 3 | | 5 | | 14 | 2 |
| **Y** | 28 | | 12 | | 12 | | 18 | | 22 | | 38 | 20 |
| **Hf** | 12 | | 1.2 | | 1.4 | | 1.9 | | 2.4 | | 1.6 | 1.92 |
| **La** | 65 | | 3.2 | | 3.8 | | 4.4 | | 5.2 | | 3.5 | 3.66 |
| **Ce** | 145 | | 5.3 | | 5.9 | | 6.7 | | 7.6 | | 5.8 | 4.56 |
| **Yb** | 2.2 | | 1.1 | | 1.2 | | 1.4 | | 1.6 | | 1.2 | 1.39 |
| | | | | | | | | | | | | |
| **Ti/Zr** | 60.04 | | 469.03 | | 409.60 | | 381.60 | | 326.75 | | ##### | 93.33 |
| **Zr/Y** | 16.86 | | 2.92 | | 3.75 | | 2.22 | | 2.50 | | 3.89 | 3.60 |
| **Zr/P** | 0.15 | | 0.03 | | 0.04 | | 0.04 | | 0.04 | | 0.11 | 0.16 |
| **P/Ti** | 0.11 | | 0.08 | | 0.06 | | 0.07 | | 0.08 | | 0.07 | 0.06 |
| **La/Y** | 2.32 | | 0.27 | | 0.32 | | 0.24 | | 0.24 | | 0.09 | 0.18 |
| **Zr/Nb** | 5.36 | | 11.67 | | 11.25 | | 13.33 | | 11.00 | | 10.57 | 36.00 |
| **La/Yb** | 29.55 | | 2.91 | | 3.17 | | 3.14 | | 3.25 | | 2.92 | 2.63 |

| | 7 | | 8 | | 9 | | 10 | | 11 | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Well** | | | | | | | | | | |
| **Depth** | | | | | | | | | | |
| **Sample reference** | F1: Tholeiitic (Lower; 2a) | *Faroes Lower II,23 (-460m)* | F2: Tholeiitic (Middle;2a; -ve) | *Faroes Middle 15578 (+1384m)* | Balder: Tholeiitic (Upper;2b;/+ve) | NS 16/7a-2 *44 | Post Balder: Tholeiitic (2c) | *No equivalent* | Post Balder: Alkaline (2c;GAT) | *No equivalent* |
| **Number of analyses** | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| **Normalised Data** | | | | | | | | | | |
| **$SiO_2$** | 46.42 | 48.43 | 46.79 | 48.54 | 46.32 | 48.54 | 47.17 | | 54.96 | |
| **$TiO_2$** | 3.31 | 3.54 | 3.28 | 3.63 | 1.10 | 3.78 | 0.90 | | 1.76 | |
| **$Al_2O_3$** | 12.40 | 12.54 | 13.58 | 12.82 | 11.77 | 12.12 | 12.93 | | 14.64 | |
| **$Fe_2O_3$** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | | 0.00 | |
| **FeO** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | | 0.00 | |
| **MnO** | 0.20 | 0.22 | 0.17 | 0.19 | 0.13 | 0.34 | 0.17 | | 0.23 | |
| **MgO** | 5.31 | 5.51 | 5.71 | 5.65 | 7.64 | 5.32 | 6.84 | | 1.09 | |
| **CaO** | 9.33 | 9.98 | 10.41 | 9.34 | 11.37 | 9.30 | 10.12 | | 2.15 | |
| **$Na_2O$** | 2.38 | 2.50 | 2.62 | 2.30 | 2.19 | 2.34 | 2.07 | | 8.56 | |
| **$K_2O$** | 0.68 | 0.64 | 0.23 | 0.38 | 0.12 | 0.83 | 0.17 | | 3.81 | |
| **$P_2O_5$** | 0.36 | 0.41 | 0.31 | 0.34 | 0.14 | 0.50 | 0.13 | | 0.83 | |
| **LOI** | 5.12 | 0.89 | 5.85 | 2.28 | 5.95 | | 5.75 | | 6.26 | |
| **Total** | 99.87 | 100.36 | 99.47 | 99.75 | 99.94 | 98.04 | 98.98 | | 99.93 | |
| | | | | | | | | | | |
| **$FeO^T$** | 14.35 | 15.15 | 10.51 | 13.62 | 13.21 | 15.96 | 12.71 | | 5.64 | |
| **Mg #** | 0.43 | 42.38 | 0.52 | 0.46 | 0.54 | 0.40 | 0.52 | | 0.28 | |
| **$TiO_2/FeO^T$** | 0.23 | 0.23 | 0.31 | 0.27 | 0.08 | 0.24 | 0.07 | | 0.31 | |
| **TA ($Na_2O$ + $K_2O$)** | 3.06 | 3.14 | 2.85 | 2.68 | 2.30 | 3.17 | 2.25 | | 12.37 | |
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| **CIPW Norm** | | | | | | | | | | |
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| **V** | 410 | 434 | 395 | | 272 | | 243 | | 72 | |
| **Cr** | 84 | 63 | 175 | | 1245 | | 1455 | | 9 | |
| **Ni** | 58 | 52 | 132 | | 420 | | 960 | | 6 | |
| **Sr** | 295 | 303 | 264 | | 84 | | 62 | | 723 | |
| **Rb** | <5 | | 16 | | <5 | | <5 | | 264 | |
| **Ba** | 83 | | 135 | | <5 | | <5 | | 88 | |
| **Zr** | 165 | | 242 | | 38 | | 45 | | 1985 | |
| **Nb** | 19 | | 28 | | 3 | | 3 | | 485 | |
| **Y** | 45 | | 44 | | 22 | | 16 | | 92 | |
| **Hf** | 2.5 | | 1.9 | | 1.7 | | 2.8 | | 10 | |
| **La** | 4.9 | | 4.1 | | 3.9 | | 5.7 | | 74 | |
| **Ce** | 7.2 | | 6.3 | | 6.1 | | 8.2 | | 160 | |
| **Yb** | 1.5 | | 1.3 | | 1.2 | | 1.9 | | 1.9 | |
| | | | | | | | | | | |
| **Ti/Zr** | 120.44 | | 81.40 | | 174.32 | | 120.32 | | 5.31 | |
| **Zr/Y** | 3.67 | | 5.50 | | 1.73 | | 2.81 | | 21.58 | |
| **Zr/P** | 0.10 | | 0.18 | | 0.06 | | 0.08 | | 0.55 | |
| **P/Ti** | 0.08 | | 0.07 | | 0.09 | | 0.11 | | 0.34 | |
| **La/Y** | 0.11 | | 0.09 | | 0.18 | | 0.36 | | 0.80 | |
| **Zr/Nb** | 8.68 | | 8.64 | | 12.67 | | 15.00 | | 4.09 | |
| **La/Yb** | 3.27 | | 3.15 | | 3.25 | | 3.00 | | 38.95 | |

**Table 2: Sr & Nd isotope data and Zr/Nb values**

| Suite | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Zr/Nb** | 5.36 | 11.67 | 11.25 | 13.33 | 11 | 10.57 | 8.68 | 8.64 | 12.67 | 15 | 4.09 |
| **Sr(58)** | 0.70488 | 0.70401 | 0.70418 | 0.70372 | 0.70436 | 0.70452 | 0.70466 | 0.70471 | 0.70385 | 0.70358 | 0.70494 |
| **Nd(58)** | 0.51256 | 0.5128 | 0.51279 | 0.51285 | 0.51274 | 0.51268 | 0.51266 | 0.51261 | 0.51283 | 0.51286 | 0.51255 |