S237 Course Unit - 1975

Handbook Section VII Classification and origin of basalts

Contents

Objectives

When you have completed the work for this Section of the *Handbook* you should be able to:

1 Demonstrate your comprehension of the terms, principles and concepts in Table A by writing a definition in your own words, by commenting on given definitions, and by distinguishing between true and false statements.

2 List and explain the advantages and disadvantages of modal and normative analyses. (SAQ 1)

3 Explain the general principles involved in calculation of a normative analysis and explain (i) how the distribution of Al_2O_3 determines the distribution of normative corundum, anorthite and acmite, (ii) how the distribution of SiO_2 determines the distribution of normative nepheline, hypersthene, olivine and quartz. (SAQs 2 and 3)

4 Given major element, petrographic and normative data for a basalt, classify it as an alkali basalt, an olivine tholeiite or a quartz tholeiite and comment on its degree of silica saturation. (SAQs 4 and 5)

5 Given a ternary phase diagram and melt compositions, identify thermal divides and comment on their effect upon processes of crystal fractionation and partial melting. (SAQs 10–14)

6 Explain the importance of (i) changing positions of thermal divides with increasing pressure (depth), (ii) the concentration of incompatible elements, (iii) the degree of crystal fractionation and recrystallization in determining the composition of a basalt magma erupted at the Earth's surface. (SAQs 15 and 16)

7 Describe the different courses of crystal fractionation of alkali and tholeiitic basalt magmas. (SAQs 17 and 18).

VII 1.0 Chemical, modal and normative analyses of igneous rocks

Study comment Here we summarize the main advantages and disadvantages of chemical and modal analyses. We show how the technique of recalculating chemical analyses into idealized minerals—a normative analysis—provides an important way of extracting additional information from chemical analyses and can therefore be used as a powerful tool in studying the chemical composition of rocks.

There are two different approaches to the description of an igneous rock which you have already met (S2–2, Unit 1; S237, Block 1).

(i) *modal analysis*, where the types and proportions of minerals present are identified;

(ii) *chemical analysis*, where the rock is first chemically analysed, and the results presented as weight per cent of oxides present.

In the following Section we introduce a third approach, *normative analysis* and show how and why it is used.

Modal analyses are carried out on thin sections of rocks using a petrological microscope and a *point counter*. This is just a device to move the rock section in a straight line past a fixed reference point in the field of view. The rock section is moved in constant steps, usually about a millimetre, by pressing a button. Every time it stops, the mineral under the point is identified and a button is pressed on an adding machine against a counter labelled with the appropriate mineral. To obtain an analysis from a single rock it is usual to count 1 000–5 000 points along a number of parallel, evenly spaced 'grid-lines' in one or more thin sections. The point-counting method is used to estimate the mineral composition, by volume, of a rock.

Modal Analysis

Disadvantages

Modal analyses have some important disadvantages which severely limit their use. Can you think of some?

① Every mineral must be identified correctly.

First, where rocks are very fine-grained or have fine-grained groundmasses, it will be difficult to identify each and every mineral that stops under the point—and *every* mineral must be correctly identified for a meaningful analysis.

② Sample must be representative

Secondly, there may be a problem in taking a representative sample for modal analysis—where rocks are very coarse-grained or are strongly porphyritic it may be necessary to study many thin sections or even large polished rock slabs to make an analysis.

A similar problem arises with rocks which have a preferred mineral orientation—schists, or lavas with flow-aligned phenocrysts, for example—because a poorly chosen section of such a rock may give a very misleading impression of the real mineral composition.

③ Relating modal analysis to chemistry

Finally, since most minerals are members of solid solution series with a wide range in chemical composition, rocks with similar modal analyses may have very different chemistry (and vice versa!), so that accurate and meaningful comparison of the chemistry of rocks on the basis of modal analysis is a difficult business. Because of these problems with *modal* analyses, and in an attempt to relate chemical analyses to mineral composition, geochemists have developed a system in which whole rock chemical analyses are recalculated into a standard, or 'normalized', set of minerals which include end-members of simple solid solution series. In the simplest such system that has been produced, for igneous rocks, these minerals are those that would be present if complete equilibrium was maintained during cooling. A chemical analysis recalculated in this fashion is known as a *normative mineral composition*. Analyses in terms of normative minerals can be quantitatively studied and accurately compared.

Although tnere are several different kinds of normative calculation, the most widely used system was originated by four American petrologists: Cross, Iddings, Pirsson and Washington. Theirs is known as the *CIPW norm* and is used to calculate chemical analyses in terms of the minerals listed in Table VII–1.

1.1 Normative minerals

When a mineral occurs in the normative composition of a rock (or 'norm' for short), regardless of whether it can be identified in a thin section, it is referred to as 'normative' —for example, 'normative quartz', or 'normative nepheline'. In addition, the normative minerals are commonly referred to by the abbreviations in the second column of Table VII–1, e.g. 'normative Q' or 'normative Ne'.

TABLE VII–1 Normative minerals

Mineral	Normative symbol		Formula
Quartz	Q		SiO_2
Corundum[1]	C		Al_2O_3
Orthoclase	Or		$KAlSi_3O_8$
Albite	Ab		$NaAlSi_3O_8$
Anorthite	An		$CaAl_2Si_2O_8$
Nepheline	Ne		$NaAlSiO_4$
Wollastonite	Wo	pyroxene	$CaSiO_3$
Enstatite	En		$MgSiO_3$
Ferrosilite	Fs		$FeSiO_3$
Forsterite	Fo	olivine	Mg_2SiO_4
Fayalite	Fa		Fe_2SiO_4
Acmite	Ac		$(NaFe)SiO_3$
Magnetite	Mt		Fe_3O_4
Hematite	Hm		Fe_2O_3
Ilmenite	Il		$FeTiO_3$
Apatite[2]	Ap		$Ca_5(PO_4)_3$
Pyrite	Pr		FeS_2
Calcite	Cc		$CaCO_3$
The following derived[3] normative minerals are used:			
Hypersthene (from En+Fs)	Hy		$(Mg,Fe)SiO_3$
Diopside (from En+Fs+Wo)	Di		$Ca(Mg,Fe)SiO_3$
Olivine (from Fo+Fa)	Ol		$(Mg,Fe)_2SiO_4$

[1] See footnote on p. 84.

[2] See footnote on p. 84.

[3] See text for discussion.

Because the norm is calculated in terms of pure end-members of several solid solution series, the minerals in Table VII–1 look more numerous and complex than they really are. For example forsterite (Fo; Mg_2SiO_4) and fayalite (Fa; Fe_2SiO_4) are the end members of the olivine solid solution series. Pyroxenes are expressed in terms of three end members: wollastonite (Wo; $CaSiO_3$), ferrosilite (Fs; $FeSiO_3$) and enstatite (En; $MgSiO_3$). But wollastonite does *not* have a pyroxene structure and so there is only partial solid solution of Mg–Fe pyroxenes with a $CaSiO_3$ component. In fact, naturally occurring pyroxene compositions can be expressed in terms of these three end-members on a triangular diagram (Fig. VII–1) which shows the composition fields of common pyroxenes. These are dominantly in two groups, both consisting of a solid solution between En ($MgSiO_3$) and Fs($FeSiO_3$), but with different amounts of Ca-substitution. The first group have compositions between En and Fs. Intermediate members of this series are called *hypersthene* (Hy; (Mg,Fe) SiO_3) and since they have a particular crystal structure (belonging

pyroxene

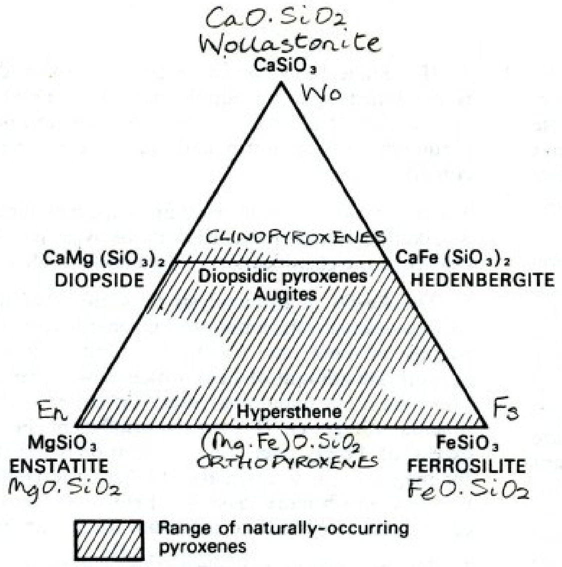

Figure VII–1 Compositions of pyroxenes expressed in terms of wollastonite ($CaSiO_3$), enstatite ($MgSiO_3$) and ferrosilite ($FeSiO_3$). The shaded area represents possible compositions of pyroxenes in volcanic rocks. See text for discussion.

Pyroxenes

to the orthorhombic crystal system) (S23–, Block 1, Section 6.1), they are referred to as *orthopyroxenes*. The second group are much more calcium-rich, containing 40–50 per cent of the $CaSiO_3$ component, and since they belong to the monoclinic crystal system are called *clinopyroxenes*. These are most commonly *augite* and *diopside*, and Figure VII–1 shows that diopside is richer in the $CaSiO_3$ component than augite. Clinopyroxene compositions are recalculated as diopside (Di; $Ca(Mg,Fe)Si_2O_6$) in normative calculations.*

In addition to these common pyroxenes, there are some alkali-rich varieties such as *aegirine* which is a member of the solid-solution series between common augite ($Ca(Mg,Fe)Si_2O_6$) and the sodium pyroxene *acmite* (Ac; $NaFe^{3+}SiO_3$). Aegirine is therefore calculated as a mixture of normal pyroxenes and acmite in the norm.

Feldspars

The three feldspar end-members are *orthoclase* (Or; $KAlSi_3O_8$), *albite* (Ab; $NaAlSi_3O_8$) and *anorthite* (An; $CaAl_2Si_2O_8$). The compositions of the feldspars and their solid solution behaviour is represented on a triangular diagram which shows the compositions of naturally occurring feldspars in Figure VII–2. There is complete solid solution between albite and anorthite and these are the components of *plagioclase feldspar*. Solid solution between albite and orthoclase is complete only at high temperatures, so that on cooling *alkali feldspar* tends to split into intergrowths of albite-rich and orthoclase-rich feldspars (S23– *Reference Handbook*). Orthoclase and anorthite, however, do not show more than negligible solid solutions under any conditions.

Felds-path-oids

Nepheline is a feldspar-like or feldspathoid mineral which has a framework structure. Although you have probably not met it before, it is fairly widespread as a minor component of certain basaltic rocks—it is also very important in the normative calculation as you will shortly see. NaO, AlO, SiO4

The last six minerals listed in Table VII–1 are all common accessory non-silicate minerals. *Magnetite, hematite,* and *ilmenite* are all oxide minerals which are present to the extent of a few per cent in almost all igneous rocks and are characteristically opaque in thin section (S23–, Block 1, Section 3.3). *Pyrite, apatite* and *calcite* are also widespread, but are generally less abundant, usually occurring to the extent of less than 1 per cent. Their appearance in the norm is reflected by the appearance of S, P_2O_5 and CO_2 respectively in the chemical analysis.

Examine carefully the list of minerals in Table VII–1. How do they compare with the minerals that occur in common igneous rocks?

Although minerals used in the calculation of normative compositions include end-members of most mineral series found in common igneous rocks, they are all *anhydrous*—they do not include amphiboles (e.g. hornblende) and micas (e.g. muscovite and biotite), which are common in intermediate and acid igneous rocks. So normative mineral compositions are best for studying basalts and other igneous rocks that have low contents of hydrous minerals.

SAQ 1 Which of the following statements apply only to normative mineral analyses, only to modal analyses or to both? Select an alternative for each statement by ticking the appropriate space below.

	Normative analyses only	Modal analyses only	Both normative and modal analyses
A Poor sampling may cause the analysed sample to be unrepresentative of the large rock body.			✓
B An accurate chemical analysis is essential.	✓		
C Produces an analysis in terms of actual minerals present in the rock.		✓	
D Analysis is determined in terms of solid solution end members of anhydrous minerals that might plausibly be present in the rock.	✓		

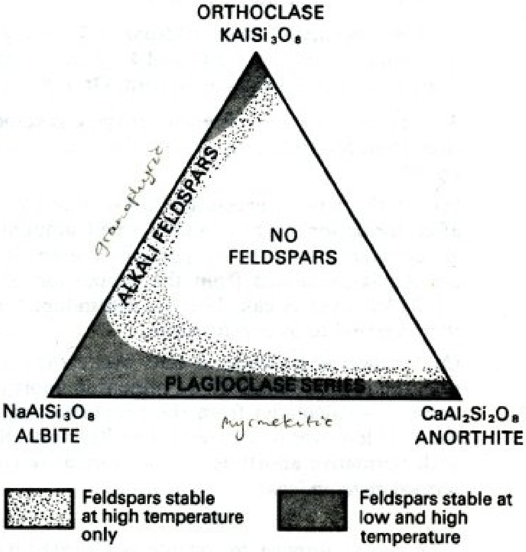

Figure VII–2 Compositions of feldspars expressed in terms of orthoclase ($KAlSi_3O_8$), albite ($NaAlSi_3O_8$) and anorthite ($CaAl_2Si_2O_8$). Shading shows compositions of feldspars in volcanic and plutonic rocks. See text for discussion.

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*Although diopside as a naturally occurring mineral is $(CaMg)Si_2O_6$, in the norm it contains all members of the diopside-hedenbergite solid solution series. In the norm, augite is calculated as a mixture of Di and Hy.

$$2MgO.SiO_2 + SiO_2 = 2MgO.2SiO_2$$

$$Mg_2SiO_4 + SiO_2 = Mg_2Si_2O_6 = 2(MgSiO_3)$$

forsterite (olivine) + quartz = enstatite (pyroxene) acmite (aegirine) $NaFeSi_2O_6$

For the reasons given earlier, we shall be dealing with the normative compositions of igneous rocks. Although normative calculations are too tedious for you to calculate yourself (they are always calculated by computer nowadays anyway!), you need to know something of the procedure involved so as to understand the significance of the analysis obtained.

Briefly, the normative calculation involves converting the constituents of the chemical analysis (usually oxides) into molecular proportions (by dividing by appropriate molecular weights), and then combining these in appropriate proportions into the minerals listed in Table VII–1 until all the elements are used up. Finally, the resultant mineral proportions have to be converted back into weight percentages. The sequence in which the elements are allocated to the normative minerals is vitally important and this is set down in qualitative fashion below. This sequence depends on doing simpler calculations first—such as where the proportion of a mineral can be calculated from the abundance of a single oxide. The later stages are more complex because they involve calculation of mineral proportions from the abundance of constituents such as SiO_2 that are common to all the minerals.

1.2 Norm calculation procedure

Study comment You will probably find difficulty with following the sequence and with doing SAQs 2 and 3. Remember that we do not expect you to memorize each stage. All we require is that you grasp how the normative calculation attempts to produce plausible mineral assemblages by making mineral combinations in a carefully defined series of calculations. We want you to be able to *explain* the procedure and why it is adopted, particularly for Stage 8. We suggest you read the stages slowly, referring to Table VII–1 for the mineral compositions. Then answer the SAQs.

1 The first normative minerals to be calculated are the accessory minerals calcite (Cc; $CaCO_3$) apatite (Ap; $Ca_5(PO_4)_3$* pyrite (Pr; FeS_2) and ilmenite (Il; $FeTiO_3$). The normative proportions of these are calculated respectively from the proportions of CO_2, P_2O_5, S, and TiO_2 in the chemical analysis combined with the appropriate amount of CaO and FeO. This usually leaves most of the CaO and FeO for major minerals.

2 The amount of alkali feldspar is formed *provisionally* by combining all the Na_2O and K_2O in the right proportions with Al_2O_3 and SiO_2 to form Or and Ab.

3 *The distribution of alumina* If there is some Al_2O_3 left over from Stage 2, as is usually the case, it is assigned to anorthite.

(a) If there is an excess of Al_2O_3 over CaO remaining after formation of the usually small amount of apatite (as compared with the proportions present in anorthite), the An is calculated from the proportion of CaO. The Al_2O_3 left over is calculated as corundum.† The rock is then referred to as *peraluminous.* norm C and An
no norm Di or Ac

Lewisian, when melted gives a peraluminous granite

(*b*) If there is an excess of CaO over Al_2O_3 (as compared with the proportions that are present in anorthite), the An content is calculated from the proportion of Al_2O_3, and the CaO left over is reserved for wollastonite. Such a rock, with normative anorthite but no normative corundum, is termed *metaluminous.* no norm C or Ac
norm Di and An

fractional melting of a transitional basalt

4 If at Stage 2 there was an excess of Na_2O over Al_2O_3, it is combined with an equal amount of Fe_2O_3 to form acmite (Ac; $(NaFe)SiO_3$). There is then no anorthite (or corundum) in the norm and the rock is *peralkaline* in composition. no norm C or An
norm Ac (+ sodium metasilicate NS if still excess Na

The distinction between peraluminous, metaluminous and peralkaline normative compositions is important, particularly in the classification of acid rocks such as rhyolites.

5 The Fe_2O_3 in the analysis (less any used up in 4) is used to calculate the amount of magnetite (Fe_3O_4 made up equally of FeO and Fe_2O_3) by combining it with the appropriate amount of FeO, which is of course subtracted from the FeO remaining after formation of pyrite and ilmenite (Stage 1). If there is insufficient FeO, i.e. an excess of Fe_2O_3 over FeO in relation to that required for magnetite, it is calculated as hematite (Fe_2O_3). It is, however, much more usual for FeO to exceed Fe_2O_3, so calculation of normative pyroxene forms the next stages. 6 & 7

6 The proportion of wollastonite (Pyroxene) is calculated from any CaO remaining from Stage 3b.

7 Enstatite and pyroxenes ferrosilite are formed *provisionally* from MgO and any FeO remaining from all the previous stages. Wollastonite is combined with an equal amount of En+Fs (the end member components of hypersthene, Hy) to form diopside (Di). The remaining En and Fs then become hypersthene (Hy) provisionally.

8 *The distribution of silica* All the cations except SiO_2 have now been assigned to actual or provisional normative mineral molecules and we now consider the distribution of SiO_2. Again there are several possibilities:

(a) If there is an excess of SiO_2 over that necessary to form all the actual or provisional normative minerals from Stages 1–7, the provisional minerals become permanent and the excess SiO_2 is calculated as quartz (Q).

(b) If there is not sufficient SiO_2 to form all the actual or provisional normative minerals from Stages 1–7, we have to change some of the provisional normative minerals from Stages 1–7 into others which contain less SiO_2. This is done by two successive Stages 8c and d below.

(c) Because Fo+Fa (the end-member components $(MgFe)_2SiO_4$ of olivine, Ol) contain less SiO_2 than Hy, then conversion of some of the Hy into Ol means that less SiO_2 is needed for these normative minerals. The amount of Hy that needs to be converted into Ol is calculated thus:

$$2(En+Fs)=(Fo+Fa)+Q$$
$$\text{i.e. } 2Hy=Ol+Q$$

Note that this equation *does not* indicate that Q is liable to appear in the norm at this stage. It just indicates that Ol (Fo+Fa) contains less SiO_2 than Hy (En+Fs), as indicated by the production of Q during conversion of Hy→Ol. So Hy is converted to Ol until the SiO_2 content matches that of the original chemical analysis (cf. 8b earlier).

(d) If, after conversion of all the provisionally formed hypersthene into olivine, there is still insufficient SiO_2 to form the normative minerals (cf. 8b), some of the albite is turned into nepheline according to the equation;

$$Ab=Ne+2Q$$

But rarely do rocks have so little silicon that there is still a deficiency when all the Ab has been converted into Ne; so we do not consider this possibility any further.

The most important result from this stage is that, for a given composition, the amount of SiO_2 determines whether a rock has Q, Hy, Ol or Ne in the norm. While rocks might have normative Q+Hy, Hy+Ol or Ne+Ol, it is important to note that Q+Ol, Hy+Ne and Q+Ne *cannot* occur in the same normative analysis (see 8d).

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*The correct formula for apatite is $Ca_5(PO_4)_3(OH)$. But, as noted earlier, the minerals calculated for the norm are all anhydrous, so apatite is calculated simply as $Ca_5(PO_4)_3$.

$10CaO.3P_2O_5.H_2O$

†Corundum Al_2O_3, never occurs as a mineral in common igneous rocks. So where C appears in the norm, this indicates the presence in the rock of an Al_2O_3–rich phase which is not listed among the normative minerals in Table VII–1. This is usually either biotite or muscovite ($KAl_2(AlSi_3O_{10})(OH)_2$).

The molecular proportions of minerals derived from the normative calculation are finally converted back to weight proportions of normative minerals by multiplication by the appropriate molecular weights. Normative analyses of six basalts are shown in Table VII–2.

TABLE VII–2 Analyses and norms of Skye basalts (from Thompson *et al.*, 1972)

		286	918	983	291	940	946
SiO_2		44.98	45.08	46.99	45.67	44.84	47.09
Al_2O_3		14.74	14.14	15.54	16.28	16.06	14.92
Fe_2O_3		2.64	1.50	3.04	1.50	1.50	3.82
FeO		10.05	10.93	7.96	11.11	12.02	7.30
MgO		10.72	10.29	9.13	8.43	8.11	9.05
CaO		9.77	8.54	12.69	10.33	9.25	12.67
Na_2O		2.74	3.16	1.83	2.83	3.17	1.87
K_2O		0.39	0.52	0.10	0.31	0.29	0.10
H_2O		0.72	3.49	1.34	2.41	2.01	1.43
CO_2		0.05	—	0.08	—	—	0.10
TiO_2		2.07	2.15	1.21	1.73	2.49	1.12
P_2O_5		0.26	0.26	0.09	0.20	0.27	0.10
MnO		0.20	0.19	0.22	0.22	0.23	0.26
TOTAL		99.33	100.25	100.22	101.02	100.24	99.83
Q		—	—	—	—	—	—
Or		2.31	3.07	0.59	1.83	1.71	0.59
Ab		18.74	22.02	15.49	20.52	23.34	15.82
An		26.77	22.86	33.89	30.80	28.74	32.02
Ne		2.41	2.56	—	1.86	2.43	—
Di	Wo	8.22	7.44	11.68	7.99	6.43	12.34
	En	4.87	4.39	6.82	4.30	3.37	7.15
	Fs	2.93	2.68	4.30	3.42	2.87	4.61
Hy	En	—	—	4.95	—	—	5.32
	Fs	—	—	3.12	—	—	3.43
Ol	Fo	15.29	14.88	7.69	11.70	11.79	7.05
	Fa	10.14	10.01	5.34	10.26	11.03	5.01
Il		3.93	4.08	2.30	3.29	4.73	2.13
Mt		2.18	2.18	2.18	2.18	2.18	2.18
Ap		0.57	0.57	0.20	0.44	0.59	0.22
Cc		0.11	—	0.18	—	—	0.23
		Alk basat	AlkB	Ol Tholeiite see p87	Alk B	Alk B	Ol Tholeiite

SAQ 2 Which of the following combinations of normative minerals might you expect to find in the same analysis?

✓ A Q+Di+Hy trachyte, diorite, andesite etc.
✓ B Di+Hy+Ol mugearite, peridotite
✗ C Di+Hy+Ne
✓ D Di+Hy+C
✗ E Q+Hy+Ne
✗ F Q+Ac+Ne
✗ G Q+Ac+An

SAQ 3 A series of basalts contain similar proportions of all major elements except SiO_2. How might their normative compositions vary between members relatively rich and relatively poor in SiO_2?

An important point about normative analyses concerns alteration. Where rocks are subjected to alteration, several changes occur. In basalts, for example, primary igneous minerals such as olivine become oxidized and altered to hydrous Mg–Fe silicates, so the H_2O content increases and Fe_2O_3 increases at the expense of FeO.

Would this relative decrease in the FeO content of a basalt be more or less likely to give a hypersthene(Hy)-normative composition? $(Mg, Fe)O.SiO_2$

Oxidation will decrease the FeO:SiO_2 ratio in the rock, which means that there will be less FeO available, after formation of ilmenite, $FeTiO_3$ (Stage 1) to make silicate minerals; so it is *less* likely that fayalite (Fa; Fe_2SiO_4 or $2FeO.SiO_2$) will appear in the norm. If the amount of FeO is diminished far enough, there will not be enough to satisfy all the SiO_2, and normative quartz will appear, as will hematite when the normative proportion of $Fe_2O_3 > FeO$. Oxidation of a basalt, without other composition changes, could therefore make what is really a Ne-normative basalt appear to be a Q-normative basalt.

Since basalts are classified according to their contents of Ne, Ol, Hy and Q, it is important to bear in mind possible alteration when studying normative analyses in general. But the analyses used in the *Case Studies* are all of fresh unaltered rocks (unless otherwise stated), so you will not need to worry about this effect.

At this point we should digress a little and introduce the concept of silica-saturation, which is mainly applied to igneous rocks, sometimes to metamorphic rocks, and hardly ever to sedimentary rocks.

In a mineralogical classification, a rock which contains quartz is termed *oversaturated*, because there is an excess of SiO_2 over and above that required to combine with all the other constituents in the rock. A rock which contains olivine and nepheline, is termed *undersaturated*, because if some SiO_2 were added to it nepheline would be converted to albite:

$$NaAlSiO_4 + 2\,SiO_2 \rightarrow NaAlSi_3O_8$$

and then olivine would be converted to hypersthene

$$(Mg,Fe)_2\,SiO_4 + SiO_2 \rightarrow 2\,(Mg,Fe)SiO_3$$

So what is a *saturated rock?*

It is one containing hypersthene and olivine, but neither nepheline nor quartz. We shall return to the concept of silica saturation later (p. 86).

VII 2.0 The classification of basalts

The history of ideas on the classification (and indeed the origin) of basalts is a long and interesting one, but we cannot do justice to it within the scope of this *Handbook*. If you wish to follow it up, there are some references in the further reading list at the end of this Section.

Basalts can be classified as alkaline or tholeiitic using simple mineralogical and chemical criteria. Alkali basalts generally contain less SiO_2 than tholeiites, and higher contents of TiO_2, Na_2O and K_2O.

Which of the following (normative or modal) minerals would you think *more* likely to be found in alkali basalts or tholeiites (tick appropriate space)?

	alkali	tholeiite
olivine $2(Mg,Fe)O.SiO_2$	✓	
quartz SiO_2		✓
nepheline $Na_2O.Al_2O_3.2SiO_2$	✓	
ilmenite $FeO.TiO_2$	✓	

Relative enrichment in silica means that there is more likely to be normative quartz than olivine or nepheline in tholeiites. On the other hand, less SiO_2 and more alkalis

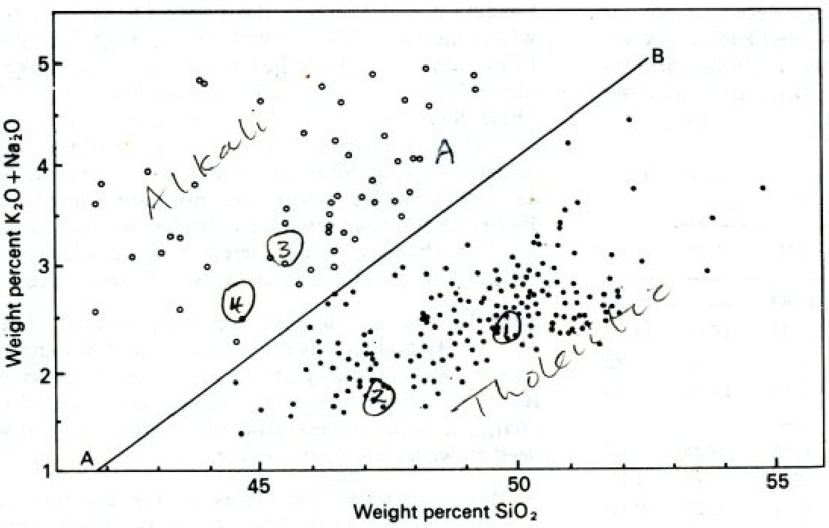

Figure VII-3 Alkali–silica plot for Hawaiian basalts. Alkali basalts (open circles) lie above the line AB. Tholeiitic basalts (filled circles) lie below AB.

Ring numbers from Summer school.

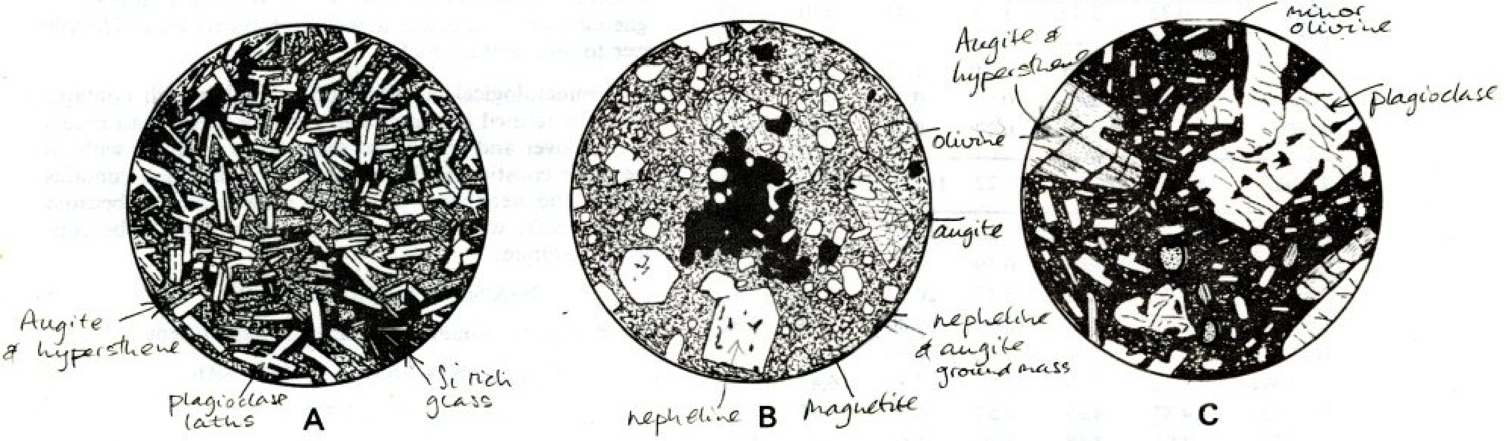

Figure VII-4 Thin sections of basalts showing main mineral components:

A Augite and hypersthene (coarse stipple), plagioclase (clear stumpy laths) with minor irregular pools of dark-brown silica-rich glass (dark colour).

B Olivine (coarse stipple, no cleavage), augite (coarse stipple and cleavage), nepheline (clear squares and hexagons) and magnetite (irregular black mass) in a fine-grained matrix consisting chiefly of smaller nepheline and augite granules.

C Hypersthene and augite (clear with closely spaced cleavage lines) minor olivine (rounded granules with coarse stipple) and plagioclase (clear with irregular lines) in a fine-grained matrix.

Diameter of field of view for A, B and C is 2 mm. All sections are shown in plane-polarized light.

and titanium mean that olivine, nepheline and ilmenite are more likely to be found in alkali basalts than tholeiites.

You already know (S2–2, Unit 1; S237, Block 7) that simple chemical criteria can be used on a statistical basis to distinguish different basalt magma types—there, TiO_2 was used to separate oceanic (island) basalts from island-arc basalts. The former were dominantly alkali, and the latter dominantly tholeiitic basalts. In the same general way, a plot of alkalis versus silica also provides a useful means of distinguishing alkali basalts from tholeiitic types (Fig. VII–3).

The normative classification The most consistent and precise way of classifying basalts is to use norms calculated from chemical analyses of unaltered samples.

Table VII–3 shows the *diagnostic* normative minerals which are used to classify basalts.

TABLE VII–3 Diagnostic normative minerals and the basalt classification

Diagnostic normative minerals	Basalt type	
Hypersthene+Quartz	(Quartz) tholeiite	over sat
Olivine+Hypersthene	Olivine tholeiite	sat.
Olivine+Nepheline	Alkali basalt	under sat

Earlier you were introduced to the concept of silica saturation.

> Which of the three basalt types defined above is under-saturated, saturated and oversaturated with silica?

You probably had little difficulty with that question. The quartz tholeiite is oversaturated; the olivine tholeiite is saturated; and the alkali basalt is undersaturated with silica, as explained earlier in Section VII–1. We also emphasized earlier that the correspondence between normative and modal compositions of rocks is closer for basalts than for any other rock type, so it is usually possible to apply the classification in Table VII–3 if you can identify the diagnostic mineral phases on microscopic examination.

Now attempt SAQs 4 and 5.

SAQ 4 Chemical and normative analyses for six Skye basalts are given in Table VII–2.

(a) Classify these basalts using the terms listed in Table VII–3.

(b) Which of the oxides listed in Table VII–2 shows the greatest and most consistent differences between the basalt types you have identified in SAQ 4 (a).

Morse p212. Tholeiitic basalts = olivine + liquid -> ortho pyroxene

K_2O / P_2O_5

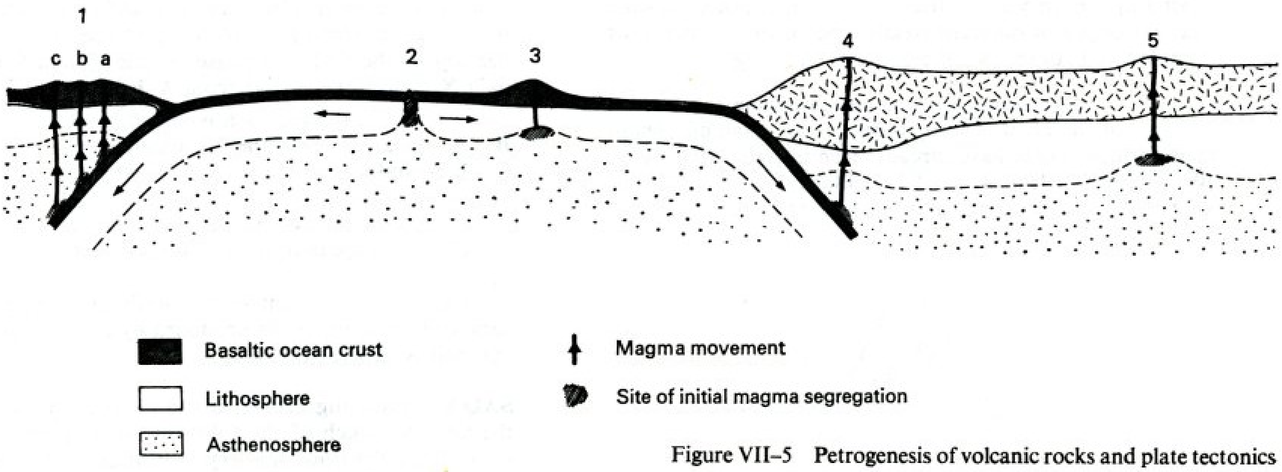

Figure VII–5 Petrogenesis of volcanic rocks and plate tectonics

1 Island arc volcanism. Lavas are chiefly basalts and andesites. The basalts are commonly low-potash tholeiites at (a), calc-alkaline or high-alumina types at (b) and more alkaline rich at (c). Analogous variations occur in the associated andesites.

2 Constructive margin volcanism. Low-potash tholeiites are the dominant, but not the only rock type.

3 Volcanism within an oceanic plate. Volcanic islands away from plate margins are commonly alkali basalt associations, but some tholeiitic associations also occur.

4 Destructive continental margin volcanism of Andean type. Lavas are dominantly andesite with subordinate calc-alkaline basalts. Lavas show a characteristically increasing alkalinity away from the destructive margin as in 1.

5 Volcanism within a continental plate. Volcanics are dominantly of alkali basalt associations, sometimes highly alkalic, but some continental tholeiitic associations also occur.

Note that the diagram is very schematic and not exactly to scale. Note also that in all settings there is liable to be substantial crystal fractionation and/or reaction with the mantle during movement from the site of generation to the volcano at the surface.

SAQ 5 Drawings of thin sections of these basalts are shown in Figure VII–4A, B and C.

(a) To which type of basalt might these correspond? Select one answer for each from (i) to (iii) below.

(i) alkali basalt B
(ii) olivine tholeiite C
(iii) quartz tholeiite A

(b) Judging from the observed mineralogy, which basalt is (i) undersaturated B; (ii) saturated C; and (iii) oversaturated A with silica?

After completing SAQ 5, you might well ask what is the point of the normative classification if you can simply make a thin section and classify a basalt using the microscope? The answer is that many basalts are extremely fine-grained, or are glassy, so that positive identification of mineral phases is not always possible. And in such a situation, very small amounts of a diagnostic mineral, such as nepheline or hypersthene, are simply not detectable with the microscope, but may nevertheless appear in the norm.

It is very important also to remember that the chemical composition of minerals is more variable than the formulae in Table VII–1 suggest; *therefore*, the presence of small amounts of normative nepheline or olivine, say, is *not* necessarily proof that these minerals are physically present in the rock.

There are other complications and refinements in basalt classifications, permitting more detailed subdivisions than those in Table VII–3. For example, tholeiitic basalts are split into *low-potassium tholeiites* (< 0.3 per cent K_2O), which are the most abundant type dredged from the ocean floors; and *continental tholeiites* (> 0.5 per cent K_2O), such as most of those on Skye.* Alkali basalts can be sub-divided on the basis of both total alkali content and the potash:soda ratio. A final group are basalts which occur in island arcs and destructive continental margins, and are therefore associated with andesites. These are termed *calc-alkaline basalts* or, since they frequently have $Al_2O_3 > 17$ per cent, they are termed *high-alumina basalt*.

With the advent of plate tectonics, we have a framework within which the magmagenetic processes responsible for different basalt types can be considered. Figure VII–5 is a schematic cross-section showing the plate tectonic setting of different basalt types.

VII 3.0 The origin of basalt

Study comment Studies of processes involved in the origin of basalt are among the most complex in modern petrology. Here we review the important variables and show how simple phase diagrams can be used to study the contrasted courses of crystallization and contrasted products of crystal fractionation of alkali and tholeiitic basalt. In discussing phase diagrams, it is most convenient to think in terms of normative minerals, as they represent pure end-members of more complicated solid solution series.

Current ideas on the origin of basalt accept that it is produced by partial melting of the Earth's mantle (S2–2, Unit 2; S237, Block 3). Factors affecting the composition of the melt produced are:

1 The mineralogy of the mantle peridotite, which varies as a function of pressure, temperature and chemical composition.

2 The depth (pressure) and temperature at which partial melting takes place.

3 The degree of partial melting.

4 The concentration of volatile compounds, chiefly H_2O and CO_2, in the zone of partial melting.

A magma formed by partial or complete melting of the Earth's mantle at depth is known as a *primary magma*. But when magmas move away from their site of formation, they start to cool and hence crystallize. So such magmas rarely reach the surface without modification, either by crystal fractionation or by reaction with surrounding rocks

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*We say 'most', because some basalts on Skye—such as those represented by analyses 946 and 983 in Table VII–2—are of oceanic tholeiite type, as indicated in the Table by their low K_2O content.

during uprise. In view of these factors, it is not surprising that the origin of different basalt types is one of the most complex and controversial aspects of petrology.

One of the most useful ways of understanding the crystallization of different basalt types is to examine phase relationships. These have already been introduced in S23–, Block 4, S2–2, Unit 4 and S237, Block 3, so assess your knowledge by attempting the revision SAQs 6, 7, 8 and 9.

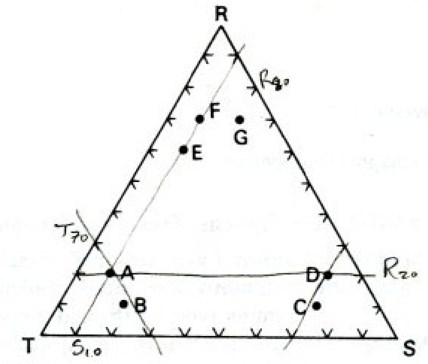


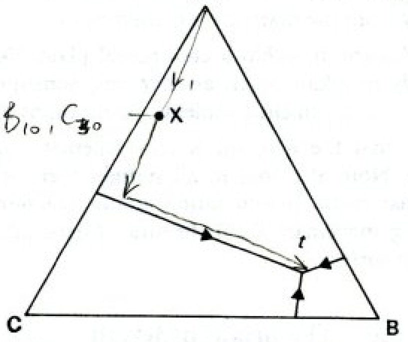
Figure VII–6 For use with SAQ 6.

SAQ 6 Which of the points plotted in the triangular diagram (Fig. VII–6) represents a composition of 20 per cent R, 10 per cent S, 70 per cent T? Select *one* point from A–G on the diagram. Give the compositions for the others.

A

$B = T_{70}, R_{10}, S_{20}$

$C = R_{10}, S_{70}, T_{20}$



melt $X = A_{70}, B_{10}, C_{30}$

Figure VII–7 For use with SAQs 7, 8 and 9.

SAQ 7 Figure VII–7 shows the composition of a melt (X) and the phase relations in a three-component system with binary eutectics and cotectic lines leading to a ternary eutectic *t* between A, B and C. Which of the following statements correctly describes the crystallization of the first two phases in the system from the melt X. Select *one* answer from A–F below.

A A crystallizes first, then is joined by B.
B A crystallizes first, then is joined by C.
C B crystallizes first, then is joined by A.
D B crystallizes first, then is joined by C.
E C crystallizes first, then is joined by A.
F C crystallizes first, then is joined by B.

SAQ 8 Write two sentences describing the change in composition of the melts produced by crystallization of the melt X in Figure VII–7.

SAQ 9 Assuming that A, B and C are all denser than the melt X, which of the following descriptions could result from the fractional crystallization path followed by the melt X in the system shown in Figure VII–7. Select *one* answer from A–C below.

A A homogeneous mixture of crystals of A, B and C.
B A layered pile of crystals containing one mineral A only at the base, and a mixture of two minerals, A and C at the top.
C A layered pile of crystals, containing two minerals at the base gradually changing to three minerals at the top.

Most of the geologically important ternary systems are more complex than Figure VII–7, and an additional concept we introduce here is that of *thermal divides*. We will illustrate the character and importance of this phenomonon by reference to the nepheline ($NaAlSiO_4$)–diopside $(CaMg)Si_2O_6$–silica(SiO_2) system at atmospheric pressure (Figs VII–8, 9 and 10). Since the compositions of both the major minerals of basalt, pyroxene and plagioclase, are represented in this system, it provides a crude analogy for natural basalt magma. The occurrence of albite between nepheline and quartz means that the nepheline–quartz part of the ternary system *cannot* be a simple eutectic like one of the sides of Figure VII–7. Study Figure VII–8 carefully, looking at the caption which explains some complications which need not concern us here; the main thing is that the nepheline-silica system is split into two binary 'subsystems' by the occurrence of albite, in each of which crystallization follows *exactly the same* principles as in a simple binary eutectic system such as diopside–anorthite (S2–2, Unit 4; S237, Block 3).

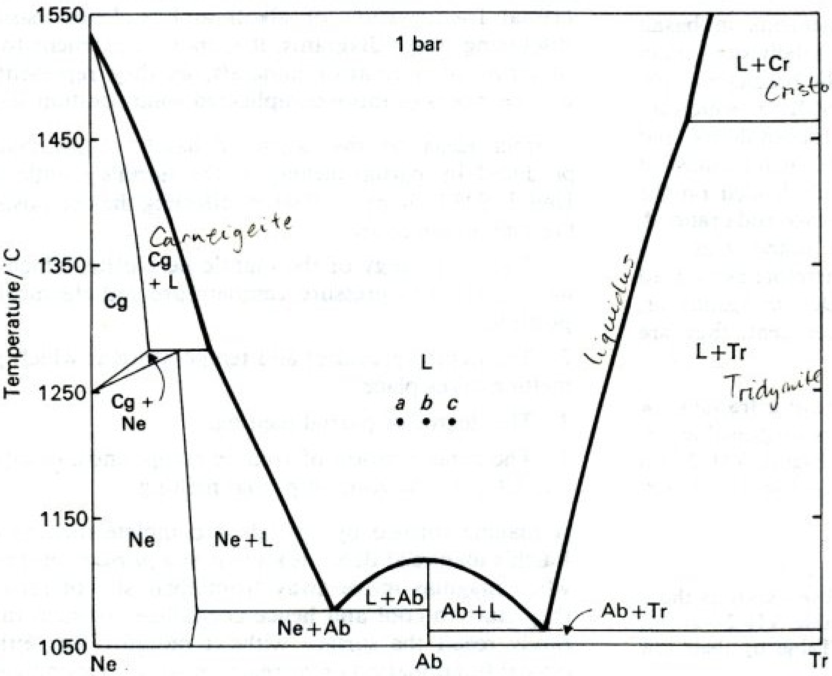


Figure VII–8 The system nepheline ($NaAlSiO_4$)–silica(SiO_2) at 1 atmosphere Ab = albite, Ne = nepheline, Tr = tridymite, Cr = cristobalite. L = liquid. The heavy line is the liquidus; lighter lines represent phase boundaries between phases that are stable below the liquidus temperature. Tridymite and cristobalite are two silica polymorphs which crystallize in place of quartz at low pressure and high temperature. Cg - carneigeite, a polymorph that crystallizes in place of nepheline at the low pressure and high temperature. See text for discussion.

SAQ 10 (a) From Figure VII–8, what will be the product of equilibrium crystallization of melts with the following compositions:

(i) 55 per cent nepheline, 45 per cent quartz (point *a*);
(ii) 50 per cent nepheline, 50 per cent quartz (point *b*);
(iii) 45 per cent nepheline, 55 per cent quartz (point *c*)?

(b) How would the end product differ in each case if strong *fractional crystallization* had taken place?

Figure VII–8 was a binary system, nepheline–silica. Now we add another component: the *ternary* phase diagram for the system nepheline–diopside–silica is given in Figure VII–9 and shows several cotectic lines and three ternary eutectics. Your answer to SAQ 10 showed that both equilibrium and fractional crystallization of melts with compositions that differ only slightly might result in solids with different mineralogies. In Figure VII–8 such compositions crystallize on either side of the albite composition, which hence acts as a *thermal divide*.

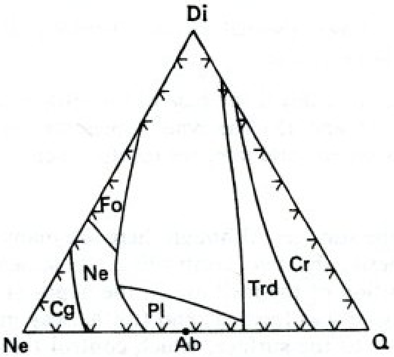


Figure VII–9 The system diopside ($CaMgSi_2O_6$)–nepheline ($NaAlSiO_4$)–silica(SiO_2) at 1 atmosphere. Fo = forsterite, Cg = carneigeite, Ne = nepheline, Di = diopside, Pl = plagioclase, Trd = tridymite, Cr = cristobalite. Carneigeite is a high-temperature polymorph of nepheline, and tridymite and cristobalite are silica polymorphs as described in the caption to Figure VII–8. See text for discussion.

How can we extend this behaviour? It is done by drawing lines *between pairs of compounds that can crystallize together on a cotectic curve*. These lines may lie along the edges or across the ternary system.

Using a coloured pencil, draw *four* such lines on to Figure VII–9*.

The lines you have drawn are all thermal divides. Their intersections with the cotectic curves represent temperature *maxima* for those curves.

SAQ 11 Put arrows on to Figure VII–9 to indicate the directions of cooling along the cotectic lines.

The distribution and directions of cooling along cotectics suggest that melts with compositions broadly scattered between albite and diopside (basaltic compositions, remember) might crystallize to form solids with very different mineral compositions. The importance of the presence and location of thermal divides is illustrated by SAQ 12.

SAQ 12 (a) What will be the sequence and final product of equilibrium crystallization of melts with the compositions labelled *a*, *b* and *c* in Figure VII–10?

(b) What will be the sequence of partial melting of rocks with the compositions *a*, *b* and *c* in Figure VII–10?

(c) Under what conditions (if any) could a melt with a composition on the right of the albite–diopside thermal divide give rise to a 'basalt' containing nepheline?

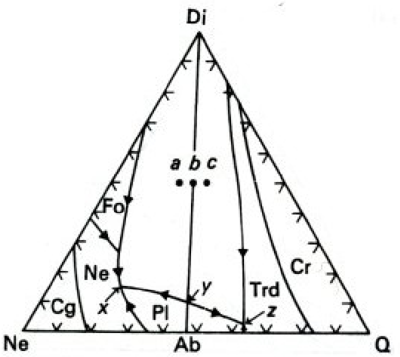


Figure VII–10 The system diopside–nepheline–silica. See caption to Figure VII–9. For use with SAQ 12.

Be sure to read and understand the answer to SAQ 12 before continuing with the text.

Because of the controls and limitations they exert on the crystallization of magmas, thermal divides are very important in studying the origin of basalts.

We now go to a further dimension: using Q, Ne, Di and Fo it is possible to build up a *tetrahedron* which will contain the compositions of all common basalts.

Although basalts *can* be plotted into a triangular phase diagram such as the Di–Ne–Q system (Figs VII–9 and 10), a tetrahedron enables basalts to be considered in terms of representatives of the essential minerals—olivine (Fo), orthopyroxene (En), clinopyroxene (Di) and plagioclase (Ab)—*and* shows variation in the content of the minor constituents quartz (Q) and nepheline (Ne) which are so important in classifying basalts. You can see how this happens in Figure VII–11, which shows the composition points of the intermediate compounds, albite (intermediate between nepheline and quartz) and enstatite (intermediate between forsterite and quartz). It is sometimes called the 'basalt' tetrahedron, and nearly all of the normative mineralogy of a basalt can be represented by a single point plotted inside the tetrahedron.

DFNQ basalt Tetrahedron
Yoder & Tilley (1962)

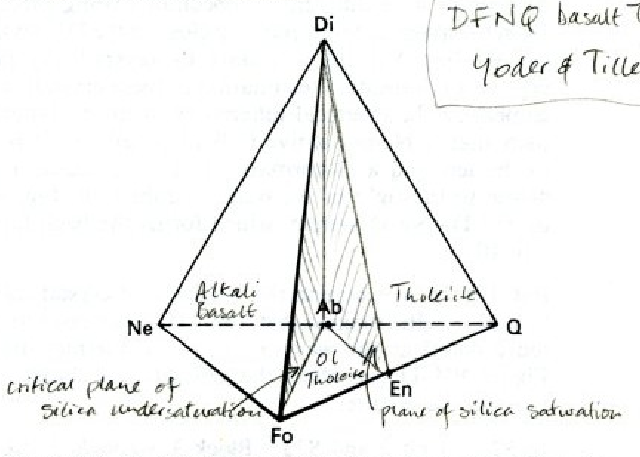


Figure VII–11 The basalt tetrahedron. See text for discussion.

SAQ 13 On Figure VII–11 draw and shade in a plane within the tetrahedron that joins the points corresponding to Di, Fo and Ab, and another plane that joins Di, Ab and En. The two planes you have shaded divide the tetrahedron into three smaller tetrahedra, each of which can be considered to include basalts containing the four minerals at its apices. Label each of those three tetrahedra with the name of a basalt type from Table VII–3.

If you look back to Figure VII–9 and 10, you will see how thermal divides occur between intermediate compounds in a complex system. Comparison of Figures VII–9 and 11 shows that the nepheline–diopside-quartz system forms the 'back' face of the basalt tetrahedron.

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*These are, of course, between Di–Ne, Ne–Q, Di–Q, *and* Di–Ab

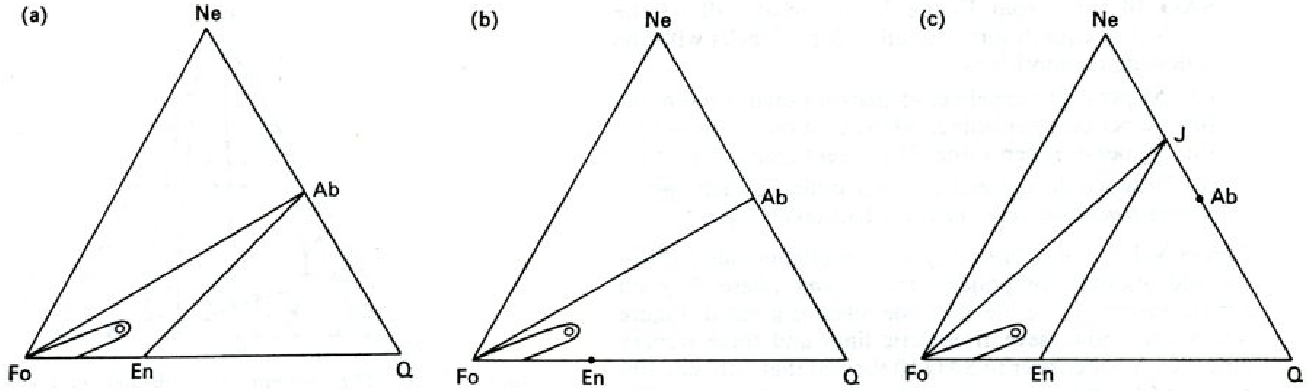

Figure VII–12 (a) The system forsterite–nepheline–silica showing thermal divides along the joins albite–forsterite and albite–enstatite.

(b) shows a thermal divide between forsterite and albite.

(c) shows thermal divides between forsterite–jadeite and enstatite–jadeite.

Note that this is the *base* of the tetrahedron shown in Figure VII–11 and 15. The point represents the composition of an undepleted peridotite. See text for discussion.

> **SAQ 14** Bearing these two pieces of information in mind, where might thermal divides be present *within* the basalt tetrahedron shown in Figure VII–11?

Thermal divides lie along the *planes* you shaded for SAQ 13 (see Fig. VII–15, p. 95). Clearly one of these, the Di–Ab–Fo plane, lies between the alkali and tholeiitic basalt groups.

> How significant is the existence of this particular thermal divide?

It confirms the importance of the distinction between these two main types of basalt magma, which was first formalized in 1933 by the British petrologist W. Q. Kennedy. The most important implication is that these two basalt magma types cannot be produced by fractional crystallization of a single magma. It also shows that although alkali and tholeiitic basalt compositions can be quite close, crystal fractionation will lead to the development of contrasted end-products of distinctive compositions such as *x* and *z*, derived by crystal fractionation of *a* and *c* in the ternary system (Fig. VII–10).

You should note very carefully that this is not the result of crystals with different compositions being precipitated from the magma. Melts plotting close to the Di–Ab thermal divide (Fig. VII–10) will start by crystallizing *identical* crystals of diopside. Precipitation of these crystals serves to emphasize the chemical differences in the remaining melt such that a Ne-normative ('alkali basalt') melt is driven to the left and a Q-normative ('tholeiitic basalt') melt is driven to the right of the basalt tetrahedron (Fig, VII–11) on the Di–Ne–Q system, which forms the back face (Fig. VII–10).

But, before we examine the products of crystal fractionation of basaltic magma (Section VII 4), we need to look in more detail at the way in which the thermal divides in Figure VII–11 can affect the generation of basalt magma types in the mantle.

In S2–2, Unit 2 and S237, Block 3, we looked at evidence that basalts could be produced by melting a peridotite mantle. Undepleted peridotite would be composed of olivine + clinopyroxene (diopside) + orthopyroxene (enstatite) + subsidiary amounts of an Al-rich mineral which would be plagioclase ($CaAl_2Si_2O_8$), spinel ($MgAl_2O_4$) or garnet ($Mg_3Al_2Si_3O_{12}$) with increasing depth.* Extraction of basalt depletes the peridotite in pyroxenes and the Al-rich minerals, eventually leaving more olivine-rich peridotite.

At the start of this Section, we mentioned the controls on the composition of the basalt melt produced and erupted at the surface. Although there are many variables in basalt genesis, the two controlling fundamentals for the composition of the melt are (i) the depth at which the primary magma was formed; and (ii) the way in which the magma came to the surface, which control the en route modifications to the primary liquid. Laboratory experiments indicate to an acceptable first-order approximation, that magma becomes more undersaturated and more alkaline with increasing depth of generation. At low pressures, less than 5 kb (17 km), tholeiites are produced. At 10 kb, or 35 km, the conditions are right for the production of alkali basalts. With greater depth, the primary magmas become progressively ultrabasic, being enriched in MgO (> 20 per cent MgO) and impoverished in SiO_2 (< 45 per cent SiO_2). Such magmas are called *picrites*.

How does this come about? It all hinges on the thermal divides. In the systems we have been studying, the phase diagrams (Figs. VII–8 to 11 and 15) all show systems at atmospheric pressure. At different pressures, some of the minerals that determine the positions of the thermal divides are unstable, so the compositions of magmas formed by melting a *single* peridotite composition can be different for different pressures. Look back at Figure VII–11.

> In which part of Figure VII–11 would a peridotite composed of 65 per cent olivine, 20 per cent enstatite, 10 per cent clinopyroxene (and 5 per cent spinel, which you can ignore for now) plot?

A peridotite of this composition will plot in the smaller diopside–albite–olivine–enstatite part of the basalt tetrahedron almost on the Di–Fo–En face. This can be projected onto the *base* of the basalt tetrahedron as shown in Figure VII–12a. We shall now consider the importance of thermal divides along the joins albite–forsterite and albit–enstatite. These separate alkali basalt, olivine tholeiite and quartz tholeiite compositions. The point shown as O represents an undepleted peridotite† and, depending on the degree of depletion, a peridotite composed of olivine,

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*It is also important to note that some aluminium substitutes for silicon in orthopyroxene and clinopyroxene crystallized at mantle depth.

†Note that a peridotite composed entirely of Fo, En and Di would plot on the face of the basalt tetrahedron represented by those minerals, hence between Fo and En on Figure VII–12. But the presence of other constituents, such as spinel, has the effect of moving the composition *into* the tetrahedron, to the position O in Figure VII–12.

clinopyroxene and orthopyroxene plots in the field shown between O and the Ol corner, more Ol-rich compositions being more depleted.

At low pressures, <5 kb (17 km), and high temperature, enstatite is unstable in this system and melts to give olivine and silica (or a silica-rich liquid, since we are talking about melting):

$$\text{enstatite} \rightarrow \text{olivine} + \text{silica}$$
$$2MgSiO_3 \quad Mg_2SiO_4 \quad SiO_2$$

At such low pressures, there is no thermal divide between enstatite and albite in Figure VII–12a, and the magma produced by partially melting peridotite at such low pressures must lie in the forsterite–albite–quartz field of Figure VII–12. This is shown in 12b. It will be a quartz tholeiite or olivine tholeiite. So it is possible to get quartz tholeiite magma from peridotite at low pressure, but at these low pressures the albite–forsterite (Fo) thermal divide prevents the generation of alkali basalt (in the Fo–Ne–Ab field) from the same peridotite. But the albite–forsterite thermal divide breaks down at pressures of greater than 15 kb (52 km), when albite becomes unstable and decomposes to form jadeite, a sodium pyroxene (which is one form of the gemstone jade) and quartz:

$$\text{Albite} \rightarrow \text{jadeite} + \text{quartz}$$
$$NaAlSi_3O_8 \quad NaAlSi_2O_6 \quad SiO_2$$

The composition of jadeite can be represented by the point J in Figure VII–12c. At high pressure the albite–forsterite thermal divide is replaced by a forsterite–jadeite and an enstatite–jadeite divide, and peridotite can yield an alkali basalt partial melt, which lies within the forsterite–nepheline–albite part of Figure VII–12a, once it rises to the surface. The net result of these changes in the position of thermal divides with pressure is that peridotite can yield tholeiite magma at low pressures and alkali basalt at high pressure. But this is only part of the story—aside from the *depth* of magma generation, the *degree of melting* and modification processes during rise to the surface are both important in modifying the composition of the melt.

To examine these factors we refer to *incompatible elements*.

As a melt rises, part of it will cool and crystallize. The major elements O, Si, Mg, Fe and Ca produced by melting of the mantle minerals combine into olivine and pyroxenes, but other elements such as K and the trace elements Rb and Ba, because of their large ionic radii, cannot enter olivine and pyroxene crystal lattices. These elements tend, therefore, to stay in the melt, and since they are *incompatible* with the main minerals, they are referred to as incompatible elements.

Because the incompatible elements are the first to enter the melt their concentration is highest where the degree of partial melting is small. You have come across this in S2–2/S237. Potassium is completely incompatible, so that its concentration in a basalt melt is inversely proportional to the degree of partial melting. The higher concentration of potassium and related incompatible elements in alkali basalts, than in tholeiitic basalt, therefore suggests that the more alkali–rich melts may result from a *smaller degree* of partial melting.

A similar factor influences the composition of melts as they leave the site of partial melting and rise towards the surface. If such a melt came to the surface rapidly there would be few changes in its composition. If, however, it made its way slowly to the surface, say by stoping or in passing through small cracks and fissures, it would react with the mantle and crustal wall rocks on the way up. Furthermore, if it paused for long enough at one level on the way up, it would alter in composition (equilibrate) to become equivalent to a magma generated at that depth (pressure).

One of the major changes in composition of a melt as it proceeds slowly to the surface is brought about by *recrystallization* during cooling. At any one level, the melt will crystallize only those minerals that are in equilibrium at the prevailing temperature and pressure conditions, that is minerals similar to those of the surrounding mantle will be formed. If this happens at 50 km, then only olivine, clinopyroxene and orthopyroxene will separate from the melt, for these are the mantle minerals stable at that depth. Furthermore, only the elements required for these minerals (Mg, Fe, Al, Si, O, Ca) will be extracted from the liquid. Other elements which cannot get into the mineral lattices of olivine, orthopyroxene or clinopyroxene will stay in the melt. These incompatible elements stay behind and become enriched in the melt.

SAQ 15 If two alkali basalts are produced at 50 km depth and one comes to the surface slowly and the other rapidly along, say, a major lithospheric fracture, what will be the differences between them? List possible differences.

SAQ 16 Listed in 1–3 below are those factors which determine the composition of a basalt melt. Place a tick in the appropriate space to indicate whether these cause the magma to become more alkaline or more tholeiitic.

	More alkaline	More tholeiitic
1 Greater depth of partial melting		
2 Higher degree of partial melting		
3 Higher degree of recrystallization during ascent		

VII 4.0 Crystal fractionation of basalt

We have already noted that as a basalt magma moves away from its site of generation, it must cool and hence crystallize. Separation of crystals from magma, or *crystal fractionation*, will cause the magma to change in composition. The nature of this process in the mantle is problematic and involves a variety of mineral phases depending on the *P–T* conditions, as noted earlier. But the effects of crystal fractionation of basalt magma are shown most clearly by alkali and tholeiitic basalt magmas, which have risen into the continental crust and cooled slowly in large intrusions. At these crustal levels (<35 km), we are below the pressure where the thermal divide between alkali and tholeiitic basalt exists. So for all of the discussions in this section, the thermal divide exerts a controlling influence on the course of crystallization of the basalt.

In such a setting, a range of basic through intermediate to acid rock types characteristically results (S2–2, Unit 4; S237, Block 7). The basaltic rocks consist largely of pyroxene and An-rich plagioclase. The intermediate and acid rocks contain much smaller proportions of pyroxene and are rich in feldspars and quartz or nepheline. This general picture applies to rocks resulting from crystal fractionation of both alkali and tholeiite basalt magma.

SAQ 17 Noting the contrasted courses of crystallization of Ne- and Q-normative melts in the Ne–Di–Q system (Figure VII–10), how might the products of crystal fractionation of Ne-normative, alkali basalt differ from the products of Q-normative, tholeiitic basalt?

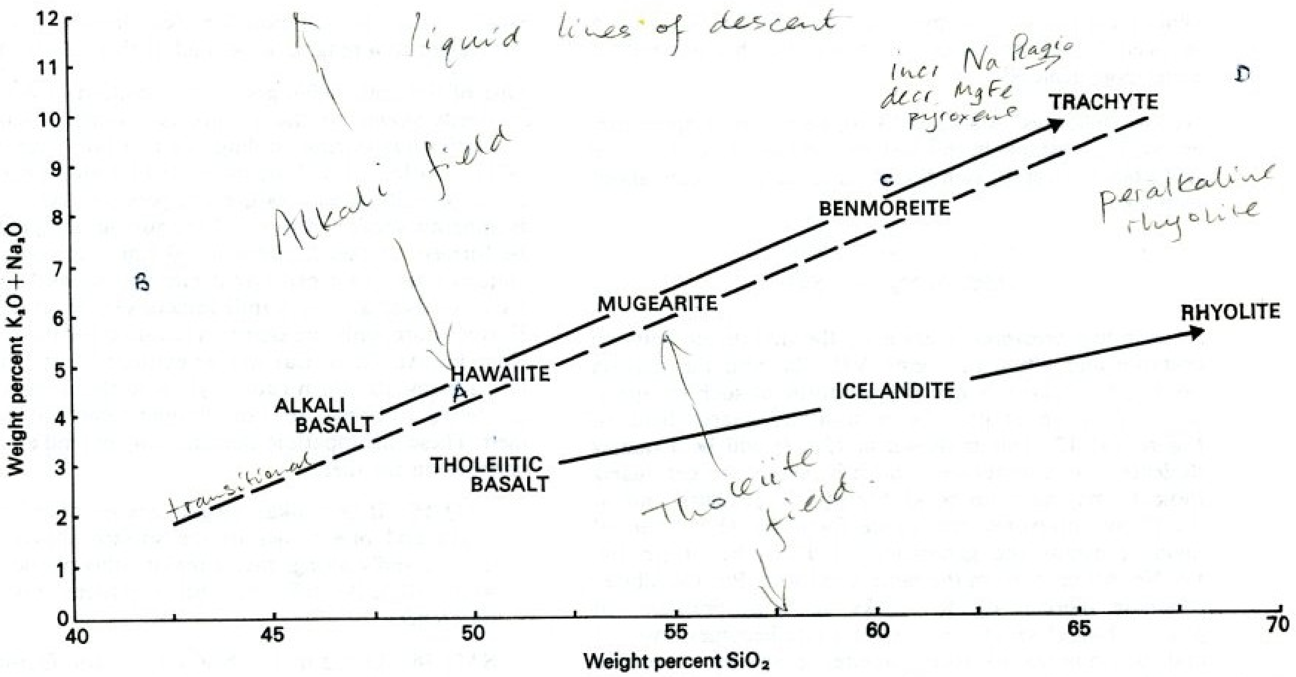

Figure VII–13 Plot of alkalis (Na_2O+K_2O) against SiO_2 showing various *magma series*. The dashed line separates silica-undersaturated basalts and their crystal fractionation products (above the line) from silica-saturated and silica-oversaturated products (below the line). Because normative compositions depend on many chemical features besides alkali content, the position of the dashed line is very approximate.

The distinction drawn between products of crystallization of alkali and tholeiitic basalt is very important and emphasizes the contrasted character of crystallization of the two magma types. Since analogous variations are seen in closely associated lava flows, for example on a single volcanic island, it is often assumed that such lavas could also have originated by crystal fractionation of basalt.

Alkali basalt parents give rise to silica-undersaturated lavas. With progressively more soda-rich plagioclase, more alkali feldspar and a lower content of Mg–Fe minerals (chiefly pyroxene), these lavas are termed *hawaiite*, *mugearite*, *benmoreite* and *trachyte* (Fig. VII–13). Formal distinctions between these terms are based on several parameters such as the An content of the normative plagioclase. Rather than lay down rigid criteria here, we shall carefully define the terms wherever they are used (note that you do not need to remember these terms!). Tholeiitic basalt magma gives rise to silica-saturated and oversaturated intermediate lavas called *icelandites*, and silica-rich *rhyolites* (which are, of course, chemically equivalent to granite). This generalization does have exceptions, related to the greater complexity of natural melts as compared with the simple systems described, and to the occurrence of processes which are not predicted by simple phase diagrams, for example, the movement of elements in a vapour phase. But the pattern described, in which the degree of saturation persists from basic to acid members of a volcanic suite, has been amply demonstrated by many recent studies.

Chemical data can be used in several ways to characterize these rock series—these involve plotting the data onto *chemical variation diagrams*. You have already seen a plot of alkalis (Na_2O+K_2O) against silica (SiO_2) in Figure VII–3, and this can be used, as shown in Figure VII–13, to distinguish between alkaline and tholeiitic lava series.

Because SiO_2 is a major variable in a fractionating sequence, it is commonly used as the ordinate in variation diagrams to show changes in the major oxides. But other components and combinations of components show analogous changes and there have been many attempts to derive other 'indices of fractionation' using a variety of chemical and normative parameters. Some of these are listed in Table VII–4.

Another useful plot is a three-component AFM (alkali, iron, magnesium) diagram of alkalis (Na_2O+K_2O), ($FeO+Fe_2O_3$) and MgO (Fig. VII–14). To plot a rock analysis on to an AFM diagram, you need to sum the weight per-

TABLE VII–4

See Cox
Bell & Pankhurst
PP 29 & 30

Index	Formula	Change with increasing differentiation	Reference
Felsic Index	$100(Na_2O+K_2O)/(Na_2O+K_2O+CaO)$	Increases	Simpson (1954)
Mafic Index	$100(FeO+Fe_2O_3)/(FeO+Fe_2O_3+MgO)$	Increases	Simpson (1954)
Larsen Index	$(\frac{1}{3}SiO_2+K_2O)-(FeO+MgO+CaO)$	Increases	Larsen (1938)
Modified Larsen Index	$(\frac{1}{3}Si+K)-(Mg+Ca)$	Increases	Nockolds and Allen (1953)
Solidification Index	$100MgO/(MgO+FeO+Fe_2O_3+Na_2O+K_2O)$	Decreases	Kuno (1968)
Differentiation Index	$Q+Or+Ab+Ne+Lc^*+Ks^*$	Increases	Thornton and Tuttle (1960)

*Lc and Ks are respectively normative leucite ($KAlSi_2O_6$) and kalsilite ($KAlSiO_4$), which are calculated in the norms of highly under-saturated rocks.

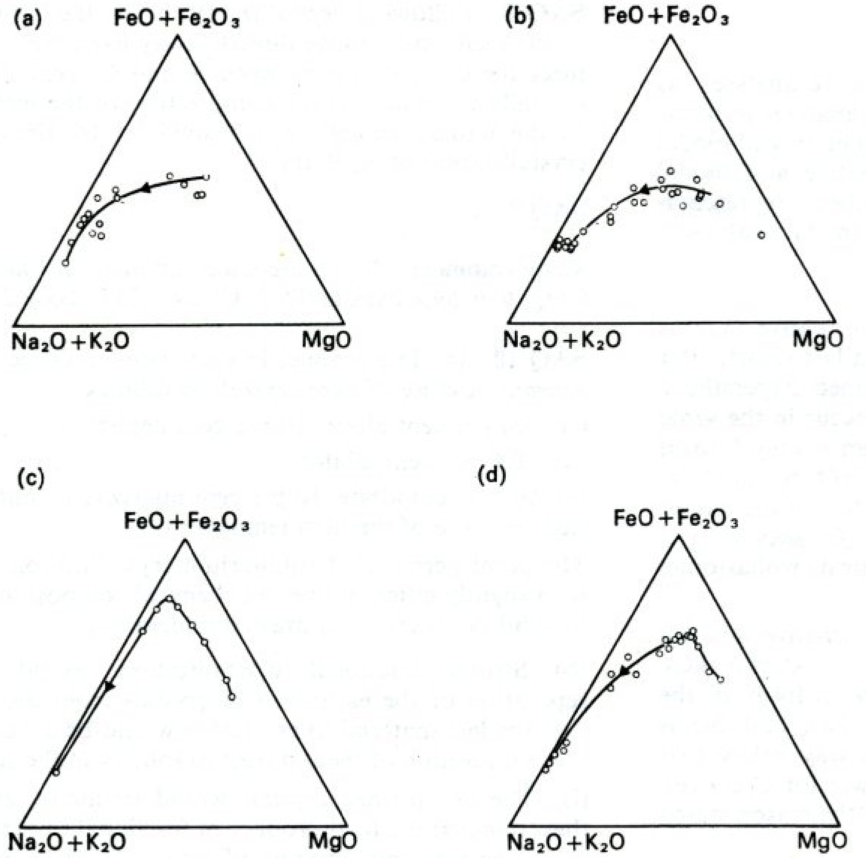

Figure VII–14 AFM diagrams of alkaline and tholeiitic rock suites:

(a) Alkali basic intrusion; Morotu, Japan.

(b) Alkali basalt lava suite; Gough Island, S. Atlantic.

(c) Tholeiitic basic intrusion; Skaergaard, E. Greenland.

(d) Tholeiitic basalt lava suite; Thingmuli, Iceland.

The actual rocks from which the trends are derived are plotted in (a), (b) and (d), but for the Skaergaard intrusion (c) it has been possible to estimate accurately the change in composition of the liquid during progressive crystallization. The points in (c), therefore, represent the composition of the liquid at different degrees of crystallization. Arrows show the direction of fractionation, from basalt to rhyolite or trachyte.

centages of the appropriate oxides and recalculate, so that A+F+M=100 per cent. Some further differences between alkaline and tholeiitic rock series, which are not immediately obvious from their normative analyses, can be seen on such a diagram.

Basic lavas such as basalt, which are rich in FeO+MgO relative to alkalis and silica, plot on the right-hand side of such a triangle, close to the F–M margin. Intermediate lavas plot more towards the inside of the triangle; whereas lavas such as trachyte and rhyolite which are rich in alkalis and silica relative to FeO+MgO, plot close to the A corner.

> What differences in the course of crystal fractionation of alkali and tholeiitic basalt magma are indicated by Figure VII–14?

The AFM diagram shows that intermediate products of crystal fractionation of tholeiitic basalt are more *iron-rich* than products from alkali basalt. This difference is distinctive and can be valuable—for example, in deciding whether an intermediate lava is a product of crystal fractionation of alkali or tholeiitic basalt magma. The icelandites which form part of tholeiitic lava series can be distinguished not only from intermediate alkali lavas by being relatively iron rich, but also from the intermediate andesites that are abundant in island arcs and continental orogenic belts (S23–, Block 4; S2–2, Units 4 and 5, and S237, Block 7)—which also plot close to the alkali basalt trend in an AFM diagram.

SAQ 18 Listed below are six characteristics of the *intermediate* members of basaltic lava suites. Which of these are characteristic of lavas that are members of (1) alkali basalt, (2) tholeiitic basalt, or (3) both types of basalt suite?

	(1) Alkali	(2) Tholeiitic	(3) Both tholeiitic and alkali
A Silica-oversaturated		×	
B Higher alkali ($Na_2O + K_2O$) and silica (SiO_2) content than basalts of the same suite.			×
C Composed mainly of alkali feldspar but no quartz.	×		
D Iron-enriched in comparison with other intermediate lavas.		×	
E Lower content of ferromagnesian minerals and more soda-rich plagioclase than associated basalts.			×
F May be Ne-normative in composition.	×		

SAQ answers and comments

SAQ 1 B and D apply only to normative analyses, as these are calculated from rock chemical analyses in terms of idealized mineral compositions. C applies only to modal analysis; and A applies to both normative and modal analysis—equal care must be taken to collect a representative rock sample whether for chemical or modal analysis.

SAQ 2 A and B only.

Hy and Ne can never occur in the same normative analysis (C) because nepheline is only formed as a last resort, after conversion of *all* the provisionally formed hypersthene into olivine (Stage 8c). C and Di never occur in the same normative analysis (D) because corundum is only formed where there is an excess of Al_2O_3 over CaO, so no clinopyroxene will appear in the norm (Stage 3a) – if there is an excess of CaO over Al_2O_3, then *all* the Al_2O_3 goes to form An (Stage 3b) and the remaining CaO forms wollastonite and eventually diopside (Stages 6 and 7).

Q and Ne cannot occur in the same normative analysis (E and F) as explained in Stage 8. Q only appears if there is an excess of SiO_2 over that necessary to form all the actual and provisional minerals (Stage 8a); and Ne is only formed where the SiO_2 content is way below that required to form these minerals (cf. answer for C above). An and Ac cannot occur together (G) for the reason stated under Stage 4.

SAQ 3 This really corresponds to the variations possible at Stage 8 in the normative calculation. If a basalt is relatively rich in SiO_2, there could be an excess over that required to form the actual or provisional minerals from Stages 1–7, so the basalt would have normative Q. If there is less SiO_2, then the basalt would have normative Hy ($\pm$Ol) (Stage 8c) and, with still less SiO_2, Hy would disappear and Ne would occur (Stage 8d). Thus the variation with decreasing silica will be Q+Hy, Hy+Ol and Ol+Ne.

SAQ 4 (a) 286, 918, 291 and 940 are all *alkali basalts* because they contain normative Ne. The remaining two basalts, 983 and 946, contain normative Hy and Ol and are *olivine tholeiites*.

(b) K_2O and P_2O_5 show the greatest and most consistent difference between the alkali basalt and olivine tholeiites distinguished above. K_2O is 0.10 per cent in the tholeiites and 0.29–0.52 per cent in the alkali basalt. Similarly P_2O_5 is 0.09–0.10 per cent in the tholeiites, but 0.20–0.27 per cent in the alkali basalts. In addition, the alkali basalts have consistently lower SiO_2, Fe_2O_3 and CaO and higher TiO_2, FeO, Na_2O contents than the tholeiites, although these differences are less marked than for K_2O and P_2O_5.

SAQ 5 (a) A, (iii); B (i); C (ii). If you had any problem with this, look back to Table VII–3 and then study Figure VII–4 and its caption again.

(b) A has a 'dark-brown silica-rich glass' in the ground-mass. Since this would be likely to contain silica, thin section A is of an oversaturated basalt (iii). B, in contrast, has abundant nepheline so is silica-undersaturated (i). C appears to contain neither nepheline nor quartz, but has olivine and hypersthene, so it is saturated with silica (ii).

SAQ 6 Point A. The compositions of the other points are as follows: B=10 per cent R, 20 per cent S, 70 per cent T; C=10 per cent R, 70 per cent S, 20 per cent T; D=20 per cent R, 70 per cent S, 10 per cent T; E=60 per cent R, 10 per cent S, 30 per cent T; F=70 per cent R, 10 per cent S, 20 per cent T; G=70 per cent R, 20 per cent S, 10 per cent T.

SAQ 7 B.

SAQ 8 Following crystallization of A, the composition of the melt would move directly away from the A apex to meet the cotectic line between A and C. Here C and A crystallize together as the composition of the melt moves to the ternary eutectic *t* and solidifies by simultaneous crystallization of A, B and C.

SAQ 9 B.

Study comment If you are uncertain about the answers to SAQs 6–9, look back at S2–2, Unit 4; S237, Block 3.

SAQ 10 (a) The product in each case would be a *homogeneous* mixture of *pure crystals* as follows:

(i) 90 per cent albite, 10 per cent nepheline;

(ii) 100 per cent albite;

(iii) 90 per cent albite, 10 per cent quartz (tridymite in this case, because of the high temperature).

The point here is that equilibrium crystallization of melts with slightly different over-all chemical compositions leads to solid products of contrasted mineralogy.

(b) Strong fractional crystallization would involve separation of the early-formed crystals from the melt so that the last material to crystallize would be a 'rock' with the composition of the last melt to solidify in the system.

(i) The first-formed crystals would be albite, and after their removal the final product of fractional crystallization would be a eutectic mixture of nepheline and albite (with about 30 per cent nepheline).

(ii) The overall melt composition is exactly that of albite, so the end-product of crystallization under any conditions is solid albite.

(iii) As in (i), the first-formed crystals are albite, but the final product of fractional crystallization is a eutectic mixture of albite and quartz (tridymite, because of the high temperature) (with about 30 per cent quartz).

As for (a), the point here is that fractional crystallization of melts with slightly different over-all chemical compositions lead to the production of 'rocks' with contrasted mineralogies and *chemical compositions*.

SAQ 11 The answer is shown in Figure VII–10 (p. 89).

SAQ 12 (a) Crystallization of *melt a* begins with formation of crystals of diopside. With cooling, the composition of the melt then moves directly away from diopside and intersects the cotectic line separating the fields of crystallization of diopside and plagioclase, where it is joined by plagioclase. Crystallization of these minerals occurs as the composition of the melt moves towards the ternary eutectic at *x*, where crystallization is completed as diopside, plagioclase and nepheline crystallize together.

The first crystals to form on cooling *melt b* are diopside, and with cooling the melt moves directly away from diopside along the thermal divide towards *y*, the diopside–albite binary eutectic. Here, albite and diopside crystallize together until solidification is complete. Note that since *b* corresponds exactly to a mixture of diopside and albite, there is no 'extra' Na or Si for the formation of either nepheline or quartz, so crystallization *must* become complete on the thermal divide at the diopside–albite eutectic *y*, even though this represents a temperature 'high' on the cotectic line.

Melt c begins to crystallize with formation of crystals of diopside. With cooling, the melt moves towards the diopside–plagioclase cotectic line where plagioclase begins to crystallize. With crystallization of these two phases, the melt moves towards the ternary eutectic at *z* and crystallization becomes complete as diopside, plagioclase and tridymite crystallize together.

(b) The product of partial melting of *a*, *b* and *c* in Figure VII–10 will be the reverse of the crystallization process you described in (a). Thus partial melting of composition *a* will begin by formation of a *melt* containing nepheline, plagioclase and diopside in proportions corresponding to the ternary eutectic *x*. After the nepheline component is exhausted, the composition of the melt will change along the plagioclase–diopside cotectic line. When plagioclase has all been extracted into the melt, fusion becomes complete by melting of diopside as the composition moves from the plagioclase–diopside cotectic line to the bulk composition *a*. Similarly, partial melting of *b* starts with formation of a plagioclase–diopside eutectic melt at *y*. When plagioclase is exhausted, melting of diopside moves the composition of the melt along the thermal divide to *b*, where fusion is complete.

Partial melting of *c* begins by formation of a melt containing diopside, tridymite and plagioclase in proportions corresponding to the ternary eutectic *z*. Tridymite is the first component to enter completely the melt, and the composition of the melt then changes along the plagioclase–diopside cotectic line. After the plagioclase has all been extracted into the melt, fusion becomes complete by melting of diopside as the composition moves from the plagioclase–diopside cotectic line to the bulk composition *c*.

These answers assume that the temperature is sufficiently high for complete partial melting to be achieved. If not, partial melting will stop somewhere along the cotectic curve and the remaining crystals will stay in equilibrium with the melt until a change in temperature takes place.

(c) A melt composition to the right of the diopside–albite thermal divide *cannot under any crystallization conditions* give rise to a solid containing nepheline, or a 'rock' composed of nepheline+diopside+plagioclase in the proportions represented by ternary eutectic *x*. Similarly a melt composition lying to the left of the diopside–albite thermal divide cannot give rise to a solid containing, or a 'rock' composed of, tridymite+diopside+plagioclase. The conclusions emphasize the comment after SAQ 11 in the text, that melts with similar over-all compositions (i.e., between *a* and *c* on Fig. VII–10) might crystallize under equilibrium conditions to solids with contrasting mineralogies. Similarly, under conditions of *fractional crystallization*, the 'rocks' produced contrast in chemical composition and mineralogy (cf, *x* and *z* in Fig. VII–10).

In summary: under equilibrium crystallization, the total product is a crystal mixture corresponding to the bulk composition (i.e., *a, b* or *c*). Under fractional crystallization conditions, the final product is a crystal mixture of *either* composition *x* (of the melt started on the left of the Di–Ab thermal divide) *or z* 3(if the melt started on the right of the Di–Ab thermal divide). Earlier stages of crystal fractionation will have removed first diopside, then diopside + plagioclase from the melt as a result of crystal settling (cf. S2–2, Unit 4; S237, Block 3).

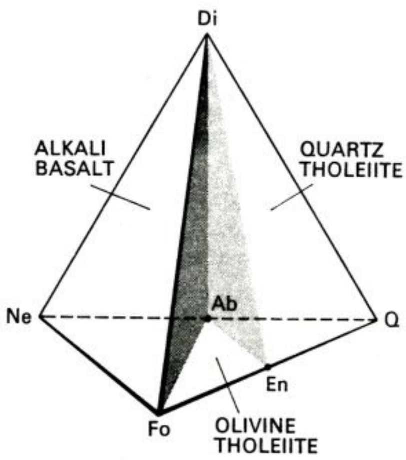

Figure VII–15 Diagram showing the answer to SAQ 13.

Because of these relationships, the existence of thermal divides and their relation to magma composition is of vital importants in geochemistry.

SAQ 13 The answer is shown in Figure VII–15.

SAQ 14 Figure VII–9 shows that thermal divides occur between intermediate compounds within a more complex system. They may, therefore, be present along the two shaded planes in Figure VII–15, which include intermediate compounds (enstatite and albite) within the basalt tetrahedron.

SAQ 15 Both will be alkali basalts, but the one that rose rapidly to the surface will be more similar to the primary melt, and Na_2O and K_2O contents will be lower (e.g. say 3.0 and 1.5 per cent, respectively). The slowly ascending magma will become enriched in incompatible elements, and this would show in the high K_2O and Na_2O content, each of, say, 3.0 per cent. Tristan da Cunha in the South Atlantic is a good example of this highly potassic basalt produced (probably) by the slow rise of alkali basalt magma.

You should note from Figure VII–12 that an alkali basalt magma (Ne–normative) cannot fractionate olivine and become tholeiitic (Ol+Hy, or Q+Hy normative), no matter how thermal divides change during its ascent. Removal of olivine will merely drive an alkali basalt towards the Ne corner.

SAQ 16 1 and 3 are factors which cause a basalt to be more alkaline, whereas 2 would result in a more tholeiitic character. If you are uncertain about these, look back at the main text (pp. 88–9).

SAQ 17 Crystal fractionation of Ne-normative alkali basalt should lead to the production of Ne-normative (undersaturated) magma, whereas fractionation of Q-normative tholeiitic basalt should lead to the production of Q-normative (oversaturated) magma. If you are uncertain about this, look back at the main text (p. 87) and the answer to SAQ 12.

SAQ 18

A (2)
B (3)
C (1)
D (2)
E (3)
F (1)

Further reading

Carmichael, I. S. E., Turner, F. J. and Verhoogen, J. (1974) *Igneous Petrology*, McGraw-Hill.

Wyllie, P. J. (1971) *The Dynamic Earth*, Wiley.

References

Kuno, H. (1968) Differentiation of basalt magmas. In Hess, H. H. and Poldervaart, A. (eds) *Basalts: The Poldervaart Treatise on Rocks of Basaltic Composition*, **2,** 623–88, Wiley.

Larsen, E. S. (1938) Some new variation diagrams for groups of igneous rocks, *J. Geol.*, **46,** 505–20.

Nockolds, S. R. and Allen R. (1953) The geochemistry of some igneous rock series, *Geochim. Cosmochim. Acta*, **4,** 105–42.

Simpson, E. S. W. (1954) The Okonjeje igneous complex, South West Africa, *Trans. geol. Soc. S. Afr.*, **58,** 125–72.

Thompson, R. N., Esson, J. and Dunham, A. C. (1972) Major element chemical variation in the Eocene lavas of the Isle of Skye, Scotland. *J. Petrology*, **13,** 219–53.

Thornton, C. P. and Tuttle, O. F. (1960) Chemistry of igneous rocks I. Differentiation index, *Am. J. Sci.*, **258,** 664–84.