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Petrology of the sedimentary and igneous rocks from the Strathmore district (Sheet 57), Scotland

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Petrology of the sedimentary and igneous rocks from the Strathmore district (Sheet 57), Scotland

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) on the regional geology of the Midland Valley of Scotland. It is part of the Science Budget funded programme which forms part of the core programme of BGS. This core programme is designed to undertake a multidisciplinary geological survey to meet user and strategic needs for geological information.

Contents

Summary

This report describes the mineralogy and petrology of a suite of basaltic to andesitic volcanic rocks and sedimentary rocks as part of the regional mapping of the Strathmore district (Sheet 57).

1 Introduction

This report describes the mineralogy and petrology of a suite of basaltic to andesitic volcanic rocks and sandstones, microconglomerates and associated sedimentary rocks of the Strathmore district (sheet 57). A total of 108 thin sections have been examined with the work forming part of a multidisciplinary project being undertaken by the British Geological Survey to examine the evolution of the Midland Valley of Scotland. This work forms part of the British Geological Survey's Integrated Geological Survey (North) programme.

2 Petrology

2.1 MONTROSE VOLCANIC FORMATION

2.1.1 Olivine-clinopyroxene phyric basalt

In thin section these basalts are typically fine-grained, anhedral granular, holocrystalline to hypocrystalline, micro- to macroporphyritic rocks (S335; S3787; S54048; S54049; S54046; S54045; S54053; S54056; S54104; S54108; S53566; S57011; S37081; S22139; S54109; S3780). They comprise an inequigranular mineral assemblage dominated by plagioclase, clinopyroxene and olivine (Plate 1) with minor to accessory opaque minerals and apatite. Phenocrysts within the basalts range up to 3.5 mm in size (typically ≤ 2.0 mm in size) and are composed of olivine (Plate 1a and b) and clinopyroxene with variable amounts of plagioclase (Plate 1c and d). These phenocrysts may exhibit a preferred shape alignment parallel to a pilotaxitic fabric locally developed within the groundmass.

Olivine forms small anhedral to subhedral microphenocrysts that are variably altered to, or pseudomorphed by mesh textured chlorite, serpentine, bowlingite and iddingsite (Plate 1a and b). The pseudomorphs after olivine are typically enclosed within a rim of opaque oxides, with thin veinlets of opaque minerals also preserving fractures within the pre-existing relict olivine. These pseudomorphs after olivine are variably replaced by later carbonate. Fresh or relict olivine is present in some samples (S3787). Olivine typically occurs as single isolated phenocrysts, however glomerophyric clusters of several smaller olivine crystals have been recorded in some samples (S54053). Clinopyroxene phenocrysts are typically finer grained and occur both as single microphenocrysts and clusters of several granular crystals. Pyroxene is pale brown to colourless and may exhibit variable alteration to chlorite. Anhedral to subhedral clinopyroxene crystals are, in general, untwinned, however, occasional simply twinned crystals are present in some rocks. Plagioclase phenocrysts, where present (S54048; S54053; S53566; S57011; S3781) are anhedral to subhedral in shape (≤ 3.0 mm) and form zoned crystals which may contain very fine-grained inclusions of pyroxene and/or chloritised glass. In sample S57011 the plagioclase phenocrysts include broken much larger crystals.

The fine-grained groundmass to the basalt is mainly composed of plagioclase with variable amounts of clinopyroxene, olivine, opaque minerals and, in some samples, rare orthopyroxene. Plagioclase forms anhedral to weakly subhedral, twinned (multiple and simple), lath-shaped to prismatic crystals which may exhibit a gradational to oscillatory zonation. In the more altered lithologies plagioclase is variably replaced or pseudomorphed by a very fine-grained turbid assemblage of white mica, clay minerals, chlorite and carbonate. In some samples (S335; S3787), plagioclase laths are aligned and define a moderate to well-developed pilotaxitic fabric (Plate 1a). This variably developed primary igneous foliation wraps around the larger phenocrysts. Clinopyroxene and opaque minerals occur intergranular to plagioclase with the remaining interstitial to intersertal areas being filled by late crystallising feldspar and variably altered (chloritised) glass. In sample S54053 intergranular clinopyroxene within the groundmass is locally subophitic (Plate 1c and d); partially enclosing finer grained plagioclase laths. In the groundmass pyroxene forms anhedral granular to elongate rod-shaped prismatic crystals. Traces of secondary pale brown to orange-brown biotite are present in sample S54053.

2.1.2 Medium- to coarse-grained basalt and basaltic andesite

In thin section these medium- to coarse-grained basalts (S50981; S50981a; S51203; S54042; S54043; S54044; S54054; S54051; S57010; S54052; S54107; S54114; S49199; S54047) and basaltic andesites (S34832; S49200; S54504) are massive to foliated, holocrystalline to hypocrystalline, aphyric to porphyritic, anhedral granular rocks comprising an inequigranular assemblage of plagioclase, clinopyroxene and olivine (Plate 2). Minor to accessory phases present include opaque minerals, orthopyroxene, biotite and rare quartz. The primary igneous mineralogy is variably altered to a fine- to very fine-grained assemblage of chlorite, Fe-oxide, biotite, amphibole, bowlingite, white mica, carbonate and serpentine. In thin section the basalts appear to grade into the slightly more feldspathic basaltic andesites. The latter being distinguished by the presence of more andesitic plagioclase feldspar, with pseudomorphs after olivine occurring within some basalts.

Phenocrysts, where present, are composed of plagioclase, clinopyroxene and variably altered olivine (Plate 2). Plagioclase phenocrysts are anhedral to subhedral in shape with the larger crystals being oscillatory zoned. These zoned crystals may show preferential alteration of their cores. Plagioclase occurs as single isolate phenocrysts as well as glomerophyric clusters of several smaller crystals. In sample S54043 olivine (typically < 1.0 mm, but occasional crystals up to 2.5 mm) has been completely replaced by carbonate and opaque oxides. However, the originally rounded to embayed nature of these microphenocrysts has been preserved by the mimetic growth of the alteration products. The preservation of these textures indicates the partial resorption of these earlier formed olivine crystals.

Plagioclase is the dominant mineral phase within the groundmass and forms anhedral, twinned (simple and multiple) crystals. A variably developed pilotaxitic fabric is defined by the preferred shape alignment of plagioclase. Radiating aggregates of elongate plagioclase laths were noted in samples S54043. Colourless to very pale brown clinopyroxene is intergranular to plagioclase and forms granular anhedral crystals. In some rocks (S54042) the clinopyroxene is subophitic (Plate 2c and d). Orthopyroxene is a very minor phase within these basalts and basaltic andesites, and is distinguished from clinopyroxene by its straight extinction. In the most intensely altered rocks (S54047) all the primary igneous ferromagnesian minerals have been replaced by a very fine-grained chloritic assemblage. Traces of biotite have been noted in some samples (S50981; S54504). The remaining interstitial to intersertal areas are filled by late crystallising plagioclase and altered glass; the latter having been replaced by chlorite or a very fine mesostasis. A small number of the basalt samples (S54109) are weakly amygdaloidal with the locally zoned amygdales being filled by either quartz or very fine-grained to cryptocrystalline chlorite.

2.1.3 Olivine microgabbro

One thin section (S3778) of a coarse-grained, anhedral granular, holocrystalline olivine microgabbro (Plate 3a and b) was examined from the Strathmore area. It comprises an inequigranular assemblage of plagioclase, Ti-augite and olivine with minor to accessory opaque minerals and apatite. This primary igneous mineral assemblage is variably altered to a fine—to very fine-grained assemblage of chlorite, iddingsite, opaque oxides, bowlingite, serpentine, biotite and carbonate. This olivine microgabbro possesses a moderate to well-developed pilotaxitic fabric defined by the preferred shape alignment of plagioclase laths. Plagioclase is the dominant mineral phase and forms anhedral, twinned, lath-shaped to prismatic crystals.

Relict to locally fresh olivine is variably replaced by a very fine-grained mesh textured assemblage of chlorite, bowlingite and serpentine. Clinopyroxene is intergranular to both plagioclase and olivine. The pale pink to brown Ti-rich augite is locally ophitic to subophitic enclosing the finer grained plagioclase laths. Traces of a dusty looking (in plane polarised light) to turbid mesostasis was noted replacing interstitial to intersertal glass. This mesostasis is itself being replaced by secondary carbonate.

2.1.4 Andesite and basaltic andesite

In thin section (S49197; S51205; S54054; S54055; S54105; S54106; S54118; S3779; S3786; S641; S3782; S49201) the andesites and basaltic andesites are highly altered, fine- to medium-grained, hypocrystalline, feldspathic, microporphyritic to macroporphyritic rocks (Plate 3c and d) which are composed of an inequigranular assemblage of plagioclase, clinopyroxene and orthopyroxene with minor to trace opaque minerals. Alteration of these feldspathic rocks resulted in the development of a very fine-grained assemblage of opaque oxide, chlorite, sericitic white mica, carbonate, iddingsite and bowlingite.

Plagioclase phenocrysts (Plate 3c and d) occur within a fine-grained to originally glassy groundmass which may possess a variably developed pilotaxitic to hyalopilitic fabric. This fabric is defined by shape aligned plagioclase laths and microlites. In sample S54118 a well developed pilotaxitic fabric is deformed by a set of narrow shear bands resulting in a SC-like fabric geometry. Plagioclase forms anhedral, twinned (simple and multiple) and occasionally zoned (gradational and oscillatory) crystals. Plagioclase phenocrysts occur as single isolated crystals as well as occasionally glomerophyric clusters of several crystals. In samples S54055, S3779 and S54106 plagioclase phenocrysts are larger ranging up to 3.5 to 4.0 mm in length. These larger phenocrysts locally contain very fine-grained rounded inclusions of chloritised glass and/or pyroxene.

In the more altered feldspathic rocks the original ferromagnesian minerals (probably pyroxene) are only a minor component and are typically pseudomorphed by a very fine-grained chloritic assemblage. In the less altered samples recognisable clinopyroxene and, in some cases, orthopyroxene occur within the groundmass forming anhedral granular looking crystals which are intergranular to plagioclase. Small clinopyroxene crystals were also noted partially enclosed within the slightly coarser grained plagioclase. Both pyroxenes are very pale brown to colourless, with orthopyroxene being distinguished by its straight extinction. Clinopyroxene was also noted forming anhedral to weakly subhedral microphenocrysts within some of the andesitic rocks (S54055; S54105). Interstitial to intersertal glass has been devitrified and is variably replaced by a turbid, dusty grey to brown looking (in plane polarised light) mesostasis. In some rocks this mesostasis contains disseminated, very fine grained granular looking opaque minerals. In samples S3786 and S3782 the mesostasis is replaced by fine-grained hematitic oxide.

A number of the samples (S51205; S54054) are weakly amygdaloidal with the vesicles and vugs filled by zoned fine to very fine-grained quartz and chlorite. Sample S54054 is cut by an irregular fracture which is filled by fine-grained siltstone. This fracture appears to follow the margin of an earlier formed quartz veinlet.

2.1.5 Pilotaxitic basaltic and andesitic rocks

Also present within the Montrose Volcanic Formation are a suite of aphyric, fine- to very fine-grained basaltic and andesitic rocks (S559; S57015; S53565; S34746; S560; S3745) which are characterised by the presence of very well developed pilotaxitic fabric. This fabric is defined by very closely packed or stacked plagioclase laths and microlites which result in a felted texture. In sample S57015 the pilotaxitic fabric is deformed by a set of narrow shear bands resulting in an SC-like fabric geometry. These feldspathic rocks are composed of an inequigranular assemblage of plagioclase with minor to accessory opaque minerals, apatite and biotite. Apatite was noted forming small subhedral to euhedral crystals which are occasionally pale purple in colour.

2.1.6 Carbonate replaced basaltic or andesitic rock

One thin section (S49198) of a highly altered basaltic or possibly andesitic rock which has been replaced by a very fine-grained aggregate of granular carbonate. The resultant carbonate-dominated rock is massive with the relict outlines of feldspar laths only locally preserving the original igneous texture.

2.1.7 Highly altered andesitic or microdioritic rock

A small number of thin sections (S815; S816) of a highly altered, medium- to coarse-grained, weakly feldspar phyric andesitic or microdioritic rock have been examined. These rocks are mainly composed of dusty pinky brown (in plane polarised light) plagioclase with minor to accessory opaque minerals, apatite and quartz. The extensive alteration of these feldspathic rocks resulted in the development of a fine-grained assemblage of chlorite, bowlingite, sericitic white mica and carbonate. Feldspar is twinned and originally zoned with localised preferential alteration of the cores of these zoned crystals. Plagioclase forms a relatively open framework between which the interstitial to intersertal areas are mainly filled by yellow-green chlorite/bowlingite. Plagioclase was also noted forming anhedral to subhedral, lath-shaped phenocrysts. Occasional chloritic pseudomorphs after a ferromagnesian mineral (probably pyroxene or amphibole) may be present. Traces of interstitial quartz are also present. However, due to the highly altered nature of these rocks it is uncertain if quartz represents a primary igneous phase or is related to very minor secondary silicification.

2.1.8 Volcaniclastic or pyroclastic rocks

A small number of thin sections (S3784; S53227; S3785) of altered volcaniclastic or pyroclastic rocks have been described from the Strathmore area. Sample S3784 is of a highly altered lapilli tuff which is mainly composed of angular lithic clasts and subordinate crystal fragments. These clasts range from ash to lapilli-grade in size. The composition of the original protolith is uncertain due to the degree of alteration. The original matrix and lithic clasts have been replaced by a very fine-grained to cryptocrystalline felsic mosaic. Although highly altered the ghost outlines of relict fragments can still be recognised. A weakly developed or preserved eutaxitic fabric can still be recognised.

Sample S53227 is of a highly altered volcaniclastic breccia which contains highly irregular clasts of a hematised basaltic rock. These lithic fragments possess complex, highly serrated or indented grain boundaries. The complexity of these grain boundaries is indicative of a very limited or no transport in a sedimentary environment. The matrix is composed of a fine-grained, massive to poorly laminated siltstone which locally forms geopetal-like infills of some intergranular voids. The basaltic rock which dominates the clast assemblage was an originally very fine-grained, plagioclase phyric rock with locally developed pilotaxitic, amygdaloidal or vesicular textures. The vesicles are partially filled by siltstone. It is possible that this breccia represents the scoraceous top to a basaltic lava flow in which the pore spaces have been filled by silt.

Sample S3785 is similar to the previously described thin section and is of a highly altered volcaniclastic breccia composed of hematised basaltic rock fragments in a fine mudstone to siltstone matrix.

2.1.9 Ophimottled basalt

In thin section (S57012; S57102; S51204) these fine-grained, inequigranular, microporphyritic to macroporphyritic basalts are characterised by the presence of ophitic clinopyroxene within the groundmass. These basalts are mainly composed of an inequigranular assemblage of plagioclase and clinopyroxene with minor to accessory opaque minerals and apatite. Alteration of this primary igneous mineral assemblage resulted in the development of chlorite, opaque oxides, bowlingite and biotite. Phenocrysts are composed of anhedral to subhedral plagioclase laths which range up to 2.0mm in size. Plagioclase forms zoned and twinned, occasionally broken crystals which are locally rounded or embayed due to partial resorption.

The groundmass is mainly composed of plagioclase with minor intergranular ophitic pale brown clinopyroxene. These ophitic clinopyroxene crystals are up to 1 mm in size and give the rock a distinctive ophimottled appearance. A well-developed pilotaxitic fabric present within the groundmass is defined by the preferred shape alignment of plagioclase laths. This fabric may wrap around the larger plagioclase phenocrysts. The crystallisation of clinopyroxene and the development of the distinctive ophimottled textured within these basalts clearly post dated the formation of the pilotaxitic fabric. The remaining interstitial to intersertal areas are filled by green to yellow-green chlorite ± green biotite. Chloritic pseudomorphs after possible olivine were noted in the groundmass of sample S51204. Traces of very fine-grained fibrous prehnite have been recorded in sample S51204.

2.2 CATTERLINE CONGLOMERATE FORMATION

2.2.1 Matrix-rich wacke sandstone

One thin section (S53649) of a fine- to medium-grained, poorly sorted, weakly compacted, immature, matrix-rich sandstone was examined from the Catterline Conglomerate Formation. This matrix-rich wacke sandstone possesses a very open-packed matrix-supported texture. No obvious primary porosity has been recognised in thin section. Clasts are angular to subangular in shape with a low sphericity. These elongate clasts exhibit a weakly developed preferred shape alignment; probably parallel to the original bedding. The clast assemblage is dominated by monocrystalline quartz with subordinate amounts of sericitised feldspar and polycrystalline quartz. Quartzose clasts exhibit minor grain boundary etching. Other minor to accessory detrital components present include muscovite, altered biotite, sericitised granitic rock fragments, opaque minerals, apatite, plagioclase, chlorite and tourmaline. Detrital micas are a common minor component within this sandstone and are locally kinked/bent, with the later probably occurring during compaction. The matrix to the sandstone is composed of a red-brown coloured (in plane polarised light) clayey silt. Traces of secondary carbonate have been recorded replacing this matrix component.

2.2.2 Quartzose litharenite

A small number of thin sections (S52631; S52732) of a quartzose litharenite have been examined from the Catterline Conglomerate Formation. In thin section they are fine- to coarse-grained, immature, matrix-poor, quartzose lithic-rich rocks which possess a very closely packed, clast-supported texture. Clasts are angular to subangular in shape with a low sphericity. However, clast shape has been modified due to pressure solution during compaction. This resulted in the main mode of cementation within these matrix-poor sandstones. Compaction also resulted in the kinking of detrital micas and localised plastic deformation of unstable lithic clasts.

The clast assemblage is dominated by volcanic rock fragments, monocrystalline quartz and subordinate amounts of plagioclase. The volcanic lithic clasts are mainly composed of a very fine-grained, aphyric possibly originally glassy andesitic to dacitic rock. Other recognisable lithologies present include a hornblende-bearing granitic rock, very fine-grained sandstone or siltstone, phyllitic or schistose biotite-bearing metasedimentary rock, siltstone and mudstone intraclasts and possible serpentinite. Other minor to accessory detrital components present within these sandstones include polycrystalline quartz, muscovite, biotite, hematised/oxidised biotite, chlorite, garnet, opaque minerals, hematised rock, sericitised rock or feldspar and microcline perthite.

No obvious cement or matrix components, or primary porosity have been recognised within these sandstones. In thin section these litharenites are massive with no obvious grading or other sedimentary structures. Sample S52732 is very highly altered with silicification largely overprinting the original texture of the sandstone.

2.2.3 Volcaniclastic microconglomerate

In thin section (S58526; S58525; S54112) the volcaniclastic microconglomerates of the Catterline Conglomerate Formation are poorly to very poorly sorted, coarse-grained, immature, lithic-rich, moderately to closely packed, clast-supported rocks (Plate 4a and b). Angular to subangular, low sphericity clasts are mainly composed of very fine-grained, originally glassy andesitic to dacitic volcanic or high level intrusive igneous rocks. These volcanic rocks include plagioclase microporphyritic andesite, pilotaxitic to hyalopilitic andesitic or dacitic rock, plagioclase-pyroxene-phyric andesitic or basaltic rock, plagioclase-biotite-phyric dacite, olivine basalt. Other lithic components present within these conglomeratic rocks include fine-grained quartzose lithic sandstone, sericitised biotite granitic rock, psammite, biotite-muscovite-schistose rock, chloritised micaceous psammite, meta-quartz-arenite, polycrystalline carbonate/limestone, biotite micaceous psammite, vein quartz, sericitic metasandstone, very fine-grained quartzose sandstone, siltstone and felsite. The sandstone rock fragments tend to be more rounded in shape than the volcanic lithic clasts. A number of the sedimentary lithic clasts also appear to represent broken fragments of much larger pebbles indicating that the sedimentary lithic component may be polycyclic in nature. Metasedimentary rock fragments are a common minor component within sample S58525. These metamorphic rock fragments are typically more rounded than the volcanic rock fragments.

Compaction resulted in localised pressure solution and plastic deformation of unstable detrital components leading to the modification of the original shape of clastic grains. The fine-grained siltstone to sandstone matrix of the microconglomerates contains angular low sphericity clasts of monocrystalline quartz, volcanic rock fragments and plagioclase. The matrix component is lithologically similar to the sandstone of sample S53649. Detrital biotite flakes are a common minor component within the matrix. Other minor to accessory detrital components present within the matrix to the microconglomerates include monocrystalline quartz, polycrystalline biotite, polycrystalline quartz, plagioclase, biotite, chlorite, muscovite/white mica and opaque minerals. A weakly developed pressure solution cleavage or compaction fabric is present within the matrix of sample S58526. Traces of secondary carbonate were recorded replacing the matrix and/or unstable detrital grains. In sample S54112 the matrix component is absent and pressure solution resulted in the main mode of cementation within this microconglomerate. A weak preferred alignment of the elongate clasts was noted in sample S58525.

2.3 AUCHMITHIE CONGLOMERATE MEMBER

2.3.1 Sandstone

A sample (S50879) of a sandstone interbedded with the conglomerates of the Auchmithie Conglomerate Member has been examined during this study. In thin section it is a fine-grained, closely packed, poorly sorted, lithic rock with a clast-supported texture. The close packing of this sandstone means that there is very little or no primary intergranular porosity. Clasts are angular to occasionally subangular in shape with a low sphericity. The clast assemblage within this relatively quartzose litharenite is dominated by monocrystalline quartz and cherty or felsitic rock fragments. Other minor to accessory detrital components include muscovite, biotite, opaque minerals, polycrystalline quartz, K-feldspar, plagioclase, chloritised biotite and staurolite. Localised etching of the grain boundaries of quartzose clasts and traces of a red-brown coloured hematitic clay cement have been noted within this sandstone.

2.3.2 Clasts within the conglomerates

A number of thin sections of clasts from the Auchmithie Conglomerate Member have been examined. These clasts are composed of porphyritic rhyolite (S53351; S53350; S53348) and an altered granitic rock (S53349).

Sample S53351 is of a fine- to very fine-grained, originally glassy (devitrified) feldspar-quartz-biotite-phyric rhyolite. Feldspar phenocrysts are variably altered to sericitic white mica and chlorite. Small phenocrysts of biotite are variably replaced or pseudomorphed by a turbid, brown coloured (in plane polarised light) very fine-grained assemblage of chlorite and opaque oxides. Quartz phenocrysts are rounded to embayed due to partial resorption and include broken fragments of larger crystals. The originally glassy groundmass to this rhyolitic rock has distinctive dusty appearance (in plane polarised light) and is variably replaced by a very fine-grained to cryptocrystalline felsitic mosaic. Snowflake devitrification textures are locally developed within the groundmass.

Sample S 53350 is of a weakly metamorphosed feldspar-quartz-biotite-phyric rhyolite containing small muscovite poikiloblasts within the recrystallised groundmass. The groundmass to this rhyolite has been replaced by a very fine-grained, granular looking quartzofeldspathic mosaic.

Sample S53348 is of a ignimbritic rhyolite containing locally broken feldspar and quartz macrophenocrysts. A well-developed parataxitic fabric is present within the glassy, variably devitrified matrix of this rock. This foliation wraps around the plagioclase, K-feldspar (perthitic) and quartz phenocrysts, and is locally overprinted by later snowflake devitrification textures. The quartz phenocrysts are rounded in shape, indicative of partial resorption.

2.4 TRAPPEAN CONGLOMERATE, SCONE SANDSTONE FORMATION

A number of thin sections of clasts from the Trappean conglomerate of the Scone Sandstone Formation have been examined. These clasts are composed of a very fine-grained, altered, originally glassy plagioclase-amphibole porphyritic andesitic rock (S338; S336). Phenocrysts are mainly composed of anhedral, locally broken plagioclase laths. Anhedral to subhedral microphenocrysts of amphibole are variably replaced or pseudomorphed by opaque oxide. The very fine-grained originally glassy groundmass exhibits a dusty appearance under plane polarised light due to the presence of finely disseminated opaque minerals. Traces of secondary, replacive carbonate were noted.

2.5 CROMLIX MUDSTONE FORMATION

In thin section (S34395; S54115; S54131; S54124) the silty mudstones, siltstones and fine-grained silty sandstones of the Cromlix Mudstone Formation (Strathmore Group) are typically fine-grained, massive to laminated rocks with a distinctive red-brown colour (under plane polarised light). All of these lithologies exhibit some replacement of the clay grade material by fine- to very fine-grained granular-looking carbonate.

The mudstones (S34395) contain angular, low sphericity fine to coarse silt grade clasts which are mainly composed of monocrystalline quartz. Other recognisable accessory detrital components include plagioclase, muscovite/white mica, opaque minerals, variably chloritised biotite and chlorite. The slightly coarser grained siltstones (S54115; S54124) contain a similar range of detrital components to the mudstones. In sample S54124 detrital micas (muscovite, biotite) are a common minor component and show a preferred shape alignment parallel to a wispy looking sedimentary lamination. In sample S54115 this lamination is highly disrupted, possibly due to liquefaction and soft sediment deformation.

In thin section the fine-grained sandstones (S54131) from the Cromlix Mudstone Formation are poorly sorted, clast to locally matrix supported rocks with a dark red-brown hematitic clay matrix or cement. Angular, low sphericity fine sand to silt grade clasts are mainly composed of monocrystalline quartz with subordinate amounts of polycrystalline quartz and plagioclase. Other minor to accessory detrital components include muscovite, microcline, very fine-grained rock fragments, carbonate, garnet, biotite, metasedimentary rock fragments and opaque minerals. The sandstones are massive with no obvious grading or other sedimentary structures.

2.6 TEITH SANDSTONE FORMATION

In thin section (S54121; S54120; S54119) the sandstones from the Teith Sandstone Formation (Strathmore Group) are fine- to coarse-grained, moderately to poorly sorted, immature, matrix-poor, quartzofeldspathic rocks which possess a closely packed clast-supported texture. The close packing of these sandstones results in very little or no primary intergranular porosity. Clastic grains are angular to subangular in shape with a low sphericity. Rare rounded to subrounded clasts have also been noted. However, the clast shape has been variably modified as a result of pressure solution during compaction.

The mixed clast assemblage is dominated by monocrystalline quartz and feldspar (plagioclase, K-feldspar, perthite) with subordinate amounts of polycrystalline quartz. Minor to accessory detrital components include opaque minerals, muscovite/white mica, chlorite, felsitic rock fragments, biotite, fibrolite-bearing metasedimentary rock, metasandstone, garnet, staurolite, apatite and rutile. Detrital micas are locally kinked due to compaction and may exhibit a preferred shape alignment, possibly parallel to bedding.

Pressure solution resulted in the main mode of cementation in the majority of these sandstones (S54121; S54120), although varying amounts of a later replacive carbonate cement have been recorded in some rocks (S54120; S54119). Sample S54119 is of a calcareous, fine-grained sandstone in which a well developed carbonate cement appears to be replacing the original matrix component and/or unstable detrital grains (e.g. lithic clasts). Traces of an early hematitic (S54121; S54119) and quartz (S54120) rim cements have been noted in some samples.

2.7 GLENVALE SANDSTONE FORMATION

The sandstones (S50878; S34547; S52151; S52141) of the Glenvale Sandstone Formation (Stratheden Group) are fine- to medium-grained, immature, poorly sorted, massive, calcareous rocks with a closely packed, clast supported to open packed, cement-supported texture (Plate 4c and d). Clastic grains are typically angular to subangular in shape with a low sphericity. However, rare subrounded grains were recorded in some samples (S50878). The development of the calcareous cement within these sandstones has resulted in the localised modification of grain shape. The clast assemblage is dominated by monocrystalline quartz with variable amounts of plagioclase and felsitic or cherty volcanic rock fragments. Other minor to accessory detrital components include plagioclase, polycrystalline quartz, muscovite, microcline, biotite, opaque minerals, micrographic intergrowth, a very fine-grained metasedimentary rock, devitrified glassy volcanic rock, sericitic slaty rock, tourmaline and zircon. Sample S50878 is characterised by rounded, elongate to irregular mudstone or fine siltstone sedimentary intraclasts.

Compaction resulted in localised pressure solution of quartzose clasts and kinking of detrital micas. The presence of a well developed replacive carbonate cement (Plate 4c and d) is a distinctive feature of the sandstones of the Glenvale Sandstone Formation. In sample S34547 the carbonate cement forms approximately 60% of the total rock. This cement appears to replace the original matrix component within the sandstone as well as unstable detrital clasts, such as rock fragments. The development of this replacive cement locally results in the etching of the grain boundaries of the quartzose clasts. The cement is composed of fine- to medium-grained, sparry carbonate with crystals up to *c*. 0.7 mm in size. The larger carbonate crystals may enclose finer grained clasts which, in some samples where the carbonate cement is well-developed, may lead to the development of an open packed cement supported texture (S34547; S52141). Traces of an early hematitic rim cement have been noted in sample S52151.

2.8 SCONE SANDSTONE FORMATION

The sandstones (S50863; S50864; S50865; S50863; S54123; S54129; S54117; S54122; S54128; S50877) of the Scone Sandstone Formation are typically fine- to medium-grained, moderately to closely packed, immature, poorly to moderately sorted, matrix-poor rocks with a clast-supported texture (Plate 5a and b). Very little or no primary porosity has been recognised within these quartzose to slightly feldspathic litharenites. Clastic grains are angular to subangular in shape with a low to moderate sphericity. However, subrounded grains are present in some samples (S50863).

The mixed clast assemblage is mainly composed of monocrystalline quartz, plagioclase feldspar and variably altered rock fragments (Plate 5a and b). The lithic clasts are mainly composed of a very fine-grained to cryptocrystalline andesitic to dacitic volcanic/igneous rock. Metamorphic rock fragments may also be present including very fine-grained, slaty or schistose metasedimentary rock, biotite-muscovite schist and possible psammite. Other detrital components include K-feldspar, microcline, felsite, cherty rock, polycrystalline quartz, hematised rock, garnet, muscovite, opaque minerals, tourmaline, biotite, chlorite, perthite, epidote, staurolite and sericitised rock. A weakly developed preferred shape alignment of elongate clasts and/or detrital phyllosilicates (muscovite, biotite, chlorite) has been recognised in some sandstones (S54129; S54117).

Compaction resulted in the kinking of detrital micas and was accompanied by the localised pressure solution of more quartzose grains. Pressure solution forms the main mode of cementation within the sandstones of the Scone Sandstone Formation. However, traces of a cryptocrystalline quartz and hematitic rim cements have been noted in some samples (S50864). A replacive carbonate cement is present in some rocks (S54123; S54129; S54128; S50877). The carbonate is locally stained by Fe-oxide, possibly recording the presence of an earlier hematitic clay cement or matrix, or alternatively that the carbonate cement originally included ferroan dolomite.

2.9 PITTENDRIECH LIMESTONE

A small number of samples (S54130; S54116; S34548) from the Pittendriech Limestone have been examined. In thin section this silty to sandy limestone is fine- to very fine-grained, massive rock containing scattered silt- to sand-grade clasts of mainly monocrystalline quartz (Plate 5c and d). Other detrital components present include biotite, muscovite, opaque minerals, chlorite, plagioclase, microcline, very fine-grained turbid possible volcanic rock, quartz-feldspar-phyric rhyolite and rare staurolite. Detrital grains are angular to subangular in shape with a low sphericity. A weakly developed preferred shape alignment of detrital micas was recognised in some samples (S54130). The bulk of the limestone is composed of fine- to very fine-grained, slightly dusty looking (in plane polarised light) granular carbonate (Plate 5c and d). Irregular patches or veinlets of slightly coarser grained carbonate are present in some samples.

2.10 DUNDEE FLAGS FORMATION

2.10.1 Quartzose litharenites

The sandstones (S52340; S55728; S53562) of the Dundee Flags Formation are typically fine- to medium-grained, immature, lithic-rich, matrix-poor, quartzose litharenites with a close to very closely packed, clast-supported texture. Very little or no primary intergranular porosity has been recorded in these sandstones. Clastic grains are angular to subangular in shape with a low sphericity. The clast assemblage is dominated by rock fragments and monocrystalline quartz with variable amounts of plagioclase. The lithic clasts are mainly composed of a very fine-grained, possibly originally glassy dacitic to rhyolitic volcanic rock. These acidic volcanic rocks may possess a well developed pilotaxitic fabric and locally preserved microporphyritic texture. Other minor to accessory detrital components present include polycrystalline quartz, biotite, garnet, chlorite, opaque minerals, apatite, muscovite, hematised rock or biotite, staurolite, microcline, epidote, sericitised rock, very fine-grained sedimentary rock, very fine-grained micaceous schistose rock, rutile and chloritised metabasaltic rock. The metamorphic rock fragments, where present, are typically more rounded in shape indicative of a more prolonged period of transport in a sedimentary environment.

Pressure solution during compaction resulted in the main mode of cementation within the sandstones of the Dundee Flags Formation. However, traces of a replacive carbonate cement and chloritic rim cement may also be developed (S52340; S53562). Compaction resulted in the kinking of detrital micas, fracturing of quartzose clasts and plastic deformation of more unstable lithic clasts which become indented or moulded around neighbouring more rigid grains. In the finer grained sandstones (S55728) the detrital micas and, to a lesser extent, elongate clasts exhibit a preferred shape alignment possibly parallel to bedding.

2.10.2 Siltstones

In thin section (S53564; S55727) the siltstones examined from the Dundee Flags Formation are fine- to coarse-grained, moderately to poorly sorted, calcareous rocks which exhibit a pronounced preferred alignment of detrital micas. Detrital grains are angular to subangular in shape with a low sphericity and mainly composed of monocrystalline quartz. Rare rounded grains have been noted. Other minor to accessory detrital components include biotite, muscovite, chlorite, plagioclase, opaque minerals, microcline and apatite. Biotite and muscovite are common minor detrital components within the siltstones. Minor to trace amounts of secondary carbonate are present replacing the clay grade component of the rock.

2.10.3 Pebbly sandstone or microconglomerate

A sample (S53563) of very coarse-grained sandstone or microconglomerate was also examined from the Dundee Flags Formation. In thin section it is a coarse- to very coarse-grained, immature, lithic-rich, matrix-poor, very poorly sorted rock with a closely to very closely packed clast-supported texture. No obvious primary porosity has been recognised within this microconglomeratic rock. Angular to subangular, low sphericity clasts are mainly composed of andesitic, dacitic to rhyolitic volcanic rock fragments. These intermediate to acidic volcanic rocks vary from aphyric to microporphyritic containing small phenocrysts of feldspar. Recognisable lithologies include biotite-feldspar-phyric dacite and pilotaxitic dacite. The finer grained sand-grade component of the microconglomerate is composed of a more mixed clast assemblage of monocrystalline quartz, volcanic rock fragments and subordinate plagioclase. Other minor to accessory detrital components include polycrystalline quartz, muscovite, very fine-grained sedimentary rock, biotite, chlorite, felsite and hematised rock.

Trace amounts of a clay-grade matrix occurs within the finer grained parts of the rock. Although pressure solution appears to have resulted in the main mode of cementation within this microconglomerate, a pore filling chloritic cement is also locally well developed. This cement is composed of very fine-grained to cryptocrystalline, green coloured chlorite. Compaction resulted in the kinking of detrital micas and plastic deformation of the more unstable lithic clasts which become indented or moulded around neighbouring more rigid grains. Flattening during compaction may have also led to the observed preferred shape alignment of clasts. A number of these unstable lithic clasts have become degraded and incorporated into the matrix of the microconglomerate.

3 Plate captions

Plate 1. (a and **b)** olivine microporphyritic basalt with relict olivine enclosed within a reaction rim of green coloured chlorite and serpentine. Note the presence of a well developed pilotaxitic fabric within the groundmass defined by aligned plagioclase laths (sample S3787). **(c** and **d)** plagioclase porphyritic basalt (sample S54053). ((a and c) plane polarised light; (b and d) crossed polarised light; objective lens x 2.5).

Plate 2. (a and **b)** olivine porphyritic basalt in which olivine has been completely replaced by a green coloured chloritic assemblage (sample S51203). **(c** and **d)** olivine porphyritic basalt in which olivine phenocrysts are replaced by secondary carbonate and opaque oxide.. Note the presence of a well developed pilotaxitic fabric within the groundmass defined by aligned

plagioclase laths (sample S54042). ((a and c) plane polarised light; (b and d) crossed polarised light; objective lens x 2.5).

Plate 3. (a and **b)** olivine microgabbro with pale brown coloured intergranular, ophitic T-augite and relict olivine (sample S3778). **(c** and **d)** basaltic andesite containing a glomerophyric cluster of plagioclase phenocrysts within a finer grained groundmass (sample S54055). ((a and c) plane polarised light; (b and d) crossed polarised light; objective lens x 2.5).

Plate 4. (a and **b)** very coarse-grained, immature, poorly sorted lithic-rich sandstone or microconglomerate from the Catterline Conglomerate Formation (sample S58525). **(c** and **d)** medium-grained, immature, poorly sorted sandstone from the Glenvale Sandstone Formation. Note the presence of a replacive carbonate cement within this sandstone (sample S50878). ((a and c) plane polarised light; (b and d) crossed polarised light; objective lens x 2.5).

Plate 5. (a and **b)** medium- to coarse-grained, immature poorly to very poorly sorted sandstone from the Scone Sandstone Formation (sample S50865). **(c** and **d)** sandy carbonate-rich rock from the Pittendriech Limestone (sample S54116). ((a and c) plane polarised light; (b and d) crossed polarised light; objective lens x 2.5).

Glossary

Grain size – (a) clay < 0.0039 mm in size; (b) silt, 0.0039 to 0.0625 mm in size; (c) fine sand, 0.0625 to 0.25 mm in size; (d) medium sand, 0.25 to 0.5 mm in size; (e) coarse sand, 0.5 to 1.0 mm in size; (f) very coarse sand, 1.0 to 2.0 mm in size; (g) granules 2.0 to 4.0 mm in size; (h) pebbles 4.0 to 64 mm in size.

Rounded – Describes the smoothness of the surface of a grain. The terms well-rounded, rounded, subrounded, subangular, angular, very angular are used to describe the increasingly angular/irregular/rough nature of the surface of detrital grains.

Sphericity – Describes the how closely a detrital grain approximates to a sphere. The terms low sphericity, moderate sphericity and high sphericity are used to describe how spherical (ball-like) the detrital grains are.

Sorting – Well sorted describes a deposit in which all the detrital grains are of approximately uniform size. In reality most fragmentary deposits contain a range of grain sizes and can be described as moderately sorted, poorly sorted or in extreme cases unsorted.

Packing – Describes, as the term suggests, how closely the individual detrital grains are packed together within a fragmentary deposit. The term closely packed is used where all the grains are in contact and there is very little obvious matrix or cement; moderately packed and open packed are used with an increase in the porosity, matrix and/or cement.

Clast supported – Describes a fragmentary deposit where all the detrital grains are in contact.

Matrix supported – Describes a fragmentary deposit where the detrital grains are, to varying degrees, isolated/supported within a finer grained matrix.

Cement supported – Describes a fragmentary deposit where the detrital grains are, to varying degrees, isolated/supported within the cement.

Cement – The material bonding the fragments of clastic sedimentary rocks together and which was precipitated between the grains after deposition.

Porosity – The volume of voids expressed as a percentage of the total volume of the sediment or sedimentary rock.

Matrix – Material, usually clay minerals or micas, forming a bonding substance to grains in a clastic sedimentary rock. The matrix material was deposited with the other grains or developed authogenically by diagenesis or slight metamorphism. Also used more generally for finer grained material in any rock in which large components are set.

Detritus – A general term for fragmentary material, such as gravel, sand, clay, worn from rock by disintegration. Detrital grains in clastic sedimentary rocks may be composed of single mineral grains (e.g. monocrystalline quartz, plagioclase), polycrystalline mineral grains (e.g. polycrystalline quartz) or lithic fragments including sedimentary, igneous and metamorphic rock fragments.

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 (less than 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 consists of large crystals of a particular mineral or minerals set in a finer grained groundmass. Porphyritic texture can be subdivided into: (a) *microporphyritic*, phenocrysts equal to or less than 2.0 mm in size; and (b) *macroporphyritic*, phenocrysts greater than 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.

Andesite – An intermediate volcanic rock, usually porphyritic, consisting of plagioclase (frequently zoned from labradorite to oligoclase), pyroxene, hornblende and/or biotite.

Basalt – A volcanic rock consisting essentially of calcic plagioclase and pyroxene. Olivine and minor feldspathoids may also be present.

Basaltic andesite – A volcanic rock with plagioclase compositions expected for andesites but containing ferromagnesian minerals more commonly found in basalts.

Dacite – A volcanic rock composed of quartz and sodic plagioclase with minor amounts of biotite and/or hornblende and/or pyroxene.

Gabbro – A coarse-grained plutonic rock composed essentially of calcic plagioclase, pyroxene and Fe-oxides. If olivine is an essential constituent it is referred to as an olivine-gabbro – if quartz, a quartz-gabbro.

Peridotite – A collective term for ultramafic rocks consisting essentially of olivine with pyroxene and/or amphibole.

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).

Rhyolite – A collective term for silicic volcanic rocks consisting of phenocrysts of quartz and K-feldspar, often with minor plagioclase and biotite, in a microcrystalline or glassy groundmass.

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

Granite – A medium- to coarse-grained plutonic rock consisting essentially of quartz, K-feldspar and plagioclase in variable amounts usually with hornblende and/or biotite.

Accessory – A minor constituent of rocks which is present only in small amounts, for example the minerals apatite, zircon, titanite.

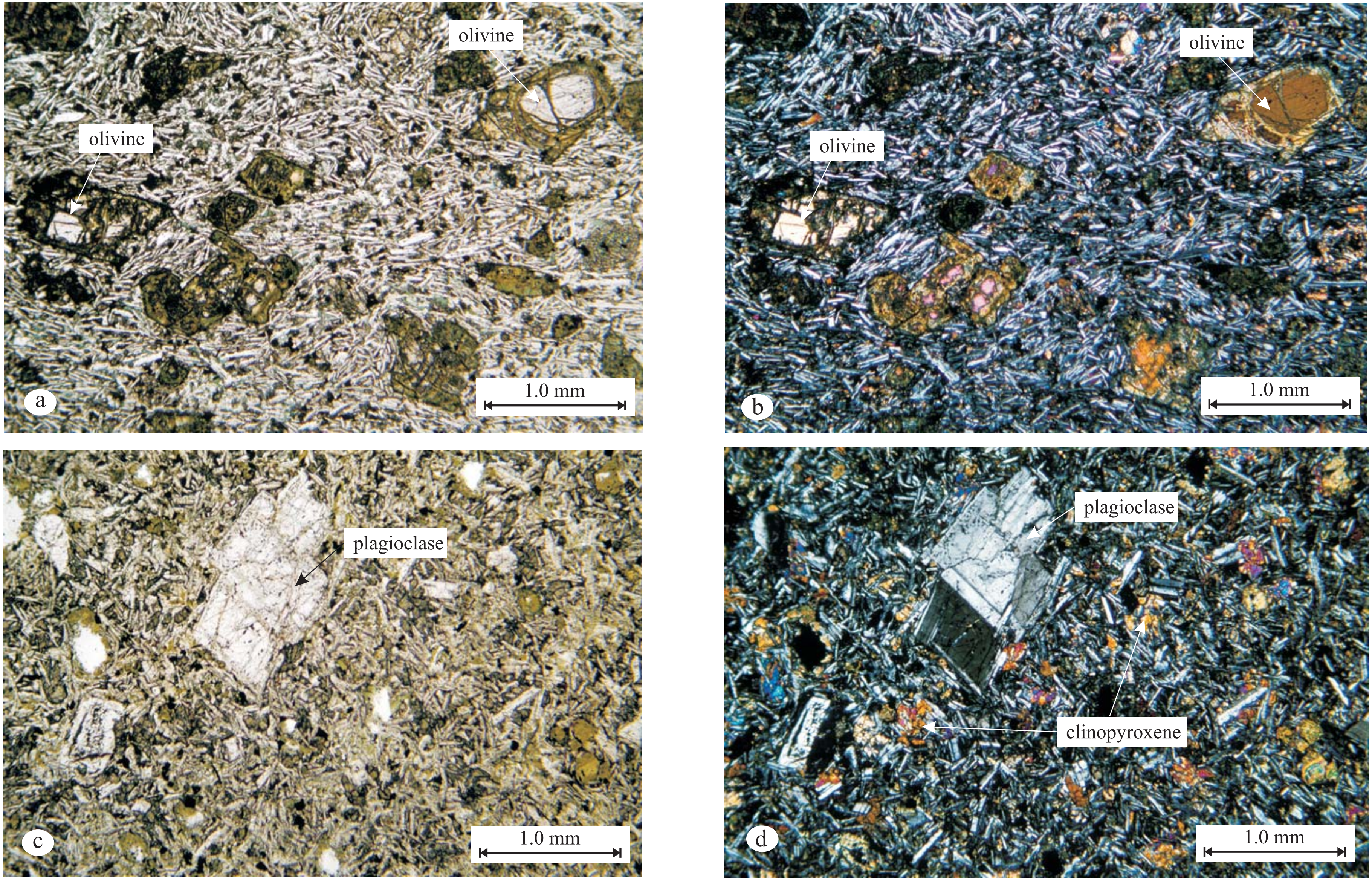
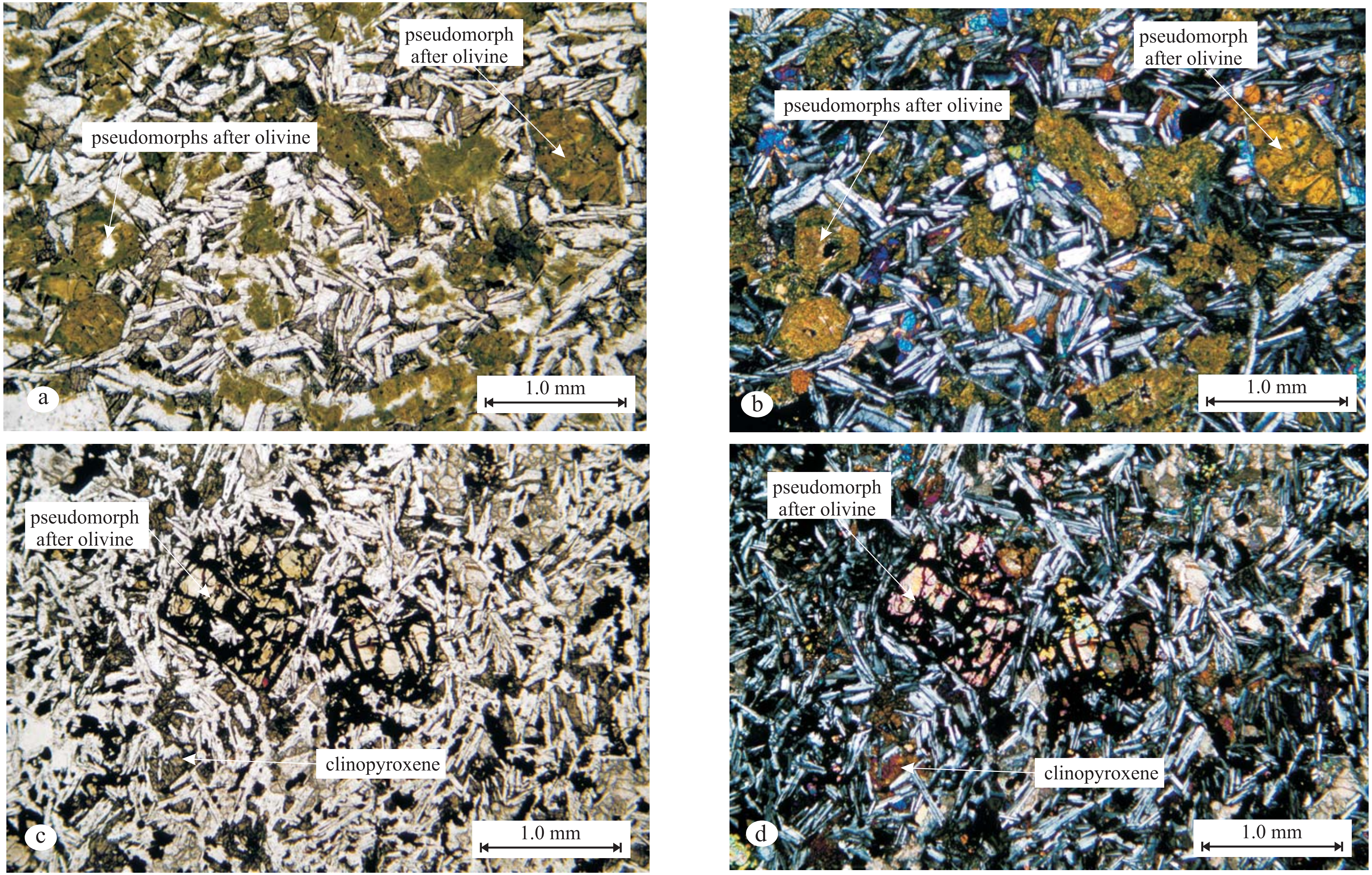


Plate 1. (a and b) olivine microporphyritic basalt with relict olivine enclosed within a reaction rim of green coloured chlorite and serpentine. Note the presence of a well developed pilotaxitic fabric within the groundmass defined by aligned plagioclase laths (sample S3787). (c and d) plagioclase porphyritic basalt (sample S54053). ((a and c) plane polarised light; (b and d) crossed polarised light; objective lens x 2.5).



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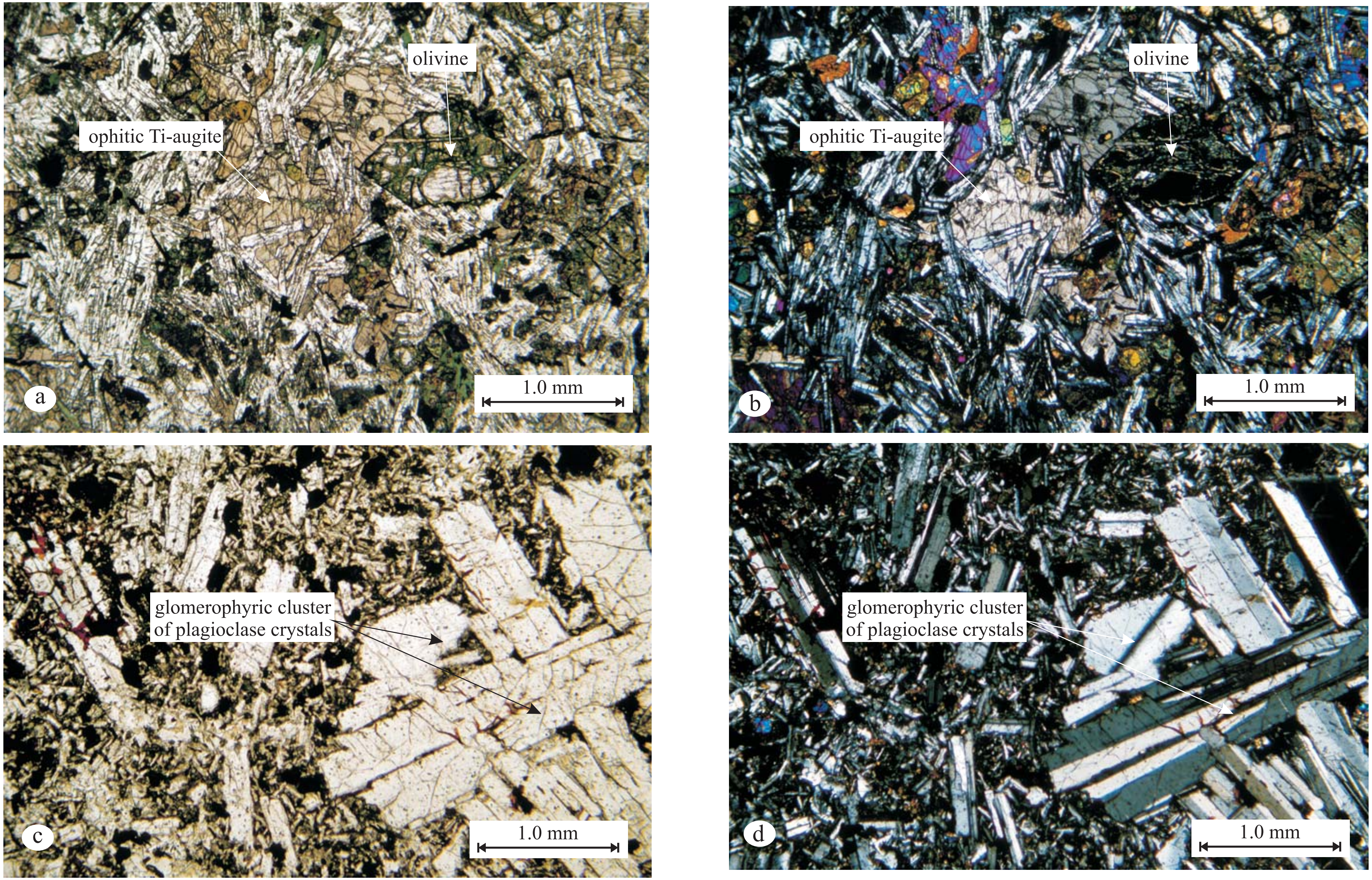

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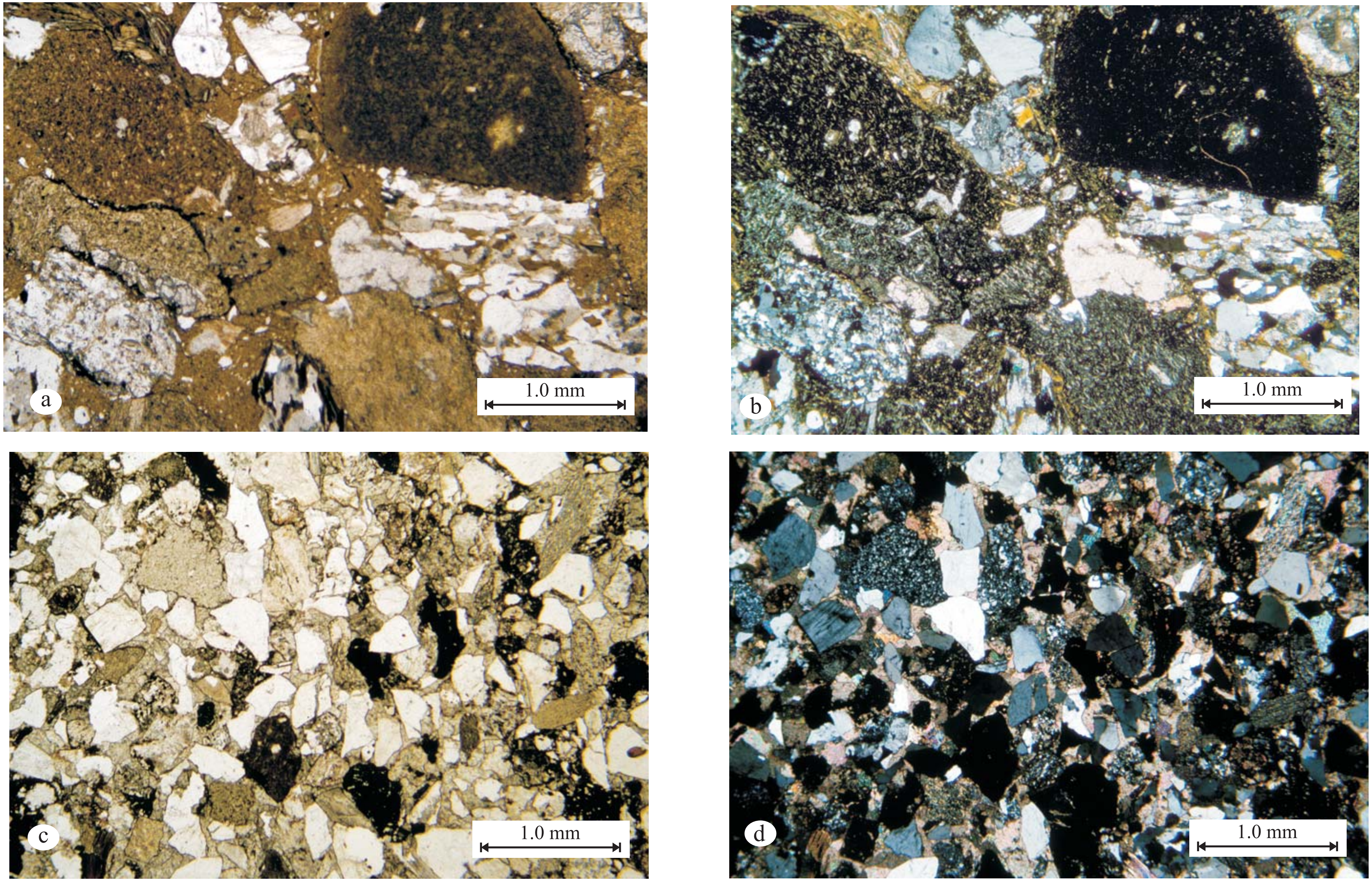

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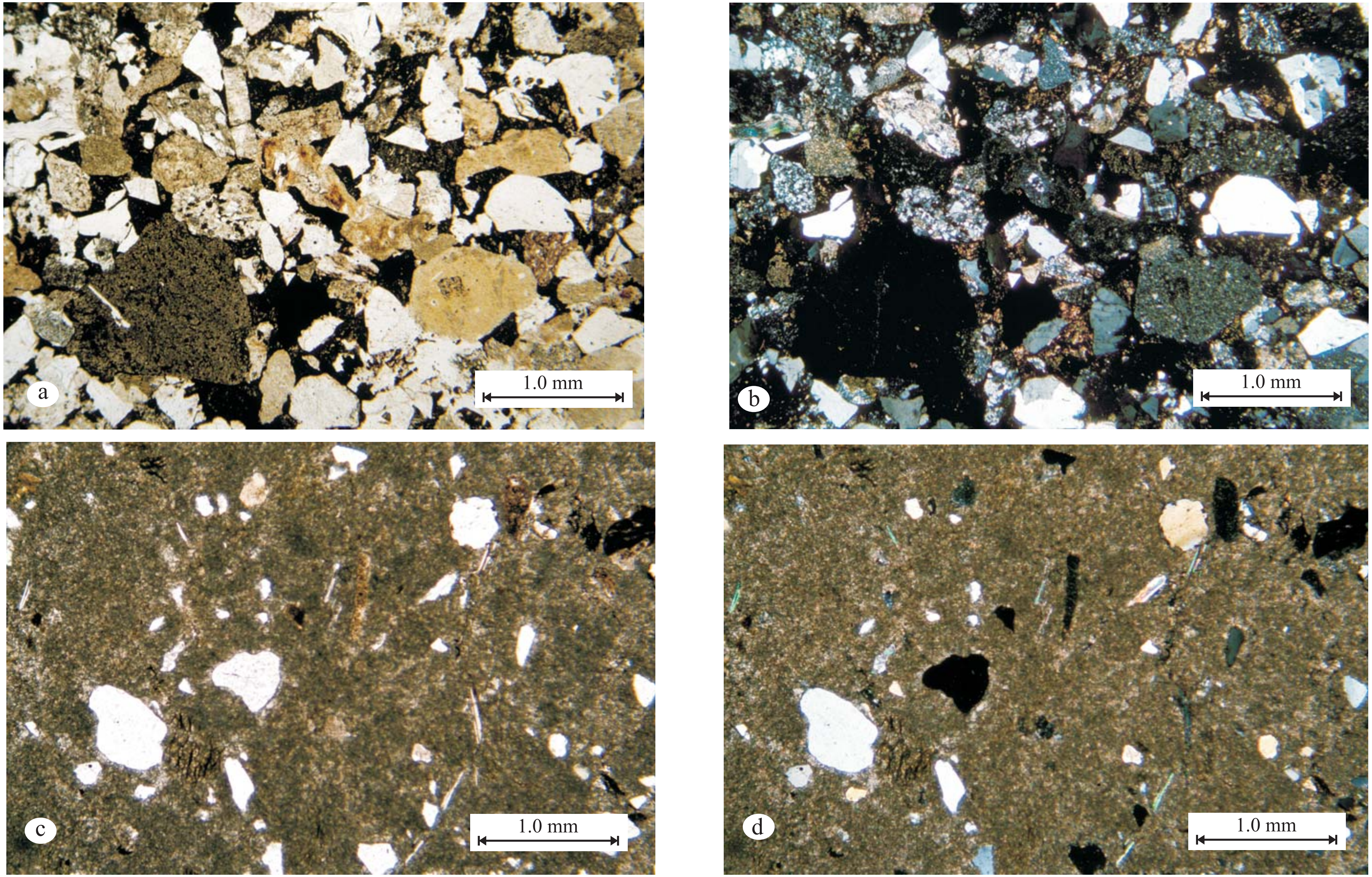

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