CRUSHED ROCK AGGREGATES: THEIR MINERALOGY AND TEXTURES USING AUTOMATED SCANNING ELECTRON MICROSCOPY

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Abstract

The mineralogy and texture of a crushed rock aggregate can be established through using a thin section and an optical microscope. However, there are limitations due to the difficulties in recognising and identifying the smallest crystals, many of which may bind the rock together or are alteration products of larger crystals that can have a marked effect on the aggregate properties. Also, mineral identification is subjective and quantification of minerals is laborious. An automated scanning electron microscope (QEMSCAN®) can be used to scan the surface of a polished sample, rapidly collecting data from backscattered electrons and X-rays generated by the electron beam that are characteristic of the elements within the minerals. In this way the textures and complete mineralogy of the rock can be determined and fully quantified. A wide range of different crushed rock aggregates have been collected mostly from active or former quarry sites in the UK and the mineralogy and textures imaged using the QEMSCAN®. Samples include granites, granodiorites, lavas, pyroclastics, gabbros, dolerites, limestones, dolostones, gritstones, greywackes, anorthosite, metamorphic rocks and blastfurnace slag. The mineralogy and texture of each is described and observations made on the relationships between the mineralogy and textures and physical properties of aggregates. Automated scanning electron microscopy has the potential to be used by companies in formally describing their aggregate products.

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INTRODUCTION

Many different rocks with varied physical properties are used as aggregates in the UK. They have a multitude of uses including road building, rail ballast and concrete products. High specification aggregates suitable for major roads have been defined as having a good skid resistance (i.e. a Polished Stone Value (PSV) of at least 58), low abrasion (i.e. an Aggregate Abrasion Value (AAV) of 16 or less) and good strength and durability (a Los Angeles Coefficient (LA) of 30 or less) (Thompson et al., 2004). Higher PSVs are required on roads with high traffic volumes and in locations where vehicles are most likely to be slowing down or accelerating. High specifications are required for rail ballast, typical aggregates having an LA of 23 or less (Harrison and Bloodworth, 1994). Lower specification aggregates with PSVs as low as 45 and higher AAVs and LA can be used on the surfaces of minor roads. All aggregates, with the exception usually of the highest specification high value types for road surfacing, are extensively used in bituminous mixes in the lower layers of roads and as concreting aggregates.

The types of crushed rocks used as aggregates include granites, diorites, basalts, dolerites, rhyolites, dacites, quartzites, schists, gneisses, hornfels, greywackes, gritstones, and limestones and dolomites of varying purity. The rock type of an aggregate is usually described through the use of thin sections and a polarising optical microscope. This has limitations due to the fine-grained nature of some aggregates and also the difficulty of identifying small crystals or grains, which may bind larger crystals or grains or are alteration products of primary minerals. Together the mineralogy and texture of an aggregate particle control its physical properties.

For the present study samples of crushed rock aggregate products were obtained from 29 quarries covering a range of rock types. Most of the quarries are currently active. The mineralogies and textures of these samples have been determined using a QEMSCAN®. This is an automated scanning electron microscope which scans the surface of the sample, producing X-ray spectra from which the quantitative mineralogy and the relationships between crystals and grains (i.e. the texture) can be established. The samples were chosen to represent aggregates with differing physical properties, particularly PSV. The results of the study are illustrated here along with descriptions of each aggregate and a short commentary on how the differing mineralogies and textures result in the aggregates having different physical properties.

SAMPLES

A list of the samples, divided by rock type and with their locations is given in Table 1 along with available information on the PSVs and other physical properties of the aggregates. Most of the samples were either from a product stockpile, or were taken from faces or blast piles. They illustrate the major type of rock or, in some cases, rocks in the quarry at the time of collection. They may not be entirely representative of an ongoing aggregate product, as a single rock type can vary within a quarry and in some quarries the aggregate product is a mixture of types. For example, in Meldon Quarry, Devon (now closed) the former aggregate product was a mixture of a very variable hornfels and chert. A few of the quarries are no longer active.

Analytical procedure

The mineralogy and textures were determined at Camborne School of Mines, University of Exeter, using a QEMSCAN® 4300 system and with settings as described in Rollinson et al., (2011). The polished surface of each sample (made as a polished thin section) was analysed using the fieldscan mode with a 10 micron X-ray resolution (Gottlieb et al. 2000, Pirrie et al. 2004), using iMeasure v.4.2 for the data acquisition and iDiscover v.4.2 for the data processing. Development of a database of minerals, resulting from the X-ray spectra from each 10 micron point, was carried out for each of the rock types examined. Mineral identification was verified by optical microscopy on the same polished thin sections using a Nikon Eclipse E600 Pol optical microscope, with an attached 5MP Nikon digital camera. This was especially useful for amphiboles and pyroxenes, which commonly have relatively similar major element compositions and thus are difficult to distinguish from the X-ray spectra alone. Similarly, zoisite can be confused chemically with plagioclase feldspars.

MINERALOGY AND TEXTURES OF AGGREGATES

Using a granite from Cornwall (Carnsew Quarry, Penryn) as an example, a comparison of a thin section image and one from the QEMSCAN® is shown in Figure 1. The false colours in the QEMSCAN® image enable easy recognition of each mineral and their mutual relationships (i.e. the texture) throughout the sample. The contacts between minerals are clearly defined. Tables 2 and 3 gives the quantitative statistics for the percentages of minerals, mean grain sizes and the contact relationships calculated from the QEMSCAN® data. The rock is an equigranular coarse-grained granite with major quartz, plagioclase and K-feldspar and two micas, typical of Cornish biotite granites. The contact relationship data show that the major minerals are mainly associated with

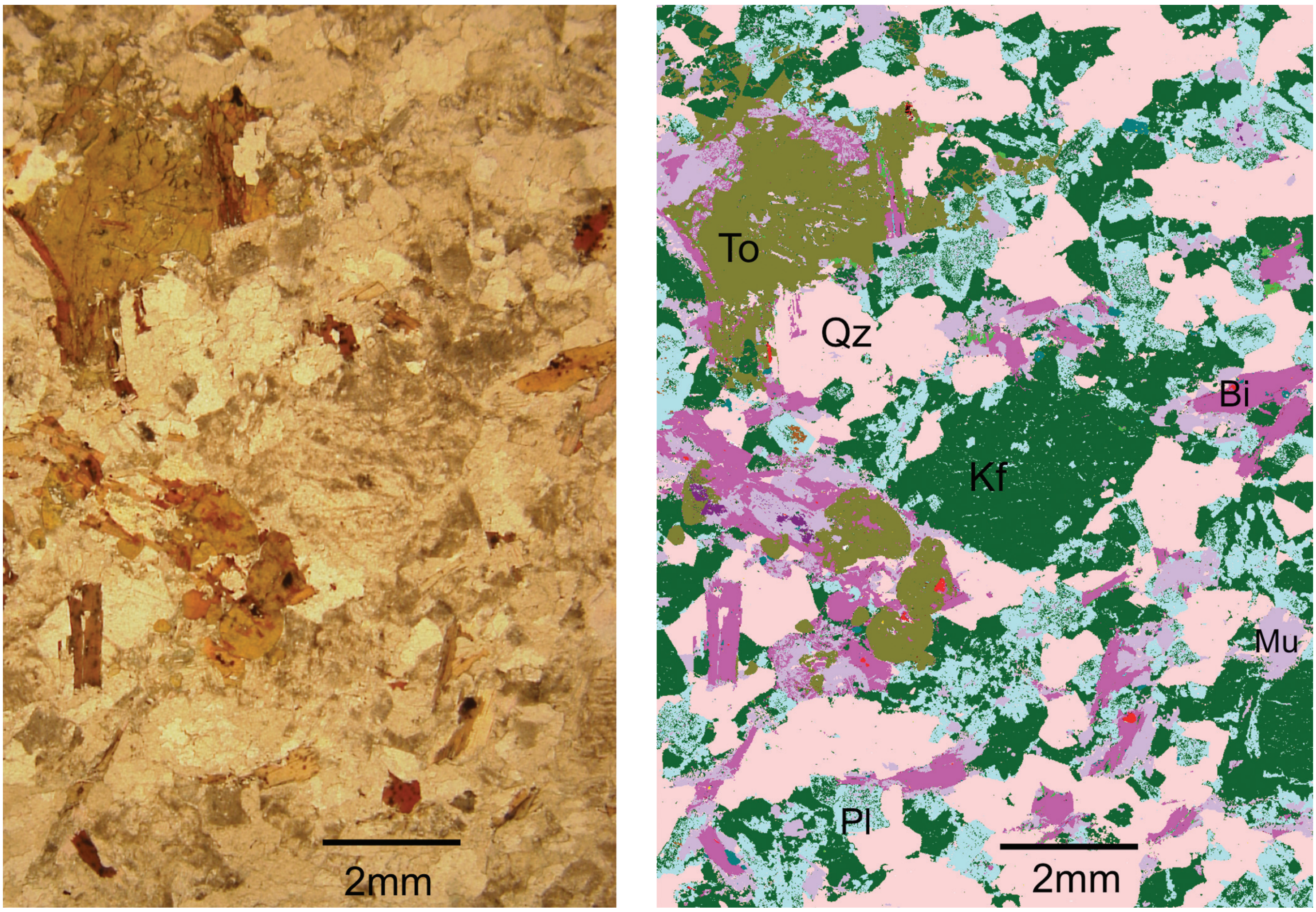

***Figure 1. Granite. Carnsew, Penryn, Cornwall** (sample 61/13). (See Tables 2 and 3). Comparison of optical (left) (plane polarised light) and QEMSCAN® (right) images from the same field of view. To – tourmaline. Qz – quartz. Kf – K-feldspar. Pl - plagioclase. Bi – biotite. Mu – muscovite. Other minerals present, but not resolved at the low magnification of the images, include calcite, fluorite, kaolinite, chlorite, apatite, zircon, cassiterite, Fe-Mn oxides and Ti-bearing minerals.*

Sample Number	Quarry name, location,	Rocktype	Stratigraphical position (BGS terminology)	PSV	AAV	LA	AIV	ACV	10%F kN	Reference
Acid plutonic rocks										
61/13	Carnsew, Penryn, Cornwall	Granite	Permo-Carboniferous	55						Cornwall Council, 2012
59/13, 60/13	Hingston Down, Gunnislake, Cornwall	-Granite -Dyke (fine grained granite) (elvan)	Permo-Carboniferous	55						Personal communication
62/13	Castle-an-Dinas, Penzance, Cornwall	Granite	Permo-Carboniferous	57 57 56	4.5 4.5 5.4		 16	 17	 283	Cornwall Council, 2012 Thompson et al., 2004 Harris, 1978
61/05	Glensanda, Morvern, Highland Region, Scotland,	Granodiorite	Strontian Granite, Silurian	52 52	3.0 3.2	27	20	20	190	Smith and Collis, 2001 Thompson et al., 2004
57/13A, 57/13B	Shap Fells, Cumbria (Shap Pink)	Granite	Devonian	54 54	3.4 3.4		23 23	25 25	150 150	Smith and Collis, 2001 Young et al., 2001
2/92, 3/92, 11/01	Mountsorrel, Mountsorrel, Leicestershire,	Granodiorite	Ordovician Mountsorrel Complex	53 51 58	3.4 2.6 3 3.1		 20 18	 20 18	 190 199	Thompson et al., 2004 Smith and Collis, 2001 Lincolnshire County Council, 2005 Harris, 1978
Lavas and pyroclastics										
23/13, 25/13	Harden, Biddlestone, Netherton, Northumberland	Dacite	Silurian – Devonian, North Britain Siluro-Devonian Calc-alkaline dyke	50-55 56 54	1.2- 2.0 1.4 1.2		12 9	27 14	220 300	Smith and Collis, 2001 Personal communication Anon., 2002 Thompson et al., 2004
39/13	Whitwick, Whitwick, Leicestershire	Lava or tuff	Neoproterozoic	58 60	3.0 3.8		 14	 16	 279	 Harris, 1978
Intermediate and basic plutonic rocks										
38/13	Old Cliffe Hill, Markfield, Leicestershire	Diorite	Neoproterozoic, South Charnwood Diorites	55 55	3.1 3					Thompson et al., 2004 Lincolnshire County Council, 2005
65/13	Greystone, Launceston, Cornwall	Dolerite	Devonian	57 57 60-62	4 5.5 4.7	 12 13	 13	 13	 295	Cornwall Council, 2012 Smith and Collis, 2001 Bardon Aggregates literature, undated
63/13	West of England, Porthoustock, Cornwall	Gabbro	Devonian	52 62 54	6 4.1 4.1		 13 17	 18 17	 189 240	Lincolnshire County Council, 2005 Harris, 1978 Smith and Collis, 2001 (Dean Quarry)
21/13	Swinburne, Northumberland	Quartz-dolerite	Carboniferous – Permian Great Whin Sill	53	4.1					Thompson et al., 2004
41/13, 42/13	Force Garth, Middleton-in-Teesdale, Co. Durham	Quartz-dolerite	Carboniferous – Permian, Great Whin Sill	55 50 54-61	5 3 3-5		 9-13	 7-12	 328-488	Thompson et al., 2004 Lincolnshire County Council, 2005 Harris, 1978 (range from 8 Whin Sill quarries)
Carbonates										
36/13	Horton, Settle, North Yorkshire	Limestone	Carboniferous, Great Scar Limestone Group	~40-45*	12		19-20	20-23	180	Smith and Collis, 2001 (data for Giggleswick and Threshfield)
77/83	Batts Combe, Cheddar, Somerset	Limestone	Carboniferous Burrington Oolite Subgroup	40	9		20	22	200	Smith and Collis, 2001 (data for Wick)
64/13	Moorcroft, Plymouth	Limestone	Devonian	38	14.3		26	28	132	Smith and Collis, 2001
29/13	Thrislington, Cornforth, Durham	Dolostone	Permian, Raisby Formation (Lower Magnesian Limestone)		10		26	24-26	160-180	Smith and Collis, 2001 (data for Raisby)
37/13	Glen, Stainton, Doncaster, South Yorkshire	Dolomitic limestone	Permian Cadeby Formation (Lower Magnesian Limestone)	53	19					Lincolnshire County Council, 2005
6/13	Morefield, Ullapool, Highland Region, Scotland	Dolostone	Cambrian, Ghrudaidh Formation		6-7		20-21	19-23		Charters and Scott, 1988
40/13	Cloud Hill, Breedon-on-the- Hill, Leicestershire	Dolostone	Carboniferous Cloud Hill Dolostone Formation, Carboniferous Milldale Limestone Formation	ca. 40-45						Estimated
58/13	Shierglas, Blair Atholl, Perthshire	Meta-morphosed limestone	Blair Atholl Dark Limestone and Dark Schist Formation, Neoproterozoic	56						Personal communication
Gritstones and greywacke										
30/13, 31/13	Roan Edge, New Hutton, Kendal, Cumbria	Gritstone	Silurian, Kirkby Moor Flag Formation	65 63 62	6 6 7.5		 15	 16	 310	Thompson et al., 2004 Lincolnshire County Council, 2005 Young et al., 2001
33/13	Ingleton, Ingleton, North Yorkshire	Greywacke	Ordovician, Ingleton Group	60-63 64 62 59	4.8 4 4 6.3 4		12 11	11 11	380 350 343	Smith and Collis, 2001 Personal communication Thompson et al., 2004 Company data Harris, 1977 Lincolnshire County Council, 2005
34/13	Arcow, Stainforth, North Yorkshire	Gritstone	Silurian, Windermere Supergroup	63 63 60 62	4.1 6 7 12		 7	 12	 350 333	Thompson et al., 2004 Lincolnshire County Council, 2005 Company data Harris, 1977
35/13	Dry Rigg, Stainforth, North Yorkshire	Gritstone	Silurian, Horton Formation	62 63 62 65	7.0 7 7 9.8		9 8	11 9	320 350 412	Smith and Collis, 2001 Lincolnshire County Council, 2005 Company data Harris, 1977
Others										
66/13, 67/13	Meldon, Devon	Chert Hornfels	Carboniferous	53						Personal communication
5/13	Nuneaton, Warwickshire	Quartzite	Hartshill Quartzite, Lower Cambrian	55-58	3		21	16		Harris, 1977
7/13, 8/13 9/13 10/13	Lingerbay, Harris, Outer Hebrides	Anorthosite	Palaeoproterozoic anorthosite	56	6		9	19		Gribble, 2002
25/83	Scunthorpe, Lincolnshire	Blastfurnace slag	-	(55)						Lincolnshire County Council, 2005 (typical values)

Notes: PSV; Polished Stone Value. AAV; Aggregate Abrasion Value. LA; Los Angeles Coefficient. AIV; Aggregate Impact Value. ACV; Aggregate Crushing Value. 10%F; 10% fines.
* estimated from other Carboniferous limestone quarries.

Table 1. *List of aggregate samples, locations and physical properties, divided according to rocktypes.*

Mineral	Carnsew Granite (61/13)		Hingston Down				Castle an Dinas Granite (62/13)		Shap			
			Granite (59/13)		Elvan (60/13)				* Granite (57/13a)		** Granite (57/13b)	
	%	Size µm	%	Size µm	%	Size µm	%	Size µm	%	Size µm	%	Size µm
Quartz	33.97	353	34.78	691	33.30	174	31.13	237	10.55	440	24.22	736
K-Feldspar	29.43	109	22.39	152	31.66	101	33.24	112	76.05	436	38.20	152
Plagioclase	20.31	84	31.42	201	25.87	92	24.96	93	10.44	62	28.05	97
Muscovite	8.90	98	10.03	152	4.95	47	7.21	77	0.22	22	1.42	24
Biotite	4.70	110	0.21	21	2.84	41	1.57	31	1.16	56	3.39	70
Chlorite	0.39	32	0.47	46	0.94	28	0.49	26	0.74	51	2.14	54
Apatite	0.30	57	0.55	124	0.18	32	0.26	52	0.16	58	0.36	54
Tourmaline	1.73	169	0.08	27	np	np	0.94	54	np	np	np	np
Kaolinite	0.04	26	0.01	18	<0.01	17	0.01	19	np	np	np	np
Pyrite	<0.01	<15	0.01	20	<0.01	<15	np	16	0.01	69	0.24	303
Others	0.22	<50	0.13	<30	0.23	<30	0.19	<30	0.67***	<50	1.98****	<50

Notes: Sample numbers are shown in brackets. n.p.; not present. * Area in sample with large K-feldspar phenocryst. ** Area of sample without large K-feldspar phenocryst.*** Includes calcite 0.29% and 0.08% iron oxides. ****Includes calcite 1.26% and 0.13% iron oxides.

Table 2. *Modal composition and mean crystal sizes for granite aggregates.*

%	Quartz	K-Feldspar	Plagioclase	Muscovite	Biotite	Tourmaline	Kaolinite	Chlorite	Apatite	Pyrite
Quartz	0.00	15.02	9.56	21.30	15.82	9.68	1.68	11.80	22.02	31.25
K-Feldspar	42.30	0.00	78.25	29.46	14.13	25.23	20.36	10.62	18.03	6.25
Plagioclase	24.16	70.16	0.00	24.73	5.89	8.12	33.18	8.57	13.52	6.25
Muscovite	20.17	9.91	9.28	0.00	37.39	13.32	37.67	13.60	15.57	0.00
Biotite	7.00	2.22	1.03	17.45	0.00	24.01	2.17	37.19	19.91	18.75
Chlorite	1.51	0.48	0.43	1.83	10.75	14.64	1.40	0.00	1.68	0.00
Apatite	1.22	0.36	0.30	0.91	2.50	0.27	0.46	0.73	0.00	12.50
Tourmaline	1.03	0.95	0.34	1.49	5.77	0.00	1.65	12.16	0.52	6.25
Kaolinite	0.03	0.11	0.21	0.63	0.08	0.24	0.00	0.17	0.13	0.00
Pyrite	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.02	0.00

Note: The table is read in column mode only. For example, 42.30% of the quartz in the sample is adjacent to K-feldspar, 15.02% of the K-feldspar is adjacent to quartz.

Table 3. *Contact relationships between the main minerals in Carnsew granite, Cornwall (sample 61/13).*

each other. This is what would be expected from an equigranular rock. Kaolinite is mainly associated with K-feldspar, plagioclase and muscovite, which is also to be expected as kaolinisation is an alteration process of these minerals.

The following sub-sections illustrate the different samples of aggregates collected for the study, divided according to the broad rock groups. Images of each sample are presented, along with a description. Statistical data of the percentage and mean size of the minerals within each sample are given in accompanying tables (Tables 4-11). The authors can provide the contact relationship data on request. A few comments on each group are made, although the images and the statistical data are self-evidently representative of the petrography of each sample.

A. Acid igneous rocks

QEMSCAN® images of other granites (Hingston Down and Castle-an-Dinas in Cornwall and Shap in Cumbria) are given in Figures 2, 3 and 4, and the percentage of minerals and their mean crystal sizes are given in Table 2. The coarse-grained equigranular or porphyritic textures and mineralogies are typical of granites. The differences between the percentages of minerals in the Shap granite data, particularly the quartz and feldspars, show how it is important to examine more than a single area if the rock is very coarse-grained or contains large crystal size variations between different minerals.

Images of granodiorite from Glensanda, Scotland and granodiorite from Mountsorrel, Leicestershire are given in Figures 3 and 5, and their mineralogical composition are given in Table 4. These are similar to the equigranular granite samples in their mineralogies and textures, but contain significantly more plagioclase relative to K-feldspar as would be expected from their names. Three samples from Mountsorrel (Figure 5) collected from different parts of the quarry show significant differences, with increased biotite in one sample (3/92) and increased chlorite in another (11/01).

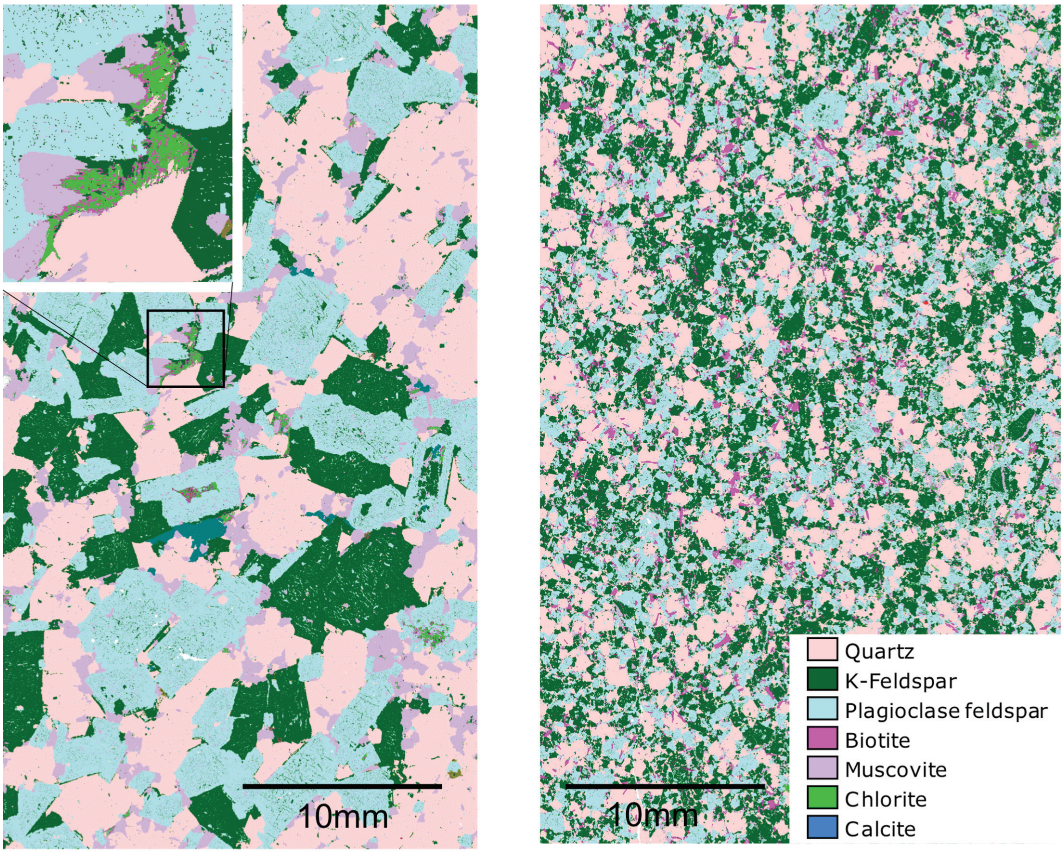

Figure 2. Granite and Elvan. Hingston Down, Callington, Cornwall. *Granite on the left (sample 59/13), and the fine-grained granitic dyke (elvan) within the quarry on the right (sample 60/13). (See Table 2). Equigranular granite with muscovite dominating over biotite, the latter mainly altered to chlorite (see inset). There is secondary calcite in the centre of the granite image. The elvan is much finer grained and equigranular with more K-feldspar and less plagioclase.*

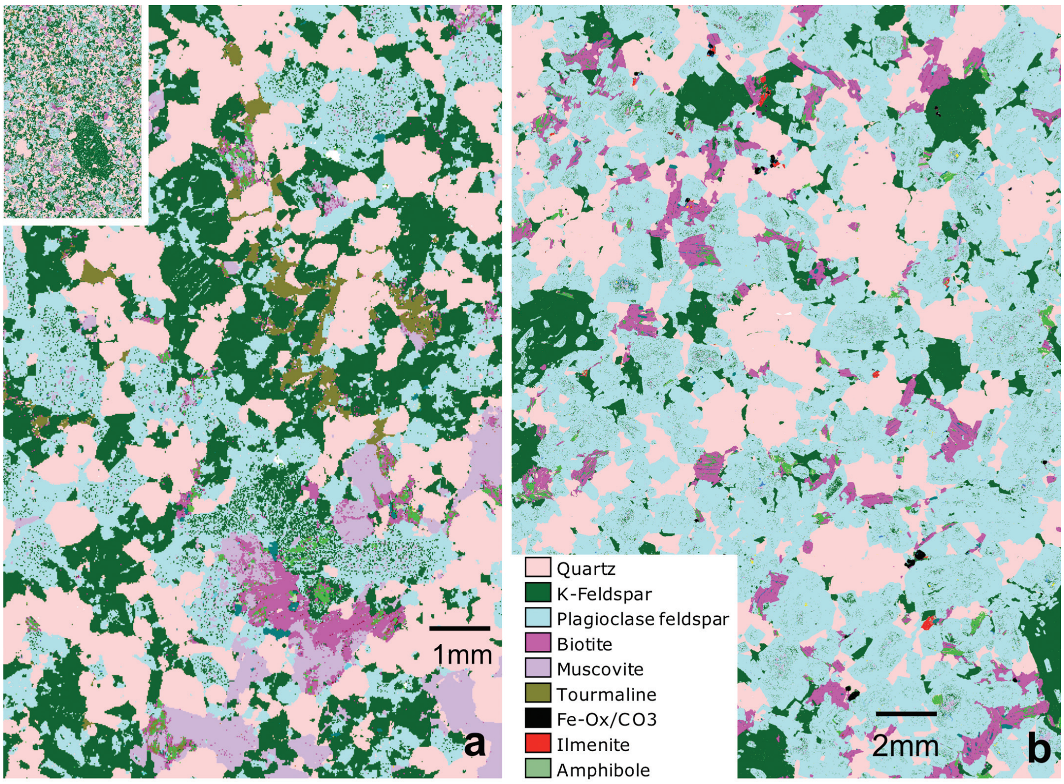

Figure 3. a (left). Granite. Castle an Dinas, Penzance, Cornwall *(sample 62/13). Coarse-grained tourmaline-bearing biotite granite with sparse K-feldspar phenocrysts. (See Table 2). Inset image (field of view 19mm across) is of a whole polished thin section that contains a phenocryst of K-feldspar.* ***b (right).Granodiorite. Glensanda, Highland Region, Scotland*** *(sample 61/05). Coarse-grained equigranular granodiorite containing abundant quartz and plagioclase and minor biotite and K-feldspar, with trace amounts of muscovite and amphibole (neither visible at the scale of the image). (See Table 4). Note: amphibole is not present in the Castle an Dinas rock and tourmaline is not present in the Glensanda rock.*

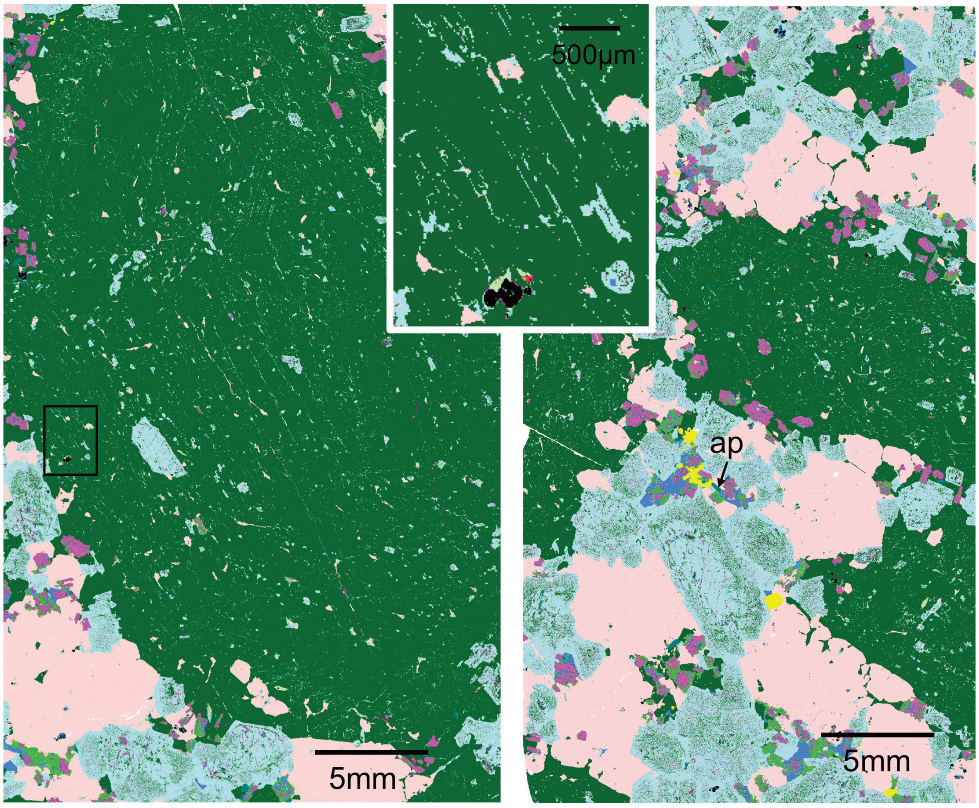

Figure 4. Granite. Shap, Cumbria *(sample 57/13a, left and sample 57/13b right). Porphyritic granite with large K-feldspar crystals. (See Table 2). The image on the left shows an area with the major part of a large K-feldspar phenocryst (green). The right image shows an adjacent area without a phenocryst. The inset shows lamellae of plagioclase (pale blue) within the large K-feldspar crystal. Also in the inset is a crystal aggregate of iron oxide (black). The right image shows small amounts of pyrite (yellow), calcite (bright blue) and apatite (dark blue), along with the main minerals K-feldspar (green), plagioclase (pale blue) with K-rich concentric growth zones (green), quartz (very pale pink) and biotite (magenta).*

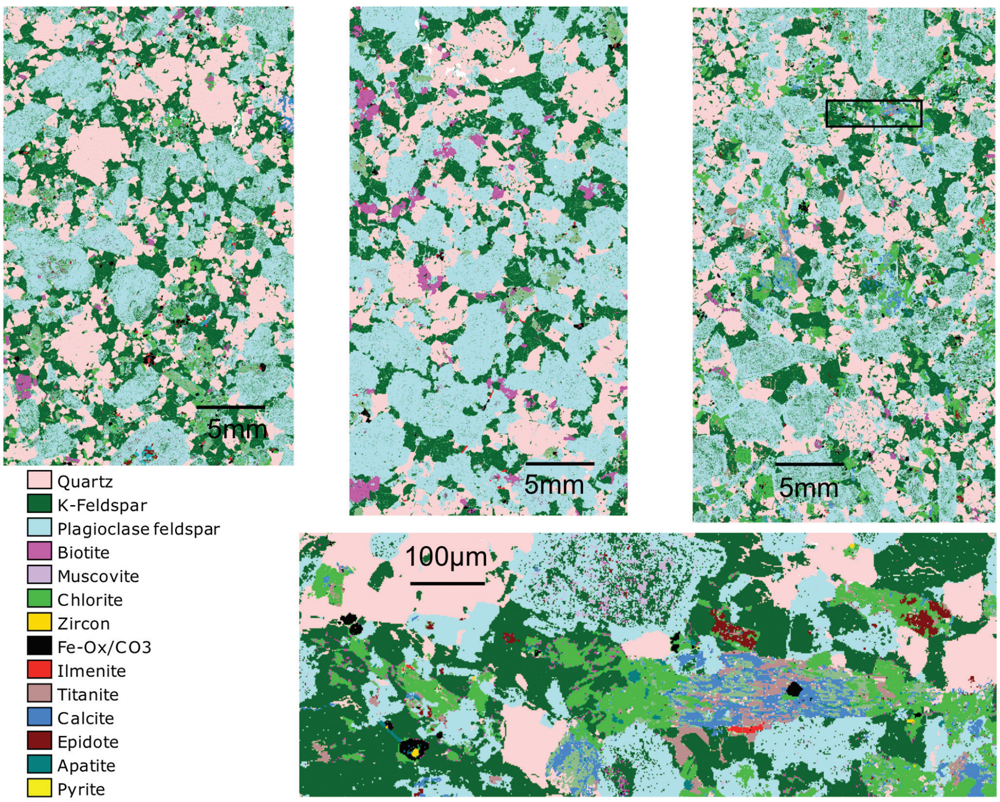

Figure 5. Granodiorite. Mountsorrel, Leicestershire *(upper images, left to right; sample numbers 2/92, 3/92, 11/01 (the inset box shows the location of the lower image)). Granodiorite, consisting predominantly of plagioclase, quartz and K-feldspar with minor amounts of biotite, muscovite, chlorite, epidote and other minerals. (See Table 4). The three top images illustrate minor differences in grain sizes and mineralogy. The sample on the right shows more alteration from the primary mineralogy of a granodiorite with the development of more chlorite (bright green), epidote (dark red) and calcite (bright blue) (see lower image) compared with the other two samples.*

	Mountsorrel, Leicestershire Granodiorite						Glensanda, Highland, Scotland Granodiorite	
Sample number	2/92		3/92		11/01		61/05	
	%	Size µm	%	Size µm	%	Size µm	%	Size µm
Quartz	29.70	434	23.12	398	26.30	288	26.78	539
K-Feldspar	26.86	83	22.47	129	22.86	67	12.00	93
Plagioclase	34.69	106	48.72	245	38.99	109	53.45	297
Biotite	1.00	40	2.68	131	0.62	30	4.91	110
Muscovite	0.66	21	0.15	19	0.69	19	0.61	25
Kaolinite	0.01	20	0.00	16	0.00	16	0.00	17
Chlorite	2.85	55	0.46	26	6.09	78	1.31	42
Zircon	0.02	40	0.01	37	0.02	35	0.02	21
Fe-Ox/CO3	0.70	57	0.39	70	0.58	55	0.15	45
Rutile	0.15	19	0.01	16	0.16	19	0.07	18
Ilmenite	0.21	44	0.16	47	0.06	37	0.08	62
Titanite	0.15	27	0.08	25	0.88	52	0.03	21
Calcite	0.18	37	0.01	19	1.01	43	0.19	29
Dolomite	0.51	38	0.00	19	0.01	19	0.00	≤15
Hornblende	1.87	55	1.55	104	1.19	29	0.07	16
Epidote	0.25	35	0.03	20	0.31	35	0.07	18
Apatite	0.20	29	0.13	29	0.23	34	0.24	46
Others	<0.01	<30	0.03	<20	<0.01	<20	0.02	<40

Note: Fe-Ox/CO3 refers to iron oxides / carbonates (these cannot be separately identified from the X-ray spectra)

Table 4. *Modal composition and mean crystal sizes for granodiorite aggregates.*

B. Lavas and pyroclastics

Two examples of intermediate to acid volcanic rocks are given in Figures 6 and 7a, with their mineralogical details in Table 5. These are both fine-grained with porphyritic textures. The mineralogies are much changed from their presumed primary assemblages, particularly the Whitwick rock, which is much chloritised and epidotised, although the textures remain essentially unaltered.

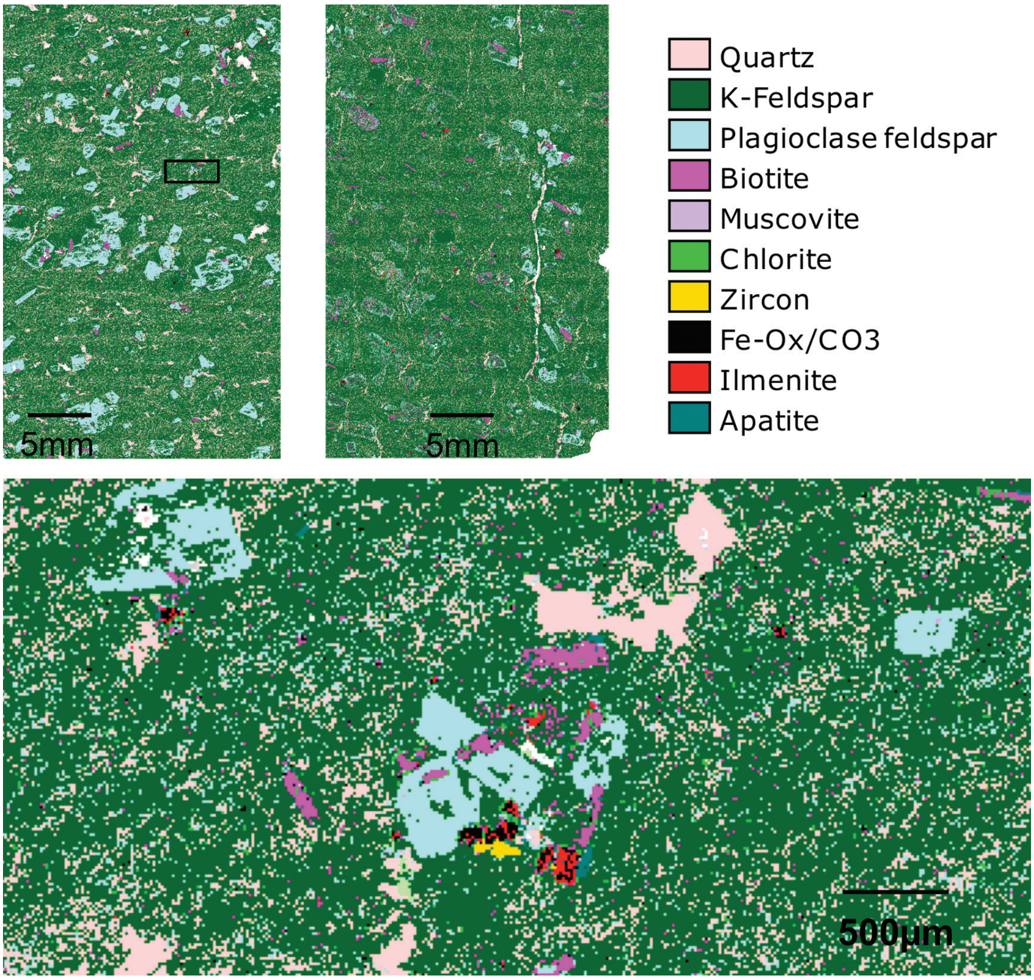

Figure 6. Dacite. Harden, Northumberland *(sample 23/13 top left and bottom (the inset box in the top left image shows the location of the bottom image), sample 25/13 top right). (See Table 5). Two samples of porphyritic lava from the same quarry with differing proportions of plagioclase and biotite phenocrysts. The matrix is a very fine-grained intergrowth of quartz and K-feldspar, which is most likely recrystallized from its original state.*