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Petrology of the igneous rocks of the Moffat District, Southern Uplands, Scotland

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Petrology of the igneous rocks of the Moffat District, Southern Uplands, Scotland

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) as part of their regional geological mapping programme. It describes the petrology of a suite igneous rocks from the Moffat District, Scotland. The work forms part of a multidisciplinary Southern Uplands Project.

Contents

PLATES

Plate 1. (a) and (b) Altered metabasalt which possess a weakly developed pilotaxitic fabric and amygdales composed of carbonate (Sample S3698; plane and crossed polarised light; objective x 2.5). (c) and (d) Medium- to coarse-grained metagabbro containing ophitic clinopyroxene (Sample S3704; plane and crossed polarised light; objective x 2.5). Scale bar = 1.0 mm.

Plate 2. (a) and (b) Coarse-grained metagabbro containing ophitic clinopyroxene (Sample S3697; plane and crossed polarised light; objective x 2.5). (c) and (d) Very fine-grained microdiorite or andesite containing fine-grained granular clinopyroxene (Sample S35248; plane and crossed polarised light; objective x 2.5). Scale bar = 1.0 mm.

Plate 3. (a) and (b) Medium- to coarse-grained amphibole-bearing lamprophyre (spessartite) (Sample S3997; plane and crossed polarised light; objective x 2.5). (c) and (d) Fine-grained tholeiitic basalt (Sample S3711; plane and crossed polarised light; objective x 2.5). Scale bar = 1.0 mm.

Summary

This report describes the mineralogy and petrology of the various igneous rocks exposed in the Moffat District (Sheet 16) of the Southern Uplands of Scotland as part of a British Geological Survey's research programme. These include Ordovician metabasalts and metagabbroic rocks, Silurian to Lower Devonian andesitic to rhyolitic high level intrusions as well as the Carboniferous tholeiitic quartz-dolerite and basalt dykes. A total of 23 thin sections of volcanic and intrusive igneous rock were examined during this study with the work forming part of the Integrated Geological Survey (North), Southern Uplands Regional Mapping Programme.

1 Introduction

This report describes the mineralogy and petrology of the various igneous rocks exposed in the Moffat District (Sheet 16) of the Southern Uplands of Scotland. These include Ordovician metabasalts and metagabbroic rocks, Silurian to Lower Devonian andesitic to rhyolitic high level intrusions as well as the Carboniferous tholeiitic quartz-dolerite and basalt dykes. A total of 23 thin sections of volcanic and intrusive igneous rock were examined during this study with the work forming part of the Integrated Geological Survey (North), Southern Uplands Regional Mapping Programme.

The rocks were classified using the classification system and nomenclature of Le Maitre (1989), following the recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks, and the British Geological Survey classification scheme for igneous rocks.

2 Thin Section Descriptions

2.1 ORDOVICIAN METABASALTIC ROCKS

The geology of the Southern Uplands is variously interpreted in terms of either a fore-arc accretionary prism model (McKerrow *et al*. 1977; Leggett *et al*. 1979), or back-arc basin to fore-land thrust model (Murphy & Hutton 1986; Stone *et al*. 1987). The basaltic volcanic rocks present within the Northern Belt (Lambert *et al*. 1981) occur either within the Moffat Shale Group, the underlying Crawford Group, or in the lower part of the overlying turbidite sequence, and have previously been interpreted as tectonically-included slivers of the original substrate to the sedimentary succession (Leggett *et al*. 1979; Stone *et al*. 1987). In the back-arc basin model, any volcanic substrate to the Moffat Shale Group could represent oceanic crust flooring an extensional basin near the leading margin of the over-riding plate. Recent geochemical studies (Phillips *et al*. 1995; Barnes *et al*. 1996) have demonstrated that the Ordovician basic volcanic rocks do not have a simple single source and in fact comprise a mixed assemblage of tholeiitic and alkaline within-plate basalts, mid-ocean ridge basalts (MORB) and volcanic-arc to transitional basalts. This complex association of basaltic volcanic rocks is difficult to reconcile with either a simple fore-arc or back-arc setting for the Southern Uplands.

Recent geochemical studies (Phillips *et al*. 1995; Barnes *et al*. 1996) have shown that the restricted volumes of basic volcanic material present within the Northern Belt of the Southern Uplands do not have a simple single source. The oldest (Arenig) volcanic rocks from the Moffat Shale Group associated with the Leadhills Fault include alkaline within-plate basalts and tholeiitic basalts which display geochemical characteristics of mid-ocean ridge basalts (MORB). In the northernmost occurrence, the alkaline and tholeiitic basalts of the Caradoc (*gracilis* Biozone) Marchburn association are entirely of within-plate ocean island (tholeiitic and alkaline) affinity. Phillips *et al*. 1999 have demonstrated that the alkaline within-plate basalts, trachybasalts and trachyandesites of the Bail Hill Volcanic Group are geochemically distinct from the within-plate basaltic volcanic rocks of the Leadhills and Marchburn associations. To the south, in the Gabsnout Burn area, the Moffat Shale Group (Caradoc; *gracilis-clingani* biozones) contains allochthonous lenticular bodies (rafts or olistoliths) of dolerite and basalt which have the characteristics of island-arc to transitional basalts (Phillips *et al*. 1995; Barnes *et al*. 1996).

Further evidence of oceanic within-plate volcanism during the Ordovician (Mid-Caradoc) is provided by the peralkaline rhyolites (pantellerite) of the Tweeddale lavas (Thirlwall 1981).

2.1.1 Metabasalt

In thin section (S3698; S3705) the metabasalts are fine- to very fine-grained, highly altered, massive to weakly pilotaxitic, originally hypocrystalline, aphyric to very weakly microporphyritic rocks (Plate 1a & b) which are composed of an inequigranular assemblage of plagioclase, chlorite, carbonate and sericite. Minor to accessory phases present include opaque minerals and quartz.

These metabasalts are mainly composed of randomly orientated to weakly shape aligned plagioclase laths which define a variably developed pilotaxitic fabric (Plate 1a & b). Plagioclase forms anhedral, twinned and untwinned, lath-shaped crystals (≤ 0.3 mm in length) which are variably altered to and locally pseudomorphed by sericite and carbonate. In sample S3702 the shape alignment of plagioclase laths defines a crude/open lattice or mesh-like fabric. Rare carbonate pseudomorphs after plagioclase microphenocrysts were also noted in sample S3698. Interstitial to intersertal phases, which probably originally included glass, have been completely replaced by a very fine-grained to cryptocrystalline assemblage dominated by pale green chlorite. Chlorite possesses a distinctive anomalous blue birefringence colour and is locally partially replaced by later carbonate. Chloritic pseudomorphs after rod-like intergranular pyroxene crystals have been recorded in some rocks.

Irregular vugs or amygdales present in sample S3698 are composed of polycrystalline, coarse-grained carbonate. These carbonate crystals are strained and possess curved twin and cleavage planes as well as a pronounced sweeping extinction. The metabasalts are also cut by a number of irregular veinlets of chlorite and carbonate, with carbonate replacing the earlier formed chlorite. Trace amounts of quartz has also been recorded within these veinlets. Mineralisation of the veins was accompanied by minor shearing which resulted in the development of a sigmoidal to curved fabric within the larger veinlets defined by acicular chlorite crystals.

2.1.2 Metagabbroic rocks

In thin section (S3710; S3704; S3701; S3700; S3699; S3697) the metagabbros are in general medium- to coarse-grained, massive, aphyric, highly altered rocks which comprise an inequigranular assemblage of clinopyroxene, plagioclase and opaque minerals (Plates 1c, 1d, 2a & 2b). The primary mineral assemblage is variably replaced by a fine-grained assemblage of Mg-chlorite, serpentine, sericite/white mica, clay minerals, carbonate, bowlingite as well as, in some rocks quartz and prehnite/pumpellyite. Primary opaque minerals may show alteration to secondary titanite and/or leucoxene.

Although altered the original igneous texture of these metagabbroic rocks (S3704) can still be recognised (Plates 1c, 1d, 2a & 2b). Plagioclase forms an open framework with intergranular clinopyroxene. The remaining interstitial to intersertal areas are filled by secondary chlorite and/or serpentine. In the most altered rocks primary plagioclase has largely been replaced by a turbid, grey-brown (under plane polarised light) assemblage of clay minerals, sericite and, in some cases, chlorite. However, minor to trace amounts of relict, possibly albitic, plagioclase may be present. Plagioclase originally formed anhedral to weakly subhedral, twinned and zoned, prismatic to lath shaped crystals. The twinned and locally zoned nature of the plagioclase laths is preserved by the mimetic growth of the alteration products. In the least altered rocks (S3701) the zoned plagioclase crystals exhibit preferential alteration of their cores.

In contrast to the plagioclase, pale brown to brown clinopyroxene is, in general, fresh and forms rounded to subhedral, fractured crystals (Plates 1c, 1d, 2a & 2b) which possess variably developed planar crystal faces. In some samples pyroxene is very weakly pleochroic. Large (up to *c*. 4.0 mm in size) clinopyroxene crystals are locally ophitic to sub-ophitic in nature (S3704;

S3697) and may possess a weakly developed zonation. In some rocks intracrystalline deformation of pyroxene resulted in the development of a variably developed undulose to sweeping extinction. In samples S3699 and S3700, clinopyroxene possesses a distinctive pinky-brown body colour indicative of Ti-augite. The presence of possible T-augite within the mineral assemblage suggests that these metamorphosed basic igneous rocks may have included alkaline gabbroic rocks.

In some samples (S3710) olivine may have formed a minor component of the original mineral assemblage. Olivine, where present, is pseudomorphed by cryptocrystalline to mesh-textured assemblage of Mg-chlorite and/or serpentine. Opaque minerals form anhedral granular to skeletal crystals which are locally rimmed by secondary titanite. In some samples (S3699) opaque minerals were observed forming rims upon and developed along fractures within earlier formed pyroxene. Samples S3701 and S3699 also contain radiating fans of dusty looking (under plane polarised light) prehnite or pumpellyite.

The finer grained metagabbroic rocks (S3700) may contain rounded to irregular amygdales composed of very fine-grained to cryptocrystalline chlorite, bowlingite and/or carbonate. The metagabbros are locally cut by thin veinlets of very fine-grained to cryptocrystalline quartz (S3704).

2.1.3 Tuffaceous rocks

In thin section (S1990) the tuffaceous rocks include a medium- to coarse-grained, deformed, altered, basaltic lapilli-tuff which is mainly composed of fragments of a fine- to very fine-grained highly altered volcanic rock. These lithic fragments are angular to irregular in shape and set within an originally ashy matrix. There is no evidence of rounding of the lithic fragments indicating that there has been very little, if any, reworking of this volcaniclastic material in the sedimentary environment. Consequently, this thin section is thought to be taken from a primary pyroclastic deposit.

The rock fragments are compositionally similar to the matrix and are broadly basaltic in composition. In detail these rock fragments are typically aphyric to rarely finely microporphyritic and appear to have been originally glassy in nature. The primary mineral assemblage has been altered to a cryptocrystalline assemblage of chlorite, sericite and dusty looking opaque oxides. A number of the lithic fragments are composed of an amygdaloidal altered pumiceous or scoraceous material.

No obvious welding or parataxitic fabrics have been recognised within this lapilli-tuff. A variably developed pressure solution cleavage present within the matrix of the tuff is defined by thin seams of opaque oxides. A similar tectonic foliation is also developed within the altered lithic clasts where it is defined by aligned, very fine-grained sericitic white mica. The development of this foliation probably accompanied the flattening/collapse of these highly altered, unstable rock fragments.

2.1.4 Volcanic breccia

A thin section (S62170) of a very coarse-grained, immature, matrix-poor volcanic breccia has been examined during this present study. This lithic-rich rock is mainly composed of lapilli sized, angular to irregular basaltic rock fragments, in particular a very fine-grained plagioclase porphyritic basalt which possess a well developed amygdaloidal texture. Chlorite and opaque pseudomorphs after rare pyroxene phenocrysts have been noted within the basalt rock fragments.

The lithic fragments are compositionally similar and are, therefore, considered to have been derived from the same source. Furthermore, these lapilli sized rock fragments are petrographically similar in appearance to the previously described metabasalts (see Section 2.1.1). The angular to irregular nature of these rock fragments also indicates that this volcanic

detritus have undergone very little reworking in a sedimentary environment. Consequently, this breccia may represent a primary pyroclastic rock.

The matrix to the breccia is composed of a pale green chloritic material containing angular (broken) fragments of hematised basalt and plagioclase crystals. Broken fragments of carbonate filled amygdales are also present, indicating that carbonate infilling of these structures occurred early during the alteration of the basalt prior to incorporation within this breccia. The finer grained lithic fragments within the matrix component of the breccia are compositionally distinct from the larger rock fragments and have undergone locally intense hematisation.

2.1.5 Plagioclase porphyritic basalt

One thin section (S3703) of a fine- to very fine-grained, plagioclase porphyritic basalt or metabasalt has bee examined from the Moffat District. This microporphyritic, feldspathic basaltic rock is composed of an inequigranular assemblage dominated by plagioclase with minor to accessory opaque minerals. Alteration and/or low grade metamorphism of this rock resulted in the development of a secondary assemblage dominated by chlorite, carbonate, quartz and serpentine.

The phenocrysts are composed of anhedral to weakly subhedral, equant to lath-shaped plagioclase. Plagioclase occurs as both twinned (simple) and untwinned crystals, and ranges up to 1.3 mm in length. The groundmass is mainly composed of fine-grained, randomly orientated plagioclase laths set within a turbid, dusty looking (under plane polarised light) mesostasis. The remainder of the interstitial to intersertal areas are filled by cryptocrystalline chloritic material.

This basalt is cut by a number of irregular veinlets composed of cryptocrystalline quartz and/or carbonate.

2.2 CALEDONIAN MINOR INTRUSIONS

Dykes exposed in the Moffat district form part of the Southern Uplands regional swarm of Caledonian (Siluro-Devonian) minor intrusions (Barnes *et al*. 1986; Rock *et al*. 1986; Rock *et al*. 1988). This suite of minor intrusions includes a varied group of generally porphyritic andesites/microdiorites, dacites/microgranodiorites and rhyolites/microgranites, originally called the “porphyrite-porphyry” series by Greig (1971). Also present are representatives of the calc-alkaline lamprophyres, hornblende-bearing spessartites and mica-bearing kersantites (Rock 1984). No age dates are available from the Leadhills district. However, radiometric age determinations obtained for the lamprophyre dykes in the Kirkcudbright district are in the range 395-418 Ma (Rb-Sr whole-rock ages and K-Ar biotite and hornblende mineral ages) (Rock *et al*. 1986; Rock *et al*. 1988).

2.2.1 Leucodioritic rock

One thin section (S72015) of a highly altered apparently leucodioritic to possibly microgranitic rock was examined from the Moffat District. This fine-grained, massive, recrystallised/altered aphyric to weakly microporphyritic rock is composed of an inequigranular assemblage of plagioclase, sericite, carbonate, muscovite and quartz. Trace amounts of an opaque mineral are also present. The rock appears to have originally been mainly composed of plagioclase with minor amounts of intergranular feldspar and quartz. Two textural varieties of feldspar have been recognised within this highly altered rock: (1) twinned, anhedral lath-shaped crystals; and (2) anhedral, irregular recrystallised crystals which lack any obvious twinning. Recrystallisation and alteration have largely overprinted the original igneous texture of the rock. However, occasional poorly preserved plagioclase phenocrysts are also present. Feldspar is variably altered to and pseudomorphed by sericite and minor amounts of carbonate. Carbonate was also noted preferentially replacing the original interstitial to intersertal phases within this leucodioritic rock.

Minor to trace amounts of muscovite are also present. Muscovite forms small, anhedral to irregular flakes. Occasional cubes of late pyrite are also present.

2.2.2 Plagioclase-porphyritic andesitic rock

In thin section (S3712) this andesite is a fine-grained, weakly microporphyritic to macroporphyritic leucocratic to possibly dacitic rock which comprises an inequigranular assemblage dominated by plagioclase with minor to trace amounts of opaque minerals and quartz. Accessory rod to needle shaped apatite crystals are also present. Alteration resulted in the development of a fine-grained assemblage of chlorite, carbonate, sericite, clay minerals, biotite and possible epidote.

The rock is mainly composed of anhedral to very weakly subhedral, twinned and zoned plagioclase laths which possess a dusty appearance under plane polarised light. Plagioclase exhibits varying degrees of alteration to very fine-grained to cryptocrystalline white mica/sericite and clay minerals. Plagioclase laths are randomly orientated to locally shape aligned defining a very weakly developed pilotaxitic fabric. Phenocrysts are typically composed of small (≤ 0.5 mm in length) plagioclase laths, however, rare 3.0 to 3.5 mm long microphenocrysts are also present.

Quartz is intergranular/interstitial to plagioclase and appears to form part of the primary mineral assemblage. Occasional chloritic pseudomorphs after biotite and/or amphibole are also present. The remaining interstitial to intersertal phases have been replaced by very fine-grained to cryptocrystalline chlorite.

2.2.3 Pyroxene-bearing microdiorite

In thin section (S38211; S35248; S17555) these melanocratic microdiorites are fine- to very fine-grained, holocrystalline, massive, aphyric to weakly microporphyritic rocks (Plate 2c & d) which are composed of inequigranular assemblage of plagioclase, clinopyroxene, biotite, quartz and orthopyroxene. Minor to accessory phases present include opaque minerals, K-feldspar and apatite. Alteration resulted in the development of a secondary assemblage comprising chlorite, epidote, carbonate and sericite.

The microdiorites are mainly composed of randomly orientated plagioclase laths and fine-grained, granular aggregates of clinopyroxene and some orthopyroxene. Plagioclase forms anhedral, twinned and zoned, equant to lath-shaped crystals. Plagioclase was also noted forming small (≤ 1.0 mm long) twinned and zoned microphenocrysts. Pyroxene is colourless to very pale brown and forms anhedral granular crystals. Orthopyroxene is distinguished from the dominant clinopyroxene by its straight extinction and slightly lower order birefringence colours. Rare pyroxene microphenocrysts were recorded in sample S35248.

Interstitial to intersertal areas are filled by feldspar (plagioclase and minor K-feldspar), quartz and trace amounts of very fine-grained myrmekite/micrographic intergrowth. Interstitial felsitic phases possess a distinctive dusty appearance under plane polarised light. Myrmekite locally forms irregular rims upon earlier formed plagioclase laths and is in optical continuity with the host feldspar.

Minor to trace amounts of biotite are also present within these diorites. Biotite forms anhedral to irregular flakes which may be locally altered to, or pseudomorphed by chlorite. Biotite occurs intergranular to both plagioclase and pyroxene. Traces of secondary carbonate were noted associated with the chloritic alteration. Sample S35248 also contains trace amounts of a dusty pink-brown coloured (under plane polarised light) mesostasis forming a late interstitial to intersertal phase. This sample also contains rounded xenoliths of a very fine-grained basaltic rock which is mainly composed of granular looking pyroxene. These xenoliths appear to be compositionally similar to the host microdiorite.

Although typically massive in nature a weakly developed pilotaxitic fabric defined by shape aligned plagioclase laths (*c*. 0.3 to 0.4 mm in length) has been noted in sample S17555.

2.2.4 Altered diorite

One thin section (S71949) of a highly altered, fine- to medium-grained, massive, originally holocrystalline, diorite was examined from the Moffat District. It is composed of an inequigranular assemblage of plagioclase, sericite, carbonate, chlorite and quartz. Minor to accessory phases present include opaque minerals, apatite and clay minerals.

This diorite was originally mainly composed of a framework of plagioclase and amphibole. The latter is completely pseudomorphed by a fine- to very fine-grained assemblage of chlorite, opaque oxides and turbid brown clay minerals. Amphibole originally formed anhedral to subhedral, equant to lozenge-shaped crystals. Plagioclase is variably altered to or locally pseudomorphed by sericite and carbonate. However, relict plagioclase is present. Interstitial phases include quartz, feldspar and myrmekite. An intergranular ferromagnesian mineral, probably biotite, has been completely replaced by very pale green, possibly Mg-rich, chlorite. Chlorite (± quartz) was also noted forming pseudomorphs after 0.5 to 1.0 mm long phenocrysts of amphibole and/or pyroxene.

2.2.5 Feldspar microporphyritic dacite or rhyodacite

In thin section (S3707) these very fine-grained, originally glassy (now devitrified), altered dacitic to rhyolitic rocks are composed of an inequigranular assemblage of plagioclase, K-feldspar and quartz. Alteration of these acidic rocks resulted in the development of a very fine-grained to cryptocrystalline assemblage of sericite/clay minerals, chlorite and carbonate.

The phenocrysts are mainly composed of K-feldspar with minor to subordinate plagioclase microphenocrysts. These occurs as glomerophyric clusters of several anhedral to subhedral crystals which locally appear to have been broken/cataclased. Both feldspar exhibit a dusty appearance under plane polarised light due to the variable alteration to sericite and/or clay minerals. Plagioclase is distinguished from K-feldspar by the presence of well developed multiple lamellae twins.

The groundmass is composed of a dusty brown coloured (under plane polarised light), cryptocrystalline felsitic mosaic which contains rounded ‘spots’ of quartz and feldspar. The groundmass may also locally contain microlites and small laths of feldspar. Traces of pale green chlorite present within the groundmass may represent pseudomorphs after biotite.

2.2.6 Hornblende lamprophyre (spessartite)

In thin section (S3997) the hornblende lamprophyres (spessartite) are fine- to medium-grained, holocrystalline, aphyric rocks which are composed of an inequigranular assemblage of plagioclase, amphibole, quartz and K-feldspar (Plate 3a & b). Minor to accessory phases present include opaque minerals and apatite. Alteration of this primary assemblage resulted in the variable development of chlorite, sericite, clay minerals and carbonate. Primary opaque minerals also exhibit alteration to secondary titanite and leucoxene.

These lamprophyres are mainly composed of a framework of plagioclase and hornblende with interstitial quartz. Amphibole is red-brown in colour and forms anhedral to subhedral, fractured, equant to lozenge shaped crystals which exhibit minor alteration to chlorite. Plagioclase is the dominant feldspar, occurring intergranular to, and locally partially enclosing amphibole. Plagioclase forms anhedral to weakly subhedral, zoned and twinned crystals which locally exhibit preferential alteration of their cores to sericite and/or clay minerals.

Interstitial to intersertal areas are mainly composed of unstrained to weakly strained quartz and feldspar (including K-feldspar). K-feldspar is untwinned and possesses a slightly shadowy

extinction. The remaining interstitial areas are filled by cryptocrystalline very pale green chlorite and traces of carbonate; the latter appears to be replacing the earlier formed chlorite. Minor biotite is typically altered to or pseudomorphed by chlorite.

2.2.7 Biotite lamprophyre (minette)

In thin section (S1991) the biotite lamprophyres (minette) are very fine-grained, hypocrystalline to holocrystalline, massive to weakly pilotaxitic, highly altered, microporphyritic rocks which are composed of an inequigranular assemblage of feldspar, biotite and quartz with minor opaque minerals. Alteration of these lamprophyric rocks resulted in the development of a secondary assemblage dominated by chlorite, sericite and carbonate.

Biotite forms small (≤ 0.4 mm in length), elongate to acicular, shape aligned flakes and microphenocrysts which define a patchily developed pilotaxitic fabric. Occasional microphenocrysts of feldspar are also present. The bulk of the rock is composed of a very fine-grained feldspathic assemblage which is variably altered to a turbid brown coloured (under plane polarised light), cryptocrystalline aggregate of sericite and carbonate. This alteration and the slightly thick nature of the thin section locally obscures/overprints the primary igneous texture of the rock.

Pseudomorphs after amphibole and/or pyroxene microphenocrysts were noted and are composed of very fine-grained chlorite, carbonate, quartz and opaque oxide.

2.3 TERTIARY MINOR INTRUSIONS

Tholeiitic dolerite and basalt dykes within the Moffat District form part of a northwest to southeast-trending regional swarm of Tertiary high-level minor intrusions which occur throughout western and central Scotland (see Cameron & Stephenson 1985).

2.3.1 Tholeiitic basalt

One thin section (S3711) of a tholeiitic basalt has been examined during this study. This fine-grained, hypocrystalline, aphyric to very weakly microporphyritic basalt (Plate 3c & d) is composed of an inequigranular assemblage of plagioclase, clinopyroxene and orthopyroxene with minor to trace amounts of opaque minerals and quartz. Alteration of these primary minerals phases resulted in the development of minor amounts of secondary chlorite and carbonate.

The rock is mainly composed of radiating to randomly orientated plagioclase laths with intergranular pyroxene; the latter including minor amounts of orthopyroxene. Plagioclase forms twinned and zoned, elongate to needle-like lath-shaped crystals which exhibit very little secondary alteration. Occasional small (≤ 0.6 mm long) zoned plagioclase microphenocrysts are present. These phenocrysts possess a distinctive rounded core indicating an early phase of plagioclase crystallisation followed by partial resorption resulting in the rounding of early formed crystals. Plagioclase laths forms a open crystal framework composed of randomly orientated to locally radiating (spherulitic) aggregates of crystals. The interstitial to intersertal areas are filled by a dusty grey-brown mesostasis which is replacing primary glass. The mesostasis also contains granular to rod shaped crystals of an opaque mineral.

Colourless, high relief pyroxene forms rounded to irregular anhedral crystals which may locally surround/enclose earlier formed plagioclase. Orthopyroxene is distinguished from the spatially related clinopyroxene by is straight extinction and slightly lower order birefringence colours. Both pyroxenes occur intergranular to plagioclase with occasional larger (≤ 0.35 mm in size) pyroxene crystals being weakly ophitic to sub-ophitic in nature. Traces of intergranular plagioclase and rare free quartz have also been noted within this tholeiitic basalt.

Glossary

Alkali – A prefix given to rocks which contain either: (a) modal feldspathoids and/or alkali amphibole or pyroxenes; or (b) normative feldspathoids or acmite.

Alkali basalt – Term originally used for basalts containing accessory feldspathoids. These rocks typically contain a Ti-augite and olivine as their main ferromagnesian phases. Now defined geochemically using the Total Alkali-Silica diagram as a variety of basalt.

Alkali gabbro – A variety of gabbro which is alkaline in character due to the presence of analcime or nepheline and ferromagnesian phases such as barkevikite, kaersutite and/or Ti-augite.

Andesite – An intermediate volcanic rock, usually porphyritic, consisting of plagioclase (frequently zoned from labradorite to oligoclase), pyroxene, hornblende and/or biotite. Now defined modally on a Quartz-Alkali feldspar-Plagioclase-Feldspathoid diagram or geochemically using the Total Alkali-Silica diagram.

Basalt – A volcanic rock consisting essentially of calcic plagioclase and pyroxene. Olivine and minor feldspathoids may also be present. Now defined modally on a Quartz-Alkali feldspar-Plagioclase-Feldspathoid diagram or geochemically using the Total Alkali-Silica diagram.

Basaltic andesite – A volcanic rock with plagioclase compositions expected for andesites but containing ferromagnesian minerals more commonly found in basalts. Now defined geochemically using the Total Alkali-Silica diagram.

Benmoreite – Defined geochemically as the sodic variety of trachyandesite using the Total Alkali-Silica diagram.

Camptonite – A variety of lamprophyre composed of phenocrysts of combination of olivine, kaersutite, Ti-augite and Ti-biotite in a matrix of the same minerals (except olivine) with plagioclase and sometimes subordinate alkali feldspar and feldspathoids.

Crinanite – A variety of olivine-analcime dolerite or gabbro composed of olivine, Ti-augite and labradorite with minor analcime. Although it has less analcime and more olivine than teschenite the two names have been used interchangeably.

Dacite – A volcanic rock composed of quartz and sodic plagioclase with minor amounts of biotite and/or hornblende and/or pyroxene. Now defined modally on a Quartz-Alkali feldspar-Plagioclase-Feldspathoid diagram or geochemically using the Total Alkali-Silica diagram.

Dolerite – A rock of intermediate grain size between a basalt and gabbro (i.e. synonym for *microgabbro*), and composed of essentially plagioclase, pyroxene and opaque minerals. Often contains an ophitic texture. If olivine is present may be called an olivine-dolerite; if quartz, a quartz-dolerite.

Felsite – A rock term initially used for the microcrystalline groundmass of porphyries. Now commonly used for microcrystalline rocks of granitic composition (i.e. dacite to rhyolite).

Hawaiite – Defined geochemically as the sodic variety of trachybasalt using the Total Alkali-Silica diagram.

Kersantite – A variety of lamprophyre consisting of phenocrysts of Mg-biotite, with or without hornblende, olivine or pyroxene in a groundmass of the same minerals plus plagioclase and occasionally alkali feldspar.

Olivine-basalt – A commonly used term for a basalt containing olivine as an essential constituent.

Quartz-dolerite – A variety of *microgabbro* (dolerite) composed mainly of plagioclase and pyroxenes with interstitial quartz. The rock has tholeiitic affinities and its pyroxenes are usually sub-calcic augite accompanied by pigeonite or orthopyroxene.

Teschenite – A variety of analcime gabbro consisting of olivine, Ti-augite, labradorite and analcime.

Essexite – a variety of nepheline monzogabbro or nepheline monzodiorite containing Ti-augite, kaersutite and/or biotite with labradorite, lesser alkali feldspar and nepheline.

Tholeiitic basalt – Commonly used term for a variety of basalt composed of labradorite, augite, hypersthene or pigeonite with olivine (often showing reaction relationship) or quartz, and often with interstitial glass.

Trachyandesite – A term originally used for volcanic rocks intermediate in composition between trachyte and andesite and containing equal amounts of alkali feldspar and plagioclase. Later used for volcanic rocks containing feldspathoids as well as alkali feldspar and plagioclase. Now defined geochemically using the Total Alkali-Silica diagram.

Trachybasalt – Term mainly used for basaltic volcanic rocks containing labradorite and alkali feldspar. Now defined geochemically using the Total Alkali-Silica diagram.

Minette – Term used for a variety of lamprophyre consisting of phenocrysts of phlogopite-biotite and occasionally amphibole in a groundmass of the same minerals plus orthoclase and minor plagioclase. Mg-olivine and diopsidic pyroxene may also be present.

Spessartite – Term used for a variety of lamprophyre consisting of phenocrysts of hornblende with or without biotite, olivine or pyroxene in a groundmass of the same minerals plus plagioclase and minor K-feldspar.

Trachyte – A volcanic rock consisting essentially of alkali feldspar. Now defined modally on a Quartz-Alkali feldspar-Plagioclase-Feldspathoid ternary diagram or geochemically using the Total Alkali-Silica diagram.

Crystallinity – (a) *holocrystalline*, an igneous rock composed of 100% crystals; (b) *holohyaline*, an igneous rock composed of 100% glass; and (c) *hypocrystalline*, intermediate between the two end-members and can be described more precisely by stating the relative proportions of crystals and glass.

Microcrystalline – crystals can be identified with a petrological microscope. Crystals only just large enough to show polarisation colours (< 0.01 mm in size) are called *microlites*.

Cryptocrystalline – crystals are too small to be identified even with the petrological microscope.

Grain size – (a) coarse-grained, crystals > 5.0 mm in size; (b) medium-grained, crystals 1.0 to 5.0 mm in size; (c) fine-grained, crystals < 1.0 mm in size.

Equigranular – all crystals are approximately the same size.

Inequigranular – crystals of substantially different grain size. Common variety, porphyritic texture, can be subdivided into: (a) *microporphyritic*, phenocrysts ≤ 2.0 mm in size; and (b) *macroporphyritic*, phenocrysts > 2.0 mm in size.

Seriate texture – continuous range in crystal size of principal minerals.

Trachytic texture – sub-parallel alignment of microcrystalline feldspar in the groundmass of a *holocrystalline* or *hypocrystalline* rocks. Sub-divided into pilotaxitic texture and *hyalopilitic* texture depending on whether the material between the feldspar is crystalline or glassy. *Trachytoid* texture, alignment of tabular, bladed or prismatic crystals which is visible to the naked eye. The terms *flow* and *fluxion* texture are sometimes used as synonyms for trachytic and trachytoid textures. However, they are best avoided due to their genetic implications.

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Plates

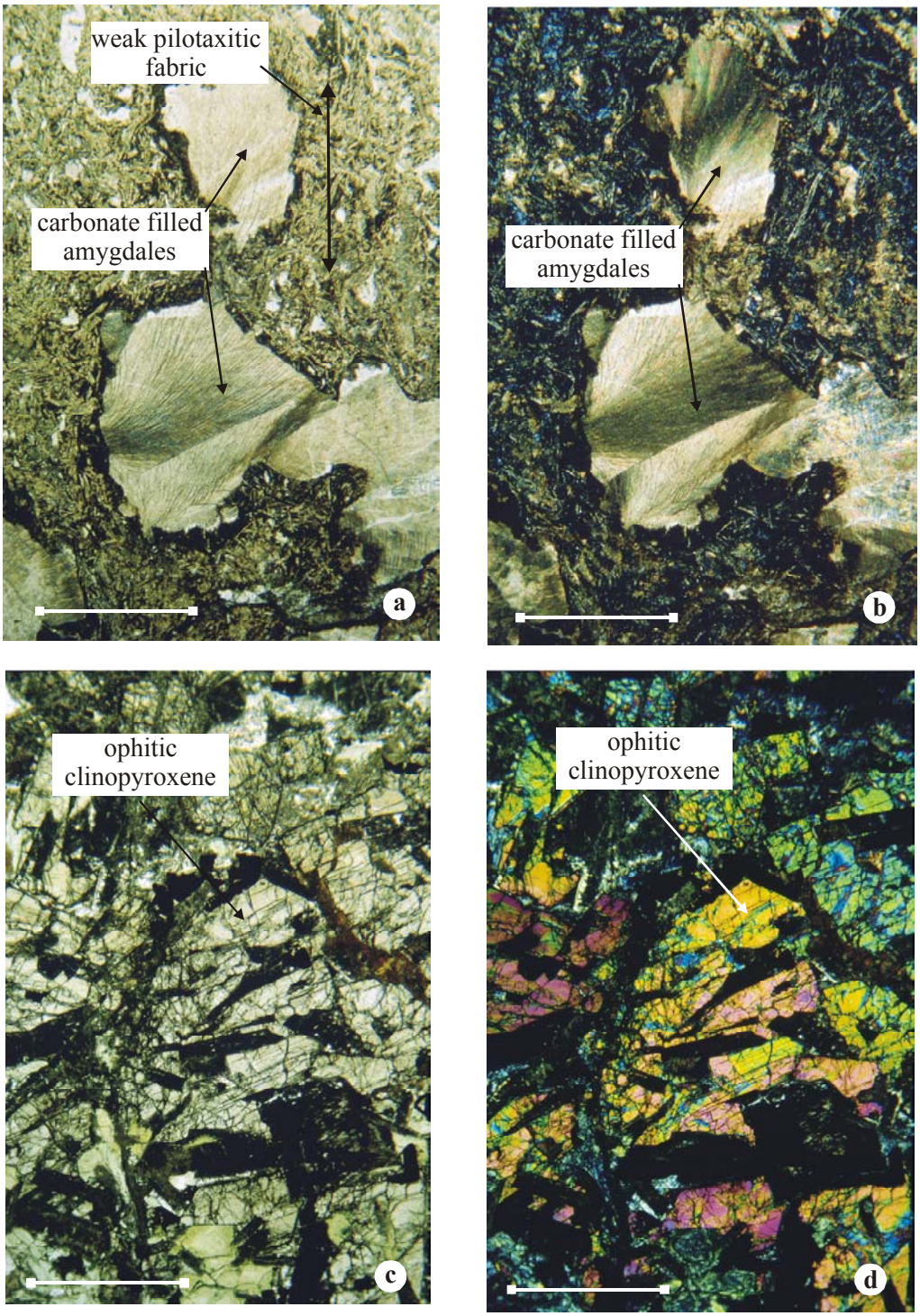

Plate 1. (a) and (b) Altered metabasalt which possess a weakly developed pilotaxitic fabric and amygdales composed of carbonate (Sample S3698; plane and crossed polarised light; objective x 2.5). (c) and (d) Medium- to coarse-grained metagabbro containing ophitic clinopyroxene (Sample S3704; plane and crossed polarised light; objective x 2.5). Scale bar = 1.0 mm.

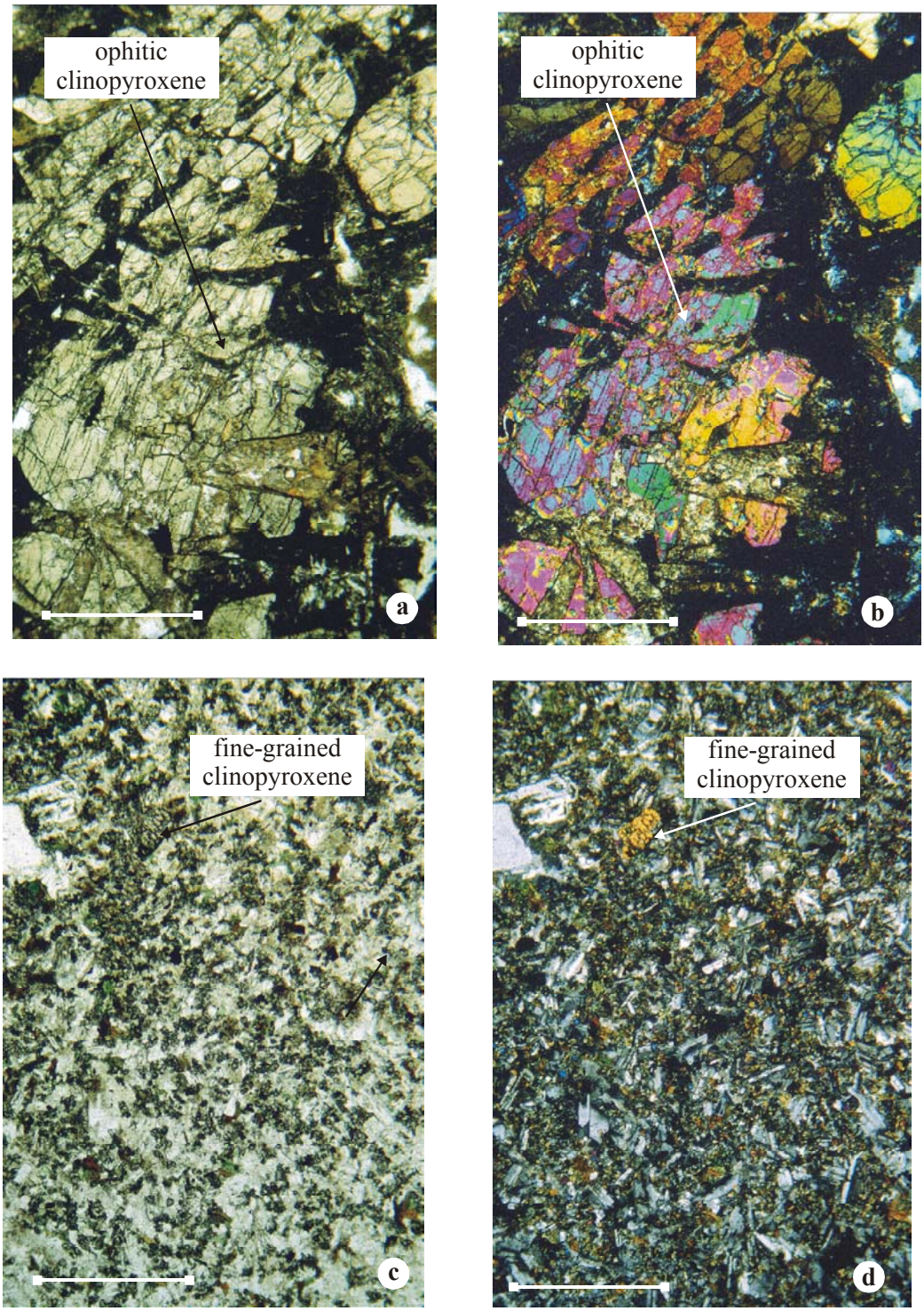

Plate 2. (a) and (b) Coarse-grained metagabbro containing ophitic clinopyroxene (Sample S3697; plane and crossed polarised light; objective x 2.5). (c) and (d) Very fine-grained microdiorite or andesite containing fine-grained granular clinopyroxene (Sample S35248; plane and crossed polarised light; objective x 2.5). Scale bar = 1.0 mm.

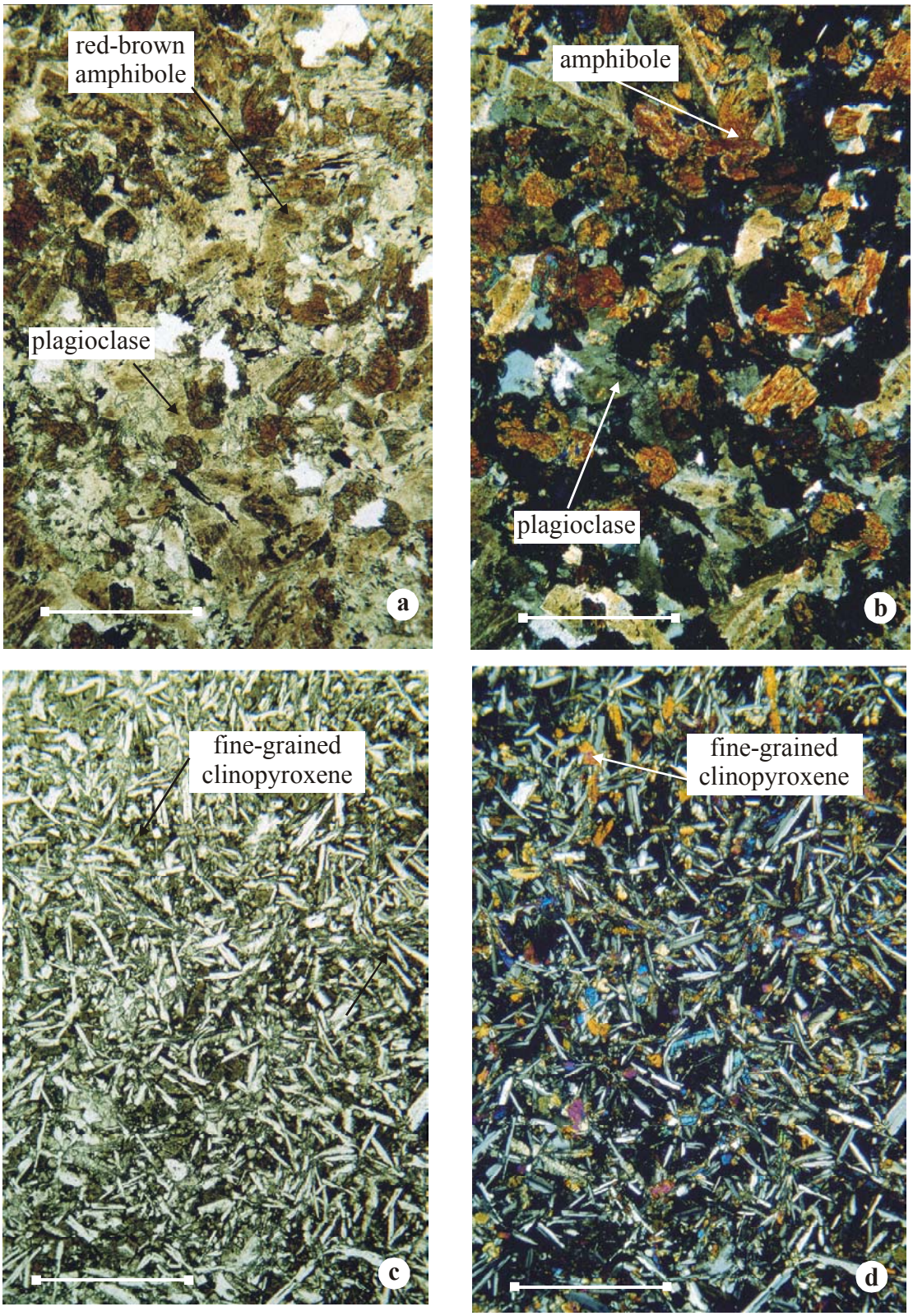

Plate 3. (a) and (b) Medium- to coarse-grained amphibole-bearing lamprophyre (spessartite) (Sample S3997; plane and crossed polarised light; objective x 2.5). (c) and (d) Fine-grained tholeiitic basalt (Sample S3711; plane and crossed polarised light; objective x 2.5). Scale bar = 1.0 mm.