A building stone assessment of the buff sandstone masonry of the Hawick Flood Protection Scheme, Scottish Borders

Decarbonisation and Resource Management programme

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BRITISH GEOLOGICAL SURVEY

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Front cover

View over the River Teviot showing part of the Hawick Flood Protection Scheme walls

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Executive summary

This report describes an investigation undertaken by the British Geological Survey (BGS) to characterise the 'buff sandstone' copestones and walling stone used within the recently completed stonework of the Hawick Flood Protection Scheme (HFPS). The copestones consist of 'Fletcher Bank sandstone' (quarried in North West England), while the walling stone is found to resemble 'Beige Pinar calcarenite' – a type of limestone quarried in Spain. The results of a programme of geological and geotechnical testing demonstrate that the 'Beige Pinar calcarenite' fails to satisfy the criteria set out in the technical specification for the works (Appendix 24/1: Brickwork, blockwork and stonework).

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1 Introduction

This report details the outcomes of an investigation undertaken by the British Geological Survey (BGS) with the aim of characterising the building stones – in terms of their geological properties and origin – that feature within the masonry associated with the Hawick Flood Protection Scheme (HFPS).

The HFPS is a significant public infrastructure project commissioned by Scottish Borders Council (SBC). Construction of the main flood defence works began in 2020, and are ongoing. Natural stone masonry has been employed extensively in the construction of the flood defence walls, which are formed of a concrete core that is faced with natural stone walling and topped by a rounded stone cope. In some of the work sections, buff sandstone has been used for the walling (**Figure 1**), whereas in others grey sandstone has been employed (**Figure 2**).

SBC informed BGS that the *buff sandstone* used to face and cap the HFPS flood defence walls is identified as “Fletcher Bank sandstone” by their supplier. It is understood, however, that the identity and origins of a significant quantity of the *buff sandstone* actually installed are in doubt. This has raised questions amongst stakeholders in the scheme concerning whether the stone used meets the approved technical specification (Appendix 24/1: Brickwork, blockwork and stonework) of materials to be used in the HFPS works.

BGS has been asked by SBC and Historic Environment Scotland (HES) to perform this building stone assessment in order to independently characterise and establish the origins of the *buff sandstone* used in the construction of the flood defence walls, and also provide technical comment on the properties of the stone(s) employed relative to those set out in the specification. This report is therefore intended to inform the resolution of any dispute between SBC and their contractor responsible for the delivery of the scheme and/or third parties involved in the supply of the materials in question.

Accordingly, this investigation had the following objectives:

- to carry out a site visit to identify and establish the distribution of the main stone types present within the masonry of the HFPS flood defence walls
- to obtain samples of the sandstone walling and coping stones present at a selection of representative locations spread across several sections of the HFPS
- to petrographically analyse each of the collected samples, thereby establishing the nature of their intrinsic properties
- to describe, based on the petrographic analysis, the geological characteristics of the *buff sandstone* type(s) recognised and, following comparison with samples held in the BGS Collection of Building Stones, provide information on the likely source(s) of the stone(s)
- to compare the geological characteristics of the *buff sandstone* type(s) recognised, including a consideration of relevant geotechnical test data[1], with those stipulated in the specification, and comment on whether the stone(s) supplied to site meet(s) the specification
- to assess and comment on (as far as possible) the performance characteristics of the *buff sandstone* type(s) recognised in terms of expected durability, and – if appropriate – compare the stone types in this respect.

A summary of the site visit, including details of the samples collected and the sampling locations, is provided in Section 2 of this report. Information on the likely source of each buff sandstone recognised is presented in Section 3, and our comments on compliance with the

[1] The test data referred to (and included in Section 4) derive from a programme of geotechnical testing undertaken by Sandberg Consulting Engineers LLP on a set of samples representing the buff sandstone. This testing was commissioned by SBC, and was based on material obtained from an on-site stockpile of buff sandstone earmarked for use as walling stone.

specification and durability considerations are provided in sections 4 and 5, respectively. Appendix 1 holds detailed petrographic descriptions for each of the collected samples, while Appendix 2 contains detailed petrographic descriptions for relevant reference specimens held in the BGS Collection of Building Stones. Further details of the petrographic analysis performed, together with explanatory notes, are provided in Appendix 3.

Figure 1 (left). Image showing the buff sandstone walling and copes featuring in part of HFPS work section 25 (Teviot Road). Ordnance Survey grid reference [NT 5020 1460].

Figure 2 (right). Image showing the grey sandstone walling and copes featuring in part of HFPS work section 26 (Wee Haugh). Ordnance Survey grid reference [NT 5030 1490].

2 Site visit

The Hawick flood defences were visited by Luis Albornoz (BGS) on the 29th of October 2024, in the company of Mike Burns (SBC) and Graham Briggs (HES). During the site visit, small samples of the buff sandstone(s) were collected at five different locations along the flood defence wall (**Figure 3**), as approved by SBC. Sampling was achieved by chiselling off small pieces from discreet locations on the wall so as not to deface it. Details of the samples and sampling locations are presented in **Figure 3** and **Table 1**, and photographs showing each of the sampled locations are provided in **Figure 4**.

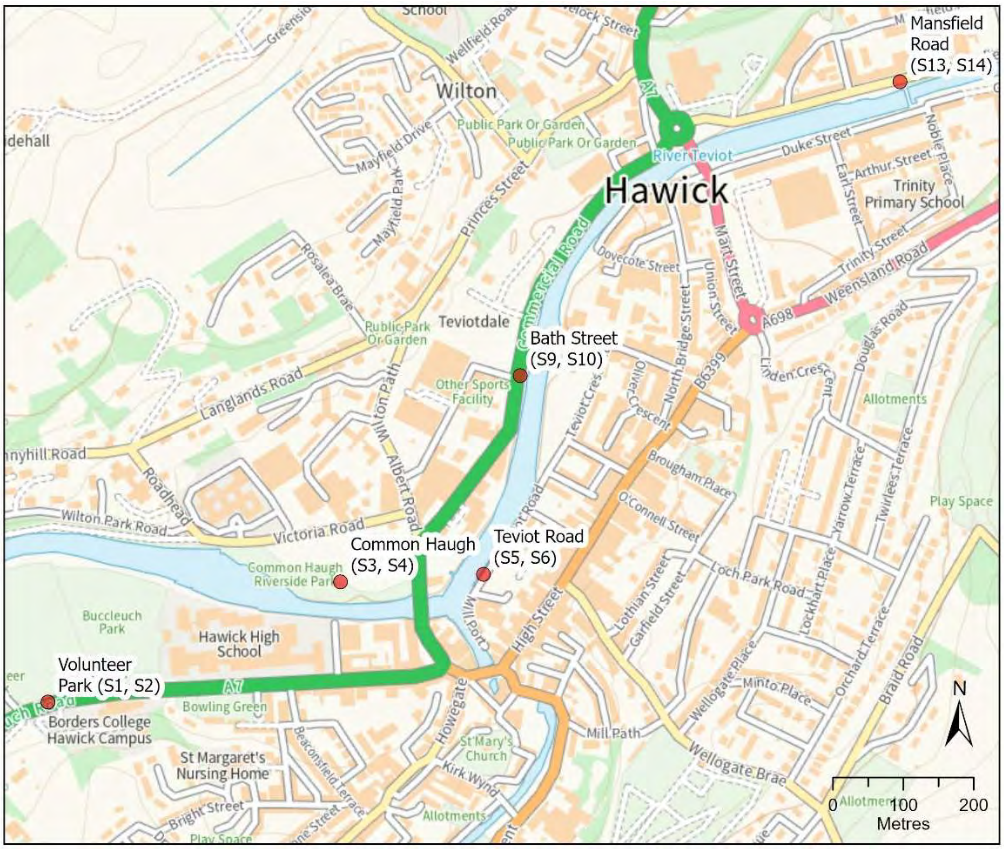

Figure 3. Map showing the five sampling locations (indicated with red dots). At each location, two samples of buff sandstone were collected – one from the copestones and the other from the walling of the flood defence wall. The labels on the map reference the numbers assigned to these samples. Contains Ordnance Survey data © Crown copyright and database rights 2025. OS AC0000824781 EUL

Table 1. Details of sampling locations and samples collected.

Location	Easting	Northing	Work Section No.	Sample	Structural Element	BGS Collection Number	Photograph
Volunteer Park	349557	614407	16	S1	Copestone	ED12509	Figure 4a
Volunteer Park	349557	614407	16	S2	Walling	ED12510	Figure 4a
Common Haugh	349973	614578	2	S3	Copestone	ED12511	Figure 4b
Common Haugh	349973	614578	2	S4	Walling	ED12512	Figure 4b
Teviot Road	350176	614589	25	S5	Copestone	ED12513	Figure 4c
Teviot Road	350176	614589	25	S6	Walling	ED12514	Figure 4c
Bath Street	350228	614871	7	S9	Copestone	ED12517	Figure 4d
Bath Street	350228	614871	7	S10	Walling	ED12518	Figure 4d
Mansfield Road	350768	615289	9	S13	Copestone	ED12521	Figure 4e
Mansfield Road	350768	615289	9	S14	Walling	ED12522	Figure 4e

Figure 4. Photographs of the buff sandstone masonry at the five sampling locations ('numbered' stickers identify the sampled masonry units):

- **a.** Volunteer Park (work section 16); samples S1 (copestone) and S2 (walling)
- **b.** Common Haugh (work section 2), samples S3 (copestone) and S4 (walling)
- **c.** Teviot Road (work section 25); samples S5 (copestone) and S6 (walling)
- **d.** Bath Street (work section 7); samples S9 (copestone) and S10 (walling)
- **e.** Mansfield Road (work section 9); samples S13 (copestone) and S14 (walling)

3 Character and source of buff sandstone masonry

This section provides a summary of the geological characteristics of the 'buff sandstone' masonry and sets out our conclusions with respect to the likely origins of the stone(s), with reference to the samples subjected to petrographic analysis (see petrographic descriptions presented in Appendix 1 and Appendix 2).

The samples collected from the HFPS clearly consist of two different stone types. All of the samples collected from the copestones are of one type, whereas all of the samples collected from the walling masonry are of another type, as follows:

- The samples (S1, S3, S5, S9 and S13) collected from the **copestones** all consist of a stone type that is classified as *subfeldspathic-arenite* (Appendix 1), according to the BGS Rock Classification Scheme (Hallsworth and Knox, 1999). The name *subfeldspathic-arenite* refers to a type of sandstone that is composed primarily of quartz sand grains, but contains minor (albeit appreciable) quantities of feldspar sand grains. There is no discernible reaction with dilute (10%) hydrochloric acid, indicating that the carbonate mineral calcite ($CaCO_3$) is absent or very scarce. Collectively, the petrographic characteristics of the five copestone samples closely resemble those of BGS-held reference specimens of Fletcher Bank sandstone (Appendix 2), which is quarried near Ramsbottom in North West England from strata assigned to the Millstone Grit Group – a geological unit that formed during the Carboniferous Period (between *c.* 359 to 299 million years ago).
- The samples (S2, S4, S6, S10 and S14) collected from the **walling** all consist of a stone type that is classified as *silici-sandy calcarenite* (Appendix 1), according to the BGS Rock Classification Scheme (Hallsworth and Knox, 1999). The name *silici-sandy calcarenite* refers to a rock which is composed primarily of carbonate debris (and thus a type of limestone by definition), but also contains a significant volume of silicate sand grains (predominantly quartz in this case). There is a vigorous reaction with dilute (10%) hydrochloric acid, suggesting that the carbonate material present includes a substantial quantity of calcite. Collectively, the petrographic characteristics of the five walling samples closely resemble those of BGS-held reference specimens (Appendix 2) of a calcarenite stone quarried in Spain that is marketed under the name "Beige Pinar" by the company Areniscas. We believe[2] that this stone is quarried at a location within Spain's Teruel province, from strata that formed during the Miocene Epoch (between *c.* 23 and 5 million years ago).

These findings are summarised in Table 2.

Thin section photographs comparing the five copestone samples with those of a BGS-held sample of Fletcher Bank sandstone are presented in **Figure 5**. Similarly, thin section photographs comparing the five walling samples with those of two BGS-held samples of Beige Pinar calcarenite are presented in **Figure 6**. A simple visual comparison of the images forming **Figure 5** with those forming **Figure 6** highlights the clear contrast that exists between the stone used for the copestones and that used for the walling in terms of compositional make-up and texture.

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[2] While BGS possesses authoritative information on active UK quarries, including comprehensive information about the geological units which they exploit, we do not possess similarly accurate information about the quarries and geology of Spain. Responses to our enquiries received from Areniscas indicate that they source 'Beige Pinar' from a quarry in Teruel that is operated by another company, but the precise location of this quarry and the geology of the site remain unknown. Our assumption that 'Beige Pinar' (and by extension the buff walling stone featuring in the HFPS) is quarried from strata of Miocene age is based on the PhD thesis of Fandos (2008; see: https://zaguan.unizar.es/record/2037/files/TESIS-2009-027.pdf), which includes an inventory of the building stones of Aragon – the region in Spain of which Teruel forms part. Fandos (op. cit.) characterised a stone referred to as 'Piedra de Alcañiz' (or 'Alcañiz Sandstone'), which is quarried in Teruel and is stated to be Miocene in age, and which appears to be virtually identical to BGS-held samples of 'Beige Pinar' in terms of mineralogy and texture. We thus consider it highly likely that 'Beige Pinar' and 'Piedra de Alcañiz' have similar geological origins, and may even be extracted at the same quarry, even though they are differently named.

The close similarity between the copestone samples and the BGS sample of Fletcher Bank sandstone (see **Figure 5**) provides strong evidence that the sampled copestones indeed consist of Fletcher Bank sandstone.

Likewise, the close similarity between the walling samples and the BGS-held samples of Beige Pinar calcarenite (see **Figure 6**) provides compelling evidence that the sampled copestones consist of Beige Pinar calcarenite. However, the possibility that the walling stone represents (or has been sold as) a (?)Miocene stone comparable to Beige Pinar, but originating from a Spanish quarry other than the main source(s) of Beige Pinar, cannot be completely ruled out on the basis of the available evidence.

We note that the contrasting reaction of the two stone types herein recognised to dilute (10%) hydrochloric acid potentially offers a rapid means of testing the in-situ masonry to distinguish the two stones. This may prove useful for verifying the identity and distribution of these stones throughout the different work sections of the HFPS: stone blocks consisting of Fletcher Bank sandstone should show no discernible reaction to a droplet of dilute hydrochloric acid whereas those consisting of Beige Pinar calcarenite will display vigorous fizzing. Such testing should have no detrimental impact on the masonry (or indeed the wider environment).

Table 2. Summary of the stone types represented by the analysed samples of HFPS masonry.

Location	Sample	Structural Element	Stone type	Likely identity / origin
Volunteer Park	S1	Copestone	subfeldspathic-arenite	Fletcher Bank sandstone, North West England
Volunteer Park	S2	Walling	silici-sandy calcarenite	Beige Pinar calcarenite, Spain
Common Haugh	S3	Copestone	subfeldspathic-arenite	Fletcher Bank sandstone, North West England
Common Haugh	S4	Walling	silici-sandy calcarenite	Beige Pinar calcarenite, Spain
Teviot Road	S5	Copestone	subfeldspathic-arenite	Fletcher Bank sandstone, North West England
Teviot Road	S6	Walling	silici-sandy calcarenite	Beige Pinar calc-arenite, Spain
Bath Street	S9	Copestone	subfeldspathic-arenite	Fletcher Bank sandstone, North West England
Bath Street	S10	Walling	silici-sandy calcarenite	Beige Pinar calcarenite, Spain
Mansfield Road	S13	Copestone	subfeldspathic-arenite	Fletcher Bank sandstone, North West England
Mansfield Road	S14	Walling	silici-sandy calcarenite	Beige Pinar calcarenite, Spain

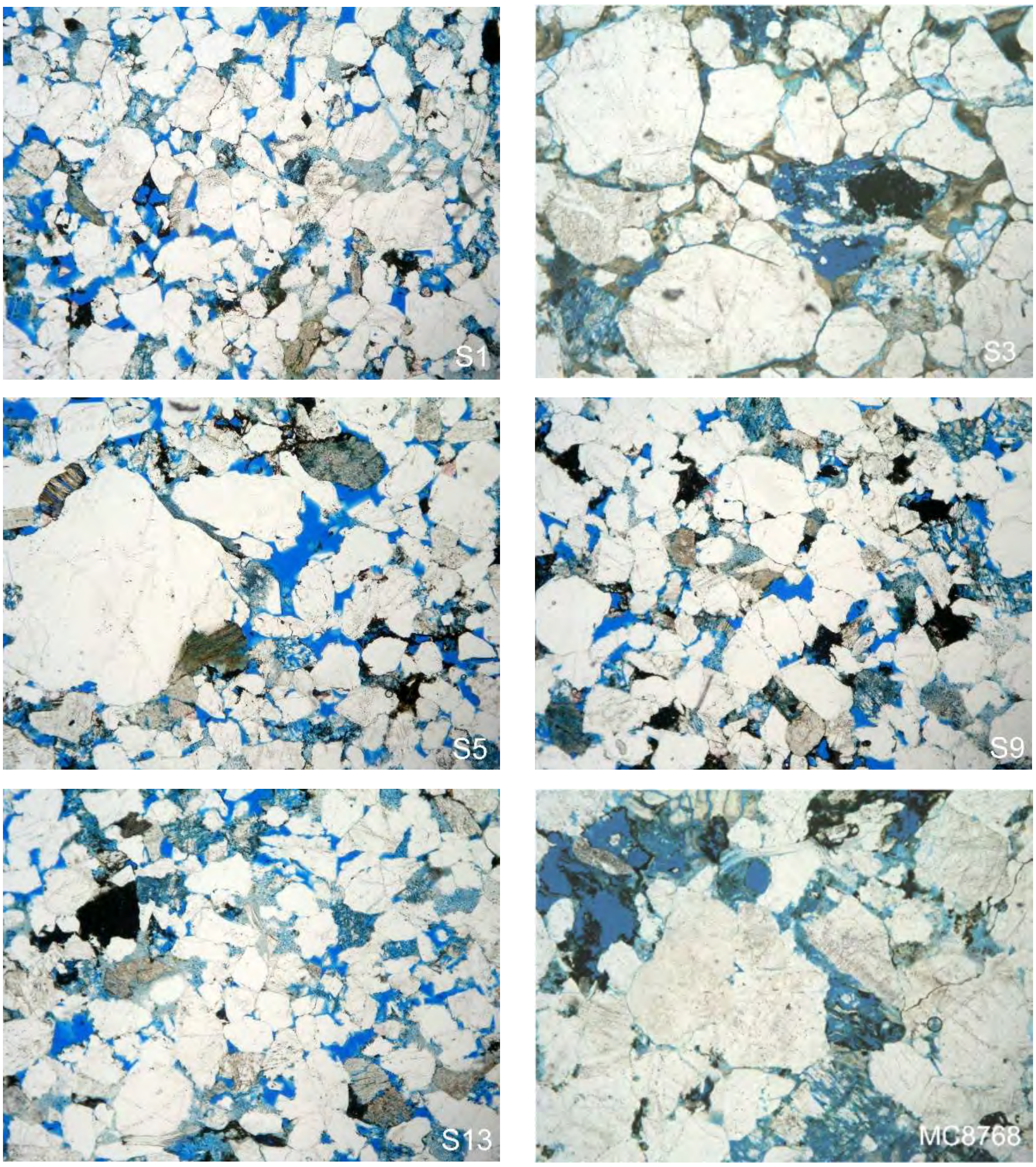


Figure 5. Thin section photographs of samples S1, S3, S5 S9 and S13 (obtained from HFPS **copestones**), along with a thin section photograph of a BGS sample of Fletcher Bank sandstone (MC8768). These samples all consist of fine to very coarse-grained sandstone, with occasional granules and pebbles. The mineral-textural characteristics of all these samples are similar: detrital constituents are mostly angular to subrounded, mono- and poly-crystalline quartz grains (70–77%) which appear white, while feldspar (3–10%) and rock fragments (*c.* 3%) display a range of grey to light brown colours. Iron oxide minerals appear black. Open pore space appears sky blue, whereas pore space occupied by growths of clay minerals appears a lighter blue-grey colour. Total porosity ranges from around 7–12% of the thin section area. The grains are cemented chiefly by quartz overgrowths, which partially surround most of the silicate grains and infill the pore space to a degree. The images were taken in plane-polarised light, and the field of view is *c.* 3.3 mm wide.

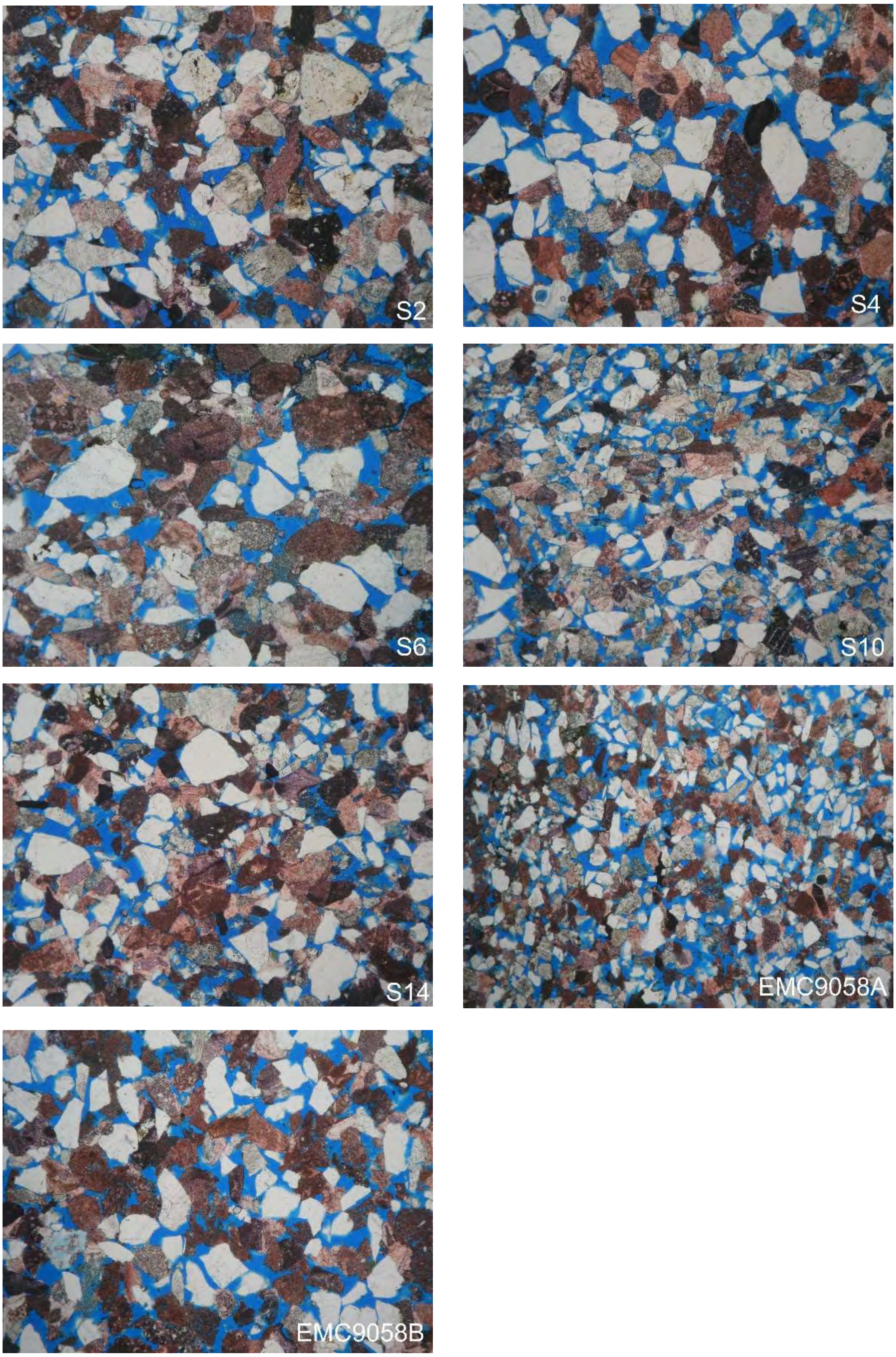


Figure 6. Thin section photographs of samples S2, S4, S6 S10 and S14 (obtained from HFPS **walling**), along with thin section photographs of two BGS samples of 'Beige Pinar' calcarenite (EMC9058A and EMC9058B). Although they vary from fine- to medium-grained, these samples are all similar in terms of their compositional make-up and texture, and contain a similar bioclast assemblage. The detrital component mostly comprises carbonate fragments (*c.* 40%), many of which are bioclasts; these appear brownish grey, pink or dark pinkish brown (dependent on composition and consequent response to the dual carbonate stain). The stone also contains numerous angular, mostly mono-crystalline, quartz grains (20–27%), which appear white. Much smaller quantities of feldspar grains and silicate rock fragments are also present. The grains are cemented chiefly by carbonate minerals, which partially infill the pore space. Open pore space appears sky blue, and total porosity ranges from around 20–26% of the thin section area. The images were taken in plane-polarised light, and the field of view is *c.* 3.3 mm wide.

4 Specification compliance

4.1 SOURCES OF INFORMATION

The specification set out by SBC with respect to the geological and geotechnical properties of the stone to be used for the walling and copestones of the HFPS masonry is detailed in *Appendix 24/1: Brickwork, blockwork and stonework* of the specification document for the works (a copy of which was provided to BGS by SBC).

The specification establishes a series of criteria that the *buff sandstone* to be used in the walling and copestones must satisfy, according to the following performance indicators: *petrographic description* (i.e. stone type)*, minimum apparent density, maximum open porosity, maximum water absorption, minimum flexural strength, frost resistance,* and *minimum compressive strength.* The test method to be used for assessing each performance indicator is specified according to the relevant British/European standard document. The specific parameters for each of the specification criteria are reproduced in Table 3, which also contains relevant test results for Fletcher Bank sandstone and Beige Pinar calcarenite. These test results have been obtained from the following sources of information:

- For both Fletcher Bank sandstone and Beige Pinar calcarenite, the results for the *petrographic description* performance indicator are drawn from the petrographic descriptions presented in Appendix 1 of this report.
- For Beige Pinar calcarenite, the results for *apparent density, open porosity, water absorption, flexural strength, frost resistance,* and *compressive strength* are reproduced from a report (ref: 78813/G) produced by Sandberg Consulting Engineers LLP (henceforth 'Sandberg') that was based on the testing of a set of samples obtained from an on-site stockpile of buff sandstone earmarked for use as HPFS walling. The values quoted are based on the mean (average) results of repeat tests detailed in Sandberg's report.
- For Beige Pinar calcarenite, the result for *salt crystallisation* is also reproduced from the report (ref: 78813/G) by Sandberg. This performance indicator can be useful for evaluating the durability of natural stone. We note, however, that this was not included as one of the specification criteria for the HFPS masonry. The value quoted is based on the mean (average) result of repeat tests detailed in Sandberg's report.
- For Fletcher Bank sandstone, the results for *apparent density, open porosity, water absorption, flexural strength, frost resistance,* and *compressive strength* are reproduced from a technical data sheet (badged by the company BBS Natural Stone Specialists Ltd.) that was provided to SBC by their supplier to demonstrate the compliance of this stone with the specification.
- For Fletcher Bank sandstone, the result for *water absorption,* (which is omitted from the above-mentioned technical data sheet from BBS Natural Stone Specialists) is instead derived from another technical data sheet produced by Marshalls Plc., the operator of the quarry that produces this stone.
- For Fletcher Bank sandstone, the result for *salt crystallisation* is taken from a technical data sheet produced by the Building Research Establishment. We note that this testing was carried out in 1997 and refers to a different standard (BR 141) to that of the salt crystallisation test carried out by Sandberg for the Beige Pinar samples (BS EN 12370). It is generally uncommon for stone suppliers to publish or include results for *salt crystallisation* tests in technical data sheets and it is not often included in specifications for natural stone construction projects.

These test results (Table 3) have been selected as the most representative available for the two stone types identified within the walling and copestones of the HFPS. We note that various other sources of this information exist, including technical datasheets produced by other UK-based suppliers of Fletcher Bank sandstone and Spanish suppliers of Beige Pinar calcarenite. These generally provide comparable values to those presented in this report (Table 3). It needs to be borne in mind that natural variation of the stone produced at a quarry over time will result in certain differences in the values that result from episodic testing for quality control purposes. The results for Fletcher Bank sandstone presented here (where possible) were selected from the technical data sheet that was provided to SBC by the supplier of stone to the scheme. There can be little doubt that the HFPS copestones consist of Fletcher Bank sandstone, and so it can be reasonably assumed that the technical datasheet supplied along with the stone ought to be accurate. On the other hand, given it has been demonstrated that the HFPS walling stone is not Fletcher Bank sandstone (and is likely to be Beige Pinar calcarenite), testing of a batch of this material that was actually supplied to site has been carried out by Sandberg and reproduced in this report. We note that Sandberg were also commissioned by SBC to independently undertake and report (ref: 78813/G/1) the results of a petrographic analysis of the sample material they were supplied with. The results of this petrographic analysis are consistent with those presented in our report for the samples of the HFPS walling stone (see Appendix 1), thereby validating the results of these geotechnical tests for assessing the compliance of this stone with the specification, and its durability characteristics.

Table 3. Comparison of specification criteria and test results for the copestone and walling stone featuring in the HFPS, showing whether these stones 'pass' or 'fail' to meet the criteria for each geological and geotechnical performance indicator within the specification. The sources of this information are detailed in the text above (section 4.1). * The results of the salt crystallisation test quoted for Fletcher Bank sandstone were carried out according to the method specified in standard BR141. Other criteria and test results pertain to the standards quoted within parentheses in the first column of the table.

Performance indicator	Specification criteria	Fletcher Bank sandstone (copestone) test results		Beige Pinar calcarenite (walling stone) test results	
Petrographic description (BS EN 12407)	Fine to medium grained lower carboniferous creamy white to buff sandstone	Carboniferous buff sandstone (subfeldspathic-arenite)	Pass	Miocene buff limestone (calcarenite)	Fail
Apparent density (BS EN 1936)	2150kg/m^3 (assumed minimum)	2310kg/m^3	Pass	2190kg/m^3	Pass
Open porosity (BS EN 1936)	18.7% (maximum)	12.80%	Pass	19.1%	Fail
Water absorption (BS EN 13755)	5.3% (maximum)	3.6%	Pass	6.3%	Fail
Flexural strength (BS EN 13161)	3.5MPa (minimum)	13.7MPa	Pass	3.7MPa	Pass
Frost resistance (BS EN 12371)	3.53MPa (minimum)	15.7MPa	Pass	3.8MPa	Pass
Compressive strength (BS EN 772-1)	60.0MPa (minimum)	87.4MPa	Pass	31MPa	Fail
Salt crystallisation (BS EN 12370)	Not specified	Nil weight loss*	N/A	68.61% weight loss	N/A

4.2 COMPLIANCE WITH THE SPECIFICATION

The outcomes of this investigation have demonstrated that the buff walling stone identified as 'Beige Pinar' calcarenite used throughout the construction of the HFPS is not compliant with the technical specification in several respects:

- The *petrographic description* performance indicator specifies that the buff sandstone to be used is to be a "…carboniferous creamy white to buff sandstone". Although it is of a broadly similar visual appearance to the specified stone, the 'Beige Pinar' walling is not a Carboniferous sandstone, it is a Miocene calcarenite (a type of limestone, not sandstone), of entirely different geological origin and mineral composition.
- Based on the geotechnical test results carried out on representative samples of the 'Beige Pinar' walling stone, this fails to comply with the criteria set out in the specification for the following performance indicators: *maximum open porosity, maximum water absorption,* and *minimum compressive strength*.
- Additionally, although not treated as performance indicators in the previous sub-section, the specification also contains two further stipulations: firstly, that "each type of stone incorporated in the works shall be supplied from a single quarry" and secondly; that the "stone copes… [should consist] of the same stone type as the cladding below". The use of Fletcher Bank sandstone for the copestones and 'Beige Pinar' calcarenite for the walling violates these stipulations.

5 Comments on durability considerations

This investigation has demonstrated that the buff walling stone used for the HFPS masonry (likely 'Beige Pinar' calcarenite) is not compliant with a specification for the works that was intended to offer assurances that the long-term weathering performance of the stonework would be satisfactory. In this respect, the likely durability of the 'Beige Pinar' calcarenite featuring within the HFPS masonry is clearly a cause for concern.

Several factors – including the highly variable character of natural stone, the wide range of natural and human factors that can influence stone decay, and the wide range of environmental settings and conditions that masonry can be subjected to – mean that it is not possible to predict with certainty how any stone will perform in masonry. Nonetheless, a suitable specification, such as that issued by SBC for the works, ought to ensure best efforts to select a stone that will perform as well as can reasonably be expected.

Based on a consideration of the available evidence, it can be concluded that the performance characteristics of the Beige Pinar calcarenite suggest it is less durable than the Fletcher Bank sandstone that was approved for the works. The following points are of note:

- For all the performance indicators set out in the specification, the test result values for 'Beige Pinar' calcarenite are inferior (in some cases considerably so) compared to those of Fletcher Bank sandstone.
- The test results for *salt crystallisation* for 'Beige Pinar' calcarenite (*c.* 69% weight loss) are markedly inferior to those for Fletcher Bank sandstone (nil weight loss). Although the reported results (**Table 1**) relate to different standard test methods, both follow a similar testing process, and considering that the result showing Fletcher Bank is relatively invulnerable to salt crystallisation-induced decay, this contrast is significant.
- Geotechnical test results for Beige Pinar calcarenite demonstrate that it fails to meet the specification for the performance indicators *maximum open porosity, maximum water absorption* and *minimum compressive strength.* Furthermore, the test results only marginally pass specification for the performance indicators *frost resistance* and *flexural strength*. For these tests (see Sandberg report ref: 78813/G), the Lowest Expected Value (which takes into account a margin of experimental error and natural variability), is below that of the specification criteria in both cases.

- The granular framework (detrital grains) of the samples of ‘Beige Pinar’ calcarenite subjected to petrographic analysis (Appendix 1 and 2) are cemented by carbonate minerals (such as calcite), which are inherently prone to chemical dissolution in the presence of moisture, particularly in acidic (pH <7) conditions. This makes the stone potentially susceptible to gradual disaggregation in a wet environment.
- The best guarantee of ‘suitable’ long-term performance for any stone is a demonstrable history of successful use in a similar structural role and setting, and under comparable climactic conditions. Fletcher Bank sandstone (and similar stones from the same geological unit, the Millstone Grit Group) has been used successfully for masonry walls of various forms in the UK for hundreds of years. We are unaware of similar examples of Beige Pinar use in the UK which could serve as reliable predictors of its likely long-term weathering performance in this country.

In conclusion, whilst it is impossible to predict with certainty how durable the ‘Beige Pinar’ stone will prove to be within the masonry of the HFPS, there is an evident risk that its use may result in unsatisfactory long-term weathering performance. Whether or not this will result in the unacceptable deterioration of the HFPS elements featuring ‘Beige Pinar’, and potentially the need for (unplanned) maintenance directly related to such deterioration, may become apparent within 5–10 years.

Appendix 1 Sample descriptions: Hawick Flood Defences masonry

A1.1. VOLUNTEER PARK (WORK SECTION 16); SAMPLES S1 AND S2

Figure 7. Wall at sampling location, Volunteer Park (work section 16). Numbered stickers on the wall indicate the blocks each sample was collected from.

Figure 8. Samples S1 and S2, which were obtained from the copestones and walling, respectively, at the Volunteer Park sampling location (work section 16).

A1.1.1. Petrographic description of sample S1 (copestone, Volunteer Park)

See Appendix 3 for notes describing each numbered item below.

Hand specimen observations

Stone type [1] (general classification):	sandstone
Stone colour [2]:	greyish buff
Stone cohesion [3]:	strongly cohesive
Stone fabric [4]:	uniform (some orientated minerals)
Distinctive features:	none

Thin section observations

Stone constituents [5]:

Granular (detrital) constituents		*Intergranular constituents*	
Quartz	70%	Silica (overgrowth)	2%
Feldspar	5%	Feldspar (overgrowth)	<<1%
Silicate rock fragments	3%	Carbonate	1%
Carbonate debris	0%	Iron/manganese oxide	2%
Mica	<1%	Clay	5%
Opaque material	<1%	Hydrocarbon	0%
Other	<<1%	Intergranular pores	5%
Intragranular pores	7%		

Stone type [1] (detailed classification):	subfeldspathic-arenite
Grain-size [6]:	fine-sand-grade to very coarse-sand-grade, with occasional granules
Grain sorting [7]:	poorly sorted
Grain roundness [8]:	angular to subrounded
Stone permeability [9]:	low
Cement distribution [10]:	silica cement discontinuous
Supergene changes [11]:	strong dissolution of feldspar grains; weak dissolution of rock fragments

Comments

1) The constituent rock fragments comprise a mix of igneous (predominantly granitic-rock), metamorphic (predominantly quartzite) and sedimentary (predominantly mudstone) types. The feldspar grains include both potassic and sodic-calcic varieties; all of these are altered to a greater or lesser extent.
2) At least some of the constituent ‘clay’ has formed as a result of the natural chemical alteration of detrital feldspar grains and rock fragments, likely before the stone was quarried. This has been taken into account in the detailed classification of the stone (see ‘Stone Type’ above).
3) A very small amount (*c.* 1%) of carbonate is present, which appears as minute sparry crystals within the pore system of the stone. The ‘response’ of the dual carbonate stain applied to the thin section suggests that the carbonate minerals dolomite and calcite are present.
4) The detrital quartz grains show evidence of suturing where in contact with one another and have locally significant developments of associated quartz overgrowth cement. These observations provide an explanation for the strongly cohesive character of the stone.
5) Both biotite (‘brown’ mica) and muscovite (‘white’ mica) are present as small flakes, which often appear deformed (due to compaction during diagenesis). Most (but not all) are broadly aligned parallel to the sedimentary bedding.
6) The minerals epidote and zircon are present in trace amounts (together accounting for <<1% of the total thin section area).
7) The sample shows no discernible reaction with dilute (10%) hydrochloric acid.

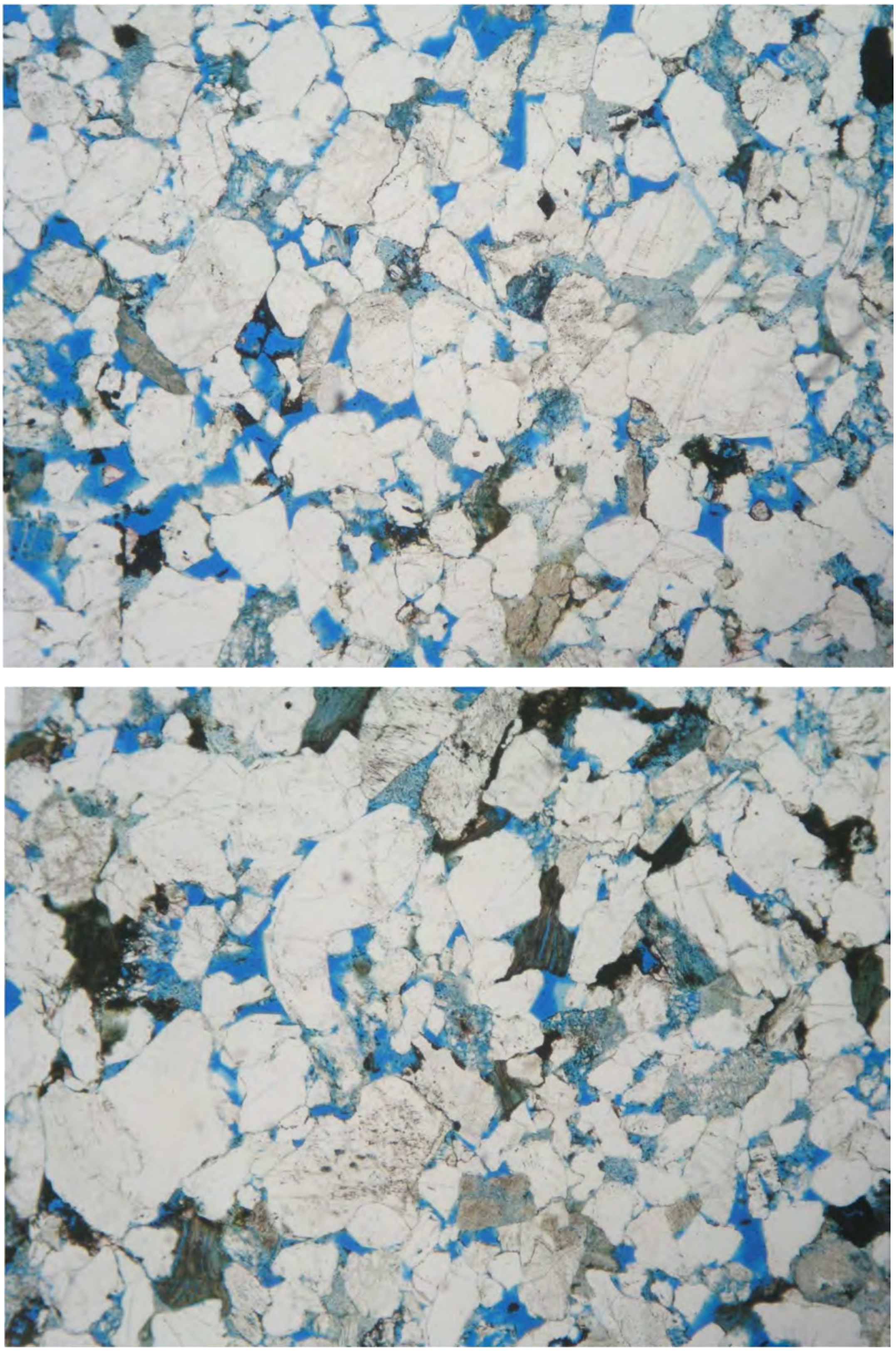


Figure 9. Thin section photographs of sample S1 (copestone, Volunteer Park).

Quartz grains appear white, while feldspar and rock fragments display a range of grey to light brown colours. Iron oxide minerals appear black. Open pore space appears sky blue, whereas pore space occupied by growths of clay minerals appears a lighter blue-grey colour. The images were taken in plane-polarised light, and the field of view is *c.* 3.3 mm wide.

A1.1.2. Petrographic description of sample S2 (walling, Volunteer Park)

See Appendix 3 for notes describing each numbered item below.

Hand specimen observations

Stone type [1] (general classification):	limestone
Stone colour [2]:	buff
Stone cohesion [3]:	strongly cohesive
Stone fabric [4]:	uniform
Distinctive features:	significant carbonate debris

Thin section observations

Stone constituents [5]:

Granular (detrital) constituents		*Intergranular constituents*	
Quartz	24%	Silica (overgrowth)	<<1%
Feldspar	2%	Feldspar (overgrowth)	0%
Silicate rock fragments	1%	Carbonate	9%
Carbonate debris	38%	Iron/manganese oxide	<1%
Mica	0%	Clay	<<1%
Opaque material	<1%	Hydrocarbon	0%
Other	<<1%	Intergranular pores	24%
Intragranular pores	1%		

Stone type [1] (detailed classification):	silici-sandy calcarenite
Grain-size [6]:	medium-sand-grade
Grain sorting [7]:	moderately well sorted
Grain roundness [8]:	angular to subrounded
Stone permeability [9]:	high
Cement distribution [10]:	carbonate cement discontinuous
Supergene changes [11]:	weak dissolution of feldspar grains; weak dissolution of rock fragments

Comments

1) The detrital content consists essentially of carbonate-based debris and quartz grains. Also present are silicate-based rock fragments (in this case, chert and quartzite), although these are a comparatively minor component overall (accounting for *c.* 1% of the modal volume).

2) The individual quartz grains are typically angular, in contrast to the carbonate-based debris, the grains of which normally show evidence of appreciable abrasion and rounding.

3) The carbonate-based debris comprises grains ('clasts') of various types and sizes. These include bioclasts (notably echinoderm and bivalve debris, together with foraminifera tests), peloids and reworked pieces of 'limestone'. Mineralogically, some of the 'clasts' are evidently calcitic, whereas others are dolomitic (based on their response to the dual carbonate stain). Micritization and/or impregnation with iron oxide minerals affect a proportion of the 'clasts'.

4) The detrital constituents collectively are held together by a discontinuous intergranular carbonate cement (mostly calcitic, but in part dolomitic). The calcite often forms conspicuous (syntaxial) overgrowths on specific bioclasts.

5) The sample reacts vigorously with dilute (10%) hydrochloric acid, reflecting the fact that the carbonate material present (including both the carbonate-based debris and intergranular carbonate cement) consists in large part of the mineral calcite.

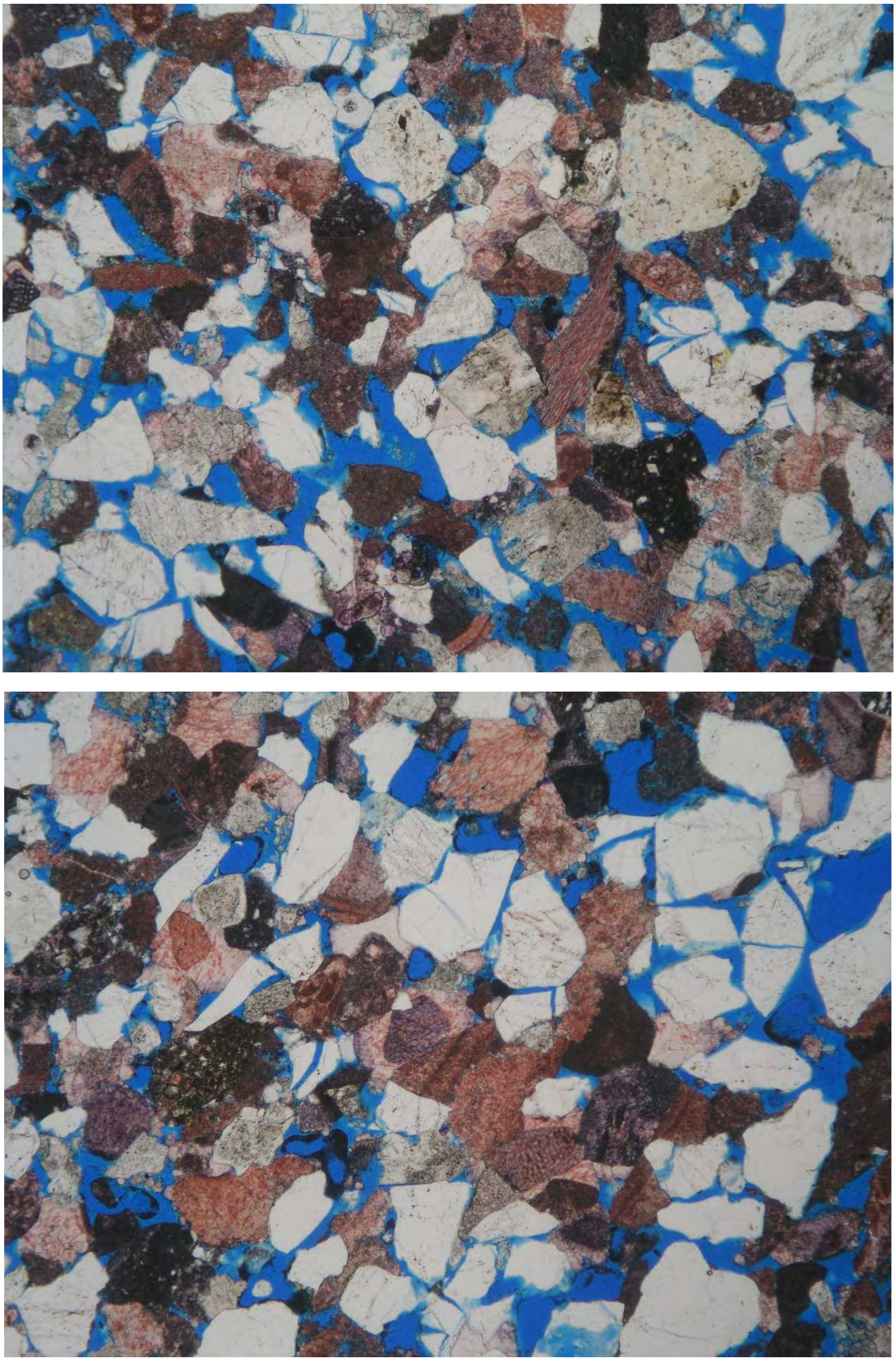


Figure 10. Thin section photographs of sample S2 (walling, Volunteer Park).

Quartz grains appear white, while carbonate-based ‘clasts’ appear light brownish grey, pink or dark pinkish brown (dependent on composition and consequent response to the dual carbonate stain). Iron oxide minerals appear black or almost black (in some cases, associated with carbonate-based ‘clasts’). Open pore space appears an intense sky blue colour. The images were taken in plane-polarised light, and the field of view is *c.* 3.3 mm wide.

A1.2. COMMON HAUGH (WORK SECTION 2); SAMPLES S3 AND S4

Figure 11. Wall at sampling location, Common Haugh (work section 2). Numbered stickers on the wall indicate the blocks each sample was collected from.

Figure 12. Samples S3 and S4, which were obtained from the copestones and walling, respectively, at the Common Haugh sampling location (work section 2).

A1.2.1. Petrographic description of sample S3 (copestone, Common Haugh)

See Appendix 3 for notes describing each numbered item below.

Hand specimen observations

Stone type [1] (general classification):	sandstone
Stone colour [2]:	greyish buff
Stone cohesion [3]:	moderately cohesive
Stone fabric [4]:	uniform
Distinctive features:	none

Thin section observations

Stone constituents [5]:

Granular (detrital) constituents		*Intergranular constituents*	
Quartz	77%	Silica (overgrowth)	2%
Feldspar	3%	Feldspar (overgrowth)	<<1%
Silicate rock fragments	2%	Carbonate	<<1%
Carbonate debris	0%	Iron/manganese oxide	1%
Mica	<1%	Clay	6%
Opaque material	1%	Hydrocarbon	0%
Other	<<1%	Intergranular pores	2%
Intragranular pores	5%		

Stone type [1] (detailed classification):	subfeldspathic-arenite
Grain-size [6]:	fine-sand-grade to very coarse-sand-grade, with occasional granules
Grain sorting [7]:	poorly sorted
Grain roundness [8]:	angular to subrounded
Stone permeability [9]:	low
Cement distribution [10]:	silica cement discontinuous
Supergene changes [11]:	strong dissolution of feldspar grains; moderate dissolution of rock fragments

Comments

1) The constituent rock fragments comprise a mix of metamorphic (predominantly quartzite) and sedimentary (predominantly mudstone) types. The feldspar grains include both potassic and sodic-calcic varieties; all of these are altered to a greater or lesser extent. Ochreous spots of up to 3 mm in diameter provide evidence of iron oxide remobilisation.

2) At least some of the constituent ‘clay’ has formed as a result of the natural chemical alteration of detrital feldspar grains and rock fragments, likely before the stone was quarried. This has been taken into account in the detailed classification of the stone (see ‘Stone Type’ above).

3) A trace amount (<<1%) of carbonate is present, which appears as sparry crystals. The carbonate mineral has not ‘taken’ the dual carbonate stain and is interpreted to be dolomite as a result.

4) The detrital quartz grains show evidence of suturing where in contact with one another. Quartz overgrowths are only moderately developed, however, which explains the moderately cohesive character of this particular sample. The common presence of intergranular clay minerals – likely equating to strongly compacted mudstone intraclasts – has potentially inhibited the development of the quartz overgrowth cement.

5) Both biotite (‘brown’ mica) and muscovite (‘white’ mica) are present as small flakes, which often appear deformed (due to compaction during diagenesis). They show no particular alignment to the sedimentary bedding.

6) The mineral zircon is present in trace amounts (together accounting for <<1% of the total thin section area).

7) The sample shows no discernible reaction with dilute (10%) hydrochloric acid.

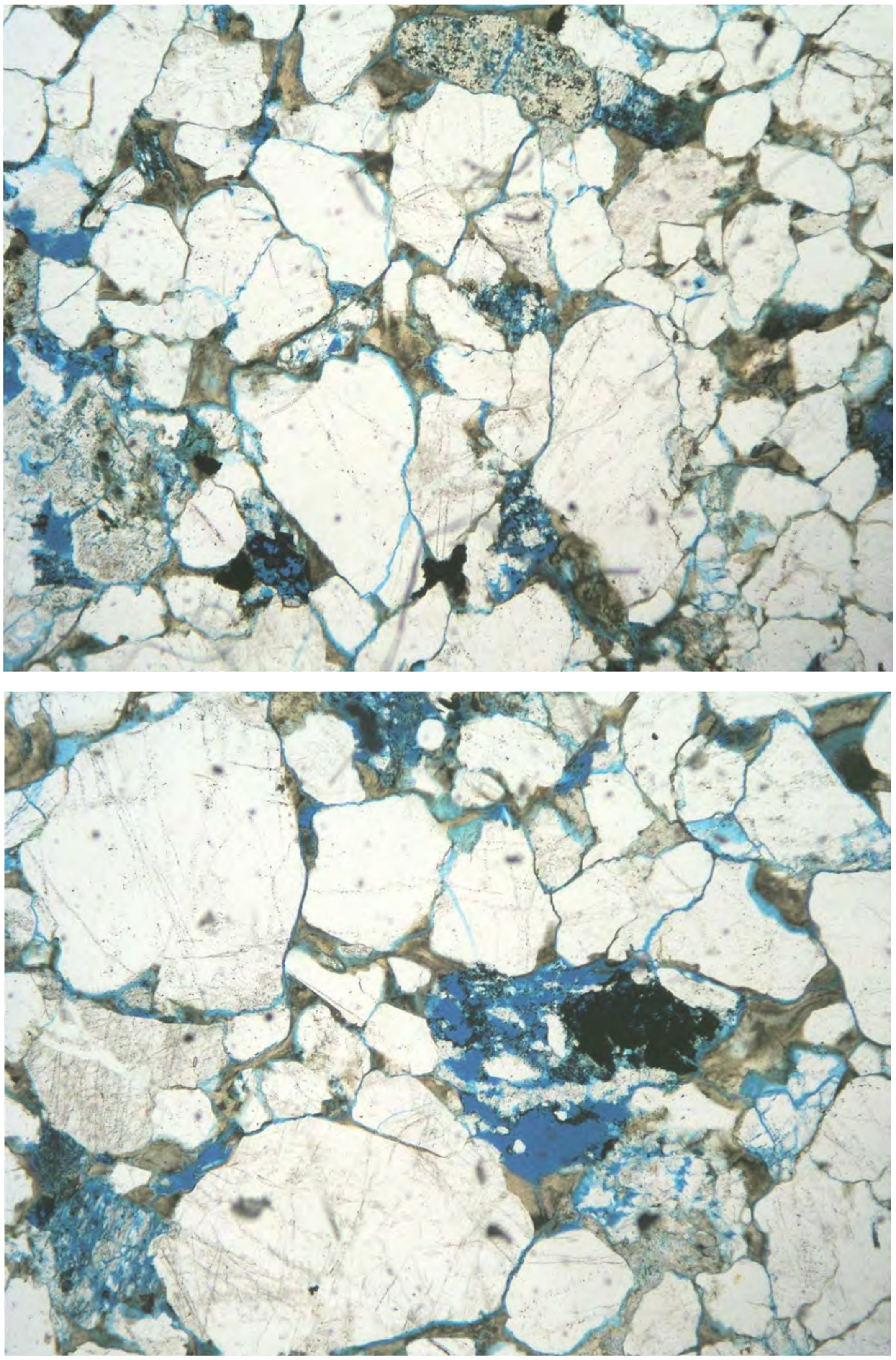


Figure 13. Thin section photographs of sample S3 (copestone, Common Haugh).

Quartz grains appear white, while rock fragments display a range of grey to light brown colours. Iron oxide minerals appear black. Open pore space appears sky blue, whereas pore space occupied by growths of clay minerals appears a lighter blue-grey colour. The images were taken in plane-polarised light, and the field of view is *c.* 3.3 mm wide.

A1.2.2. Petrographic description of sample S4 (walling, Common Haugh)

See Appendix 3 for notes describing each numbered item below.

Hand specimen observations

Stone type [1] (general classification):	limestone
Stone colour [2]:	buff
Stone cohesion [3]:	strongly cohesive
Stone fabric [4]:	uniform
Distinctive features:	significant carbonate debris

Thin section observations

Stone constituents [5]:	*Granular (detrital) constituents*		*Intergranular constituents*	
	Quartz	23%	Silica (overgrowth)	<<1%
	Feldspar	1%	Feldspar (overgrowth)	0%
	Silicate rock fragments	<1%	Carbonate	8%
	Carbonate debris	41%	Iron/manganese oxide	<1%
	Mica	0%	Clay	<1%
	Opaque material	<1%	Hydrocarbon	0%
	Other	<<1%	Intergranular pores	26%
	Intragranular pores	<1%		

Stone type [1] (detailed classification):	silici-sandy calcarenite
Grain-size [6]:	medium-sand-grade
Grain sorting [7]:	moderately well sorted
Grain roundness [8]:	angular to subrounded
Stone permeability [9]:	high
Cement distribution [10]:	carbonate cement discontinuous
Supergene changes [11]:	weak dissolution of feldspar grains; weak dissolution of rock fragments

Comments

1) The detrital content consists essentially of carbonate-based debris and quartz grains. Also present are silicate-based rock fragments (in this case, chert and quartzite), although these are a trace component overall (accounting for *c.* <1% of the modal volume).

2) The individual quartz grains are typically angular, in contrast to the carbonate-based debris, the grains of which normally show evidence of appreciable abrasion and rounding.

3) The carbonate-based debris comprises grains ('clasts') of various types and sizes. These include bioclasts (notably echinoderm and bivalve debris, together with foraminifera tests), peloids and reworked pieces of 'limestone'. Mineralogically, some of the 'clasts' are evidently calcitic, whereas others are dolomitic (based on their response to the dual carbonate stain). Micritization and/or impregnation with iron oxide minerals affect a proportion of the 'clasts'.

4) The detrital constituents collectively are held together by a discontinuous intergranular carbonate cement (mostly calcitic, but in part dolomitic). The calcite often forms conspicuous (syntaxial) overgrowths on specific bioclasts.

5) The sample reacts vigorously with dilute (10%) hydrochloric acid, reflecting the fact that the carbonate material present (including both the carbonate-based debris and intergranular carbonate cement) consists in large part of the mineral calcite.

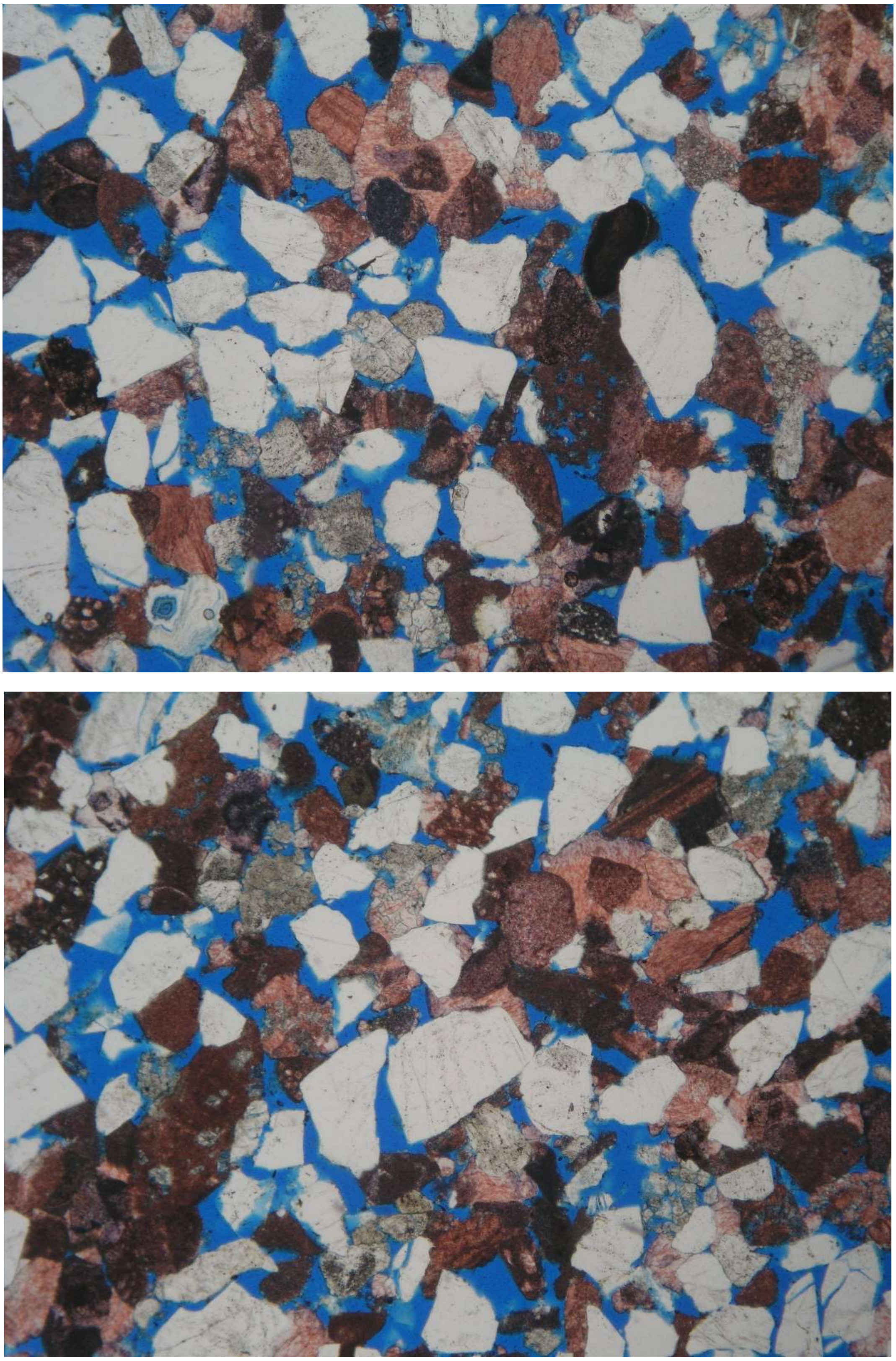


Figure 14. Thin section photographs of sample S4 (walling, Common Haugh).

Quartz grains appear white, while carbonate-based ‘clasts’ appear light brownish grey, pink or dark pinkish brown (dependent on composition and consequent response to the dual carbonate stain). Iron oxide minerals appear black or almost black (in some cases, associated with carbonate-based ‘clasts’). Open pore space appears an intense sky blue colour. The images were taken in plane-polarised light, and the field of view is *c.* 3.3 mm wide.

A1.3. TEVIOT ROAD (WORK SECTION 25); SAMPLES S5 AND S6

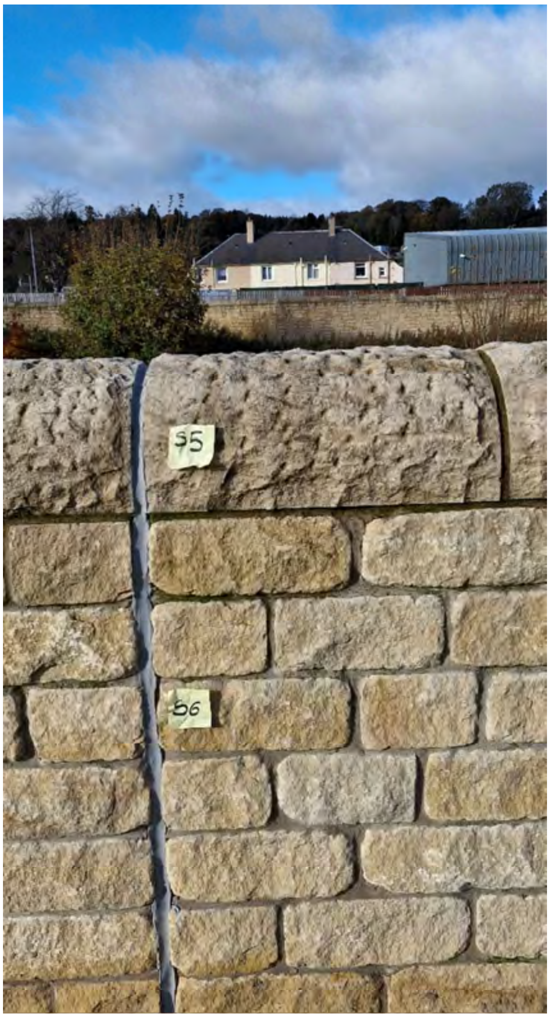


Figure 15. Wall at sampling location, Teviot Road (work section 25). Numbered stickers on the wall indicate the blocks each sample was collected from.

Figure 16. Samples S5 and S6, which were obtained from the copestones and walling respectively, at the Teviot Road sampling location (work section 25).

A1.3.1. Petrographic description of sample S5 (copestone, Teviot Road)

See Appendix 3 for notes describing each numbered item below.

Hand specimen observations

Stone type [1] (general classification):	sandstone
Stone colour [2]:	light greyish buff
Stone cohesion [3]:	strongly cohesive
Stone fabric [4]:	uniform
Distinctive features:	none

Thin section observations

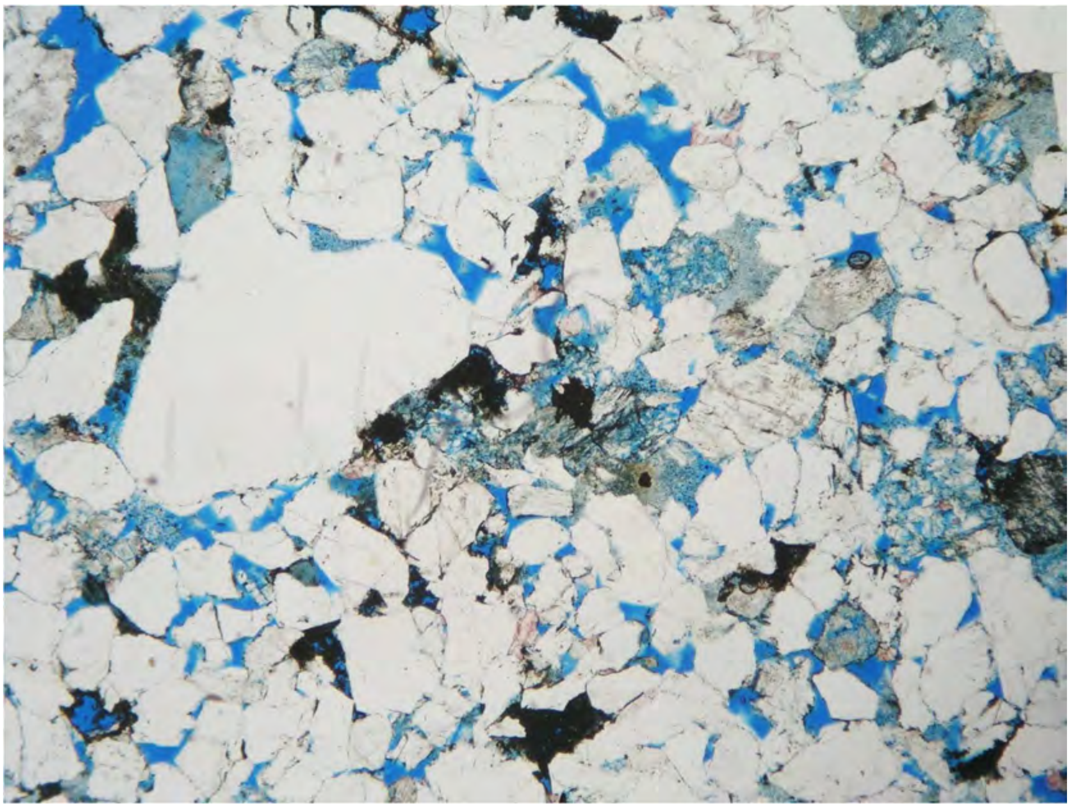
Stone constituents [5]:

Granular (detrital) constituents		*Intergranular constituents*	
Quartz	76%	Silica (overgrowth)	2%
Feldspar	4%	Feldspar (overgrowth)	<<1%
Silicate rock fragments	2%	Carbonate	<1%
Carbonate debris	0%	Iron/manganese oxide	2%
Mica	<1%	Clay	4%
Opaque material	<1%	Hydrocarbon	0%
Other	<<1%	Intergranular pores	2%
Intragranular pores	6%		

Stone type [1] (detailed classification):	subfeldspathic-arenite
Grain-size [6]:	fine-sand-grade to very coarse-sand-grade
Grain sorting [7]:	poorly sorted
Grain roundness [8]:	angular to subrounded
Stone permeability [9]:	low
Cement distribution [10]:	silica cement discontinuous
Supergene changes [11]:	strong dissolution of feldspar grains; moderate dissolution of rock fragments

Comments

1) The constituent rock fragments comprise a mix of metamorphic (predominantly quartzite) and sedimentary (predominantly mudstone) types. The feldspar grains include both potassic and sodic-calcic varieties; all of these are altered to a greater or lesser extent.
2) At least some of the constituent 'clay' has formed as a result of the natural chemical alteration of detrital feldspar grains and rock fragments, likely before the stone was quarried. This has been taken into account in the detailed classification of the stone (see 'Stone Type' above).
3) A very small amount (<1%) of carbonate is present, which appears as very small sparry crystals between the detrital grains. The 'response' of the dual carbonate stain applied to the thin section suggests that the carbonate minerals dolomite and calcite are present.
4) The detrital quartz grains show evidence of suturing where in contact with one another and have moderately to well-developed quartz overgrowths. This gives the stone a strongly cohesive character.
5) Both biotite ('brown' mica) and muscovite ('white' mica) are present as small flakes, which often appear deformed (due to compaction during diagenesis). There is no particular orientation of the mica flakes.
6) The minerals epidote and zircon are present in trace amounts (together accounting for <<1% of the total thin section area).
7) The sample shows no discernible reaction with dilute (10%) hydrochloric acid.



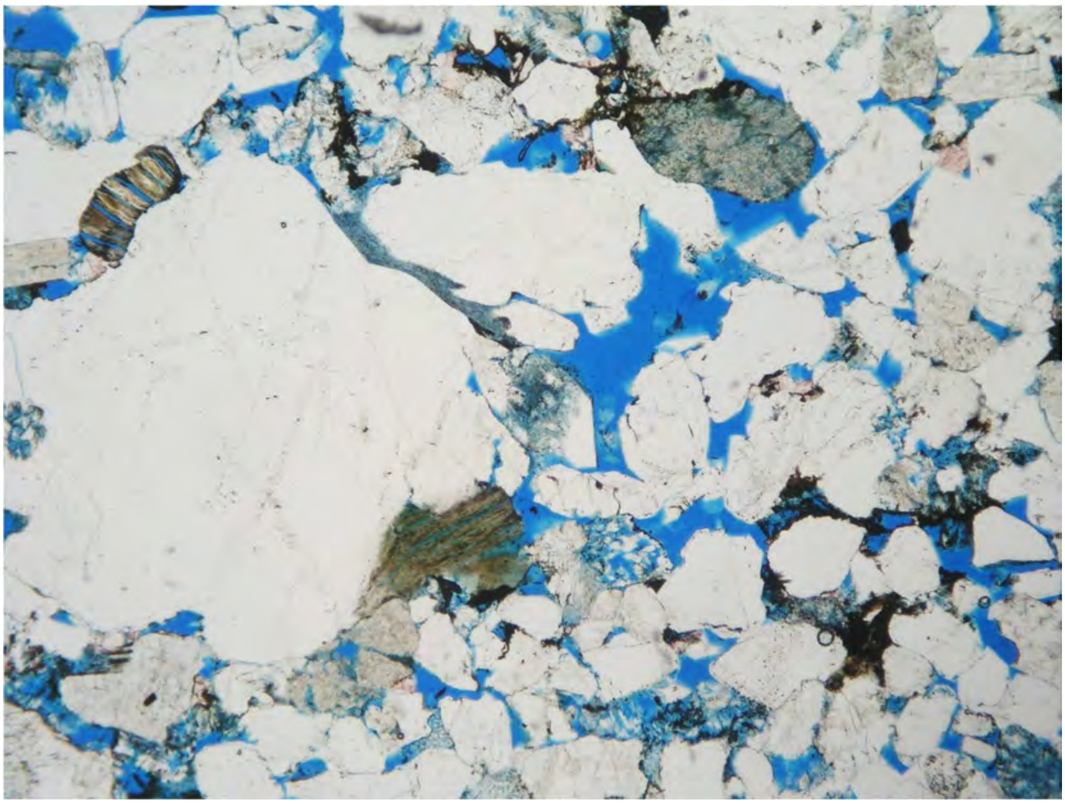


Figure 17. Thin section photographs of sample S5 (copestone, Teviot Road).

Quartz grains appear white, while rock fragments display a range of grey to light brown colours. Iron oxide minerals appear black. Open pore space appears sky blue, whereas pore space occupied by growths of clay minerals appears a lighter blue-grey colour. Very small intergranular developments of calcite appear pink. The images were taken in plane-polarised light, and the field of view is *c.* 3.3 mm wide.

A1.3.2. Petrographic description of sample S6 (walling, Teviot Road)

See Appendix 3 for notes describing each numbered item below.

Hand specimen observations

Stone type [1] (general classification):	limestone
Stone colour [2]:	buff
Stone cohesion [3]:	strongly cohesive
Stone fabric [4]:	uniform
Distinctive features:	significant carbonate debris

Thin section observations

Stone constituents [5]:

Granular (detrital) constituents		*Intergranular constituents*	
Quartz	20%	Silica (overgrowth)	<<1%
Feldspar	1%	Feldspar (overgrowth)	0%
Silicate rock fragments	<1%	Carbonate	8%
Carbonate debris	51%	Iron/manganese oxide	<1%
Mica	0%	Clay	<<1%
Opaque material	<1%	Hydrocarbon	0%
Other	<<1%	Intergranular pores	19%
Intragranular pores	0%		

Stone type [1] (detailed classification):	silici-sandy calcarenite
Grain-size [6]:	medium-sand-grade
Grain sorting [7]:	moderately sorted
Grain roundness [8]:	angular to subrounded
Stone permeability [9]:	moderate to high
Cement distribution [10]:	carbonate cement discontinuous
Supergene changes [11]:	weak dissolution of feldspar grains; weak dissolution of rock fragments

Comments

1) The detrital content consists essentially of carbonate-based debris and quartz grains. Also present are silicate-based rock fragments (in this case, chert and quartzite), although these are a trace component overall (accounting for *c.* <1% of the modal volume).
2) The individual quartz grains are typically angular, in contrast to the carbonate-based debris, the grains of which normally show evidence of appreciable abrasion and rounding.
3) The carbonate-based debris comprises grains ('clasts') of various types and sizes. These include bioclasts (notably echinoderm and bivalve debris, together with foraminifera tests), peloids and reworked pieces of 'limestone'. Mineralogically, some of the 'clasts' are evidently calcitic, whereas others are dolomitic (based on their response to the dual carbonate stain). Micritization and/or impregnation with iron oxide minerals affect a proportion of the 'clasts'.
4) The detrital constituents collectively are held together by a discontinuous intergranular carbonate cement (mostly calcitic, but in part dolomitic). The calcite often forms conspicuous (syntaxial) overgrowths on specific bioclasts.
5) The sample reacts vigorously with dilute (10%) hydrochloric acid, reflecting the fact that the carbonate material present (including both the carbonate-based debris and intergranular carbonate cement) consists in large part of the mineral calcite.

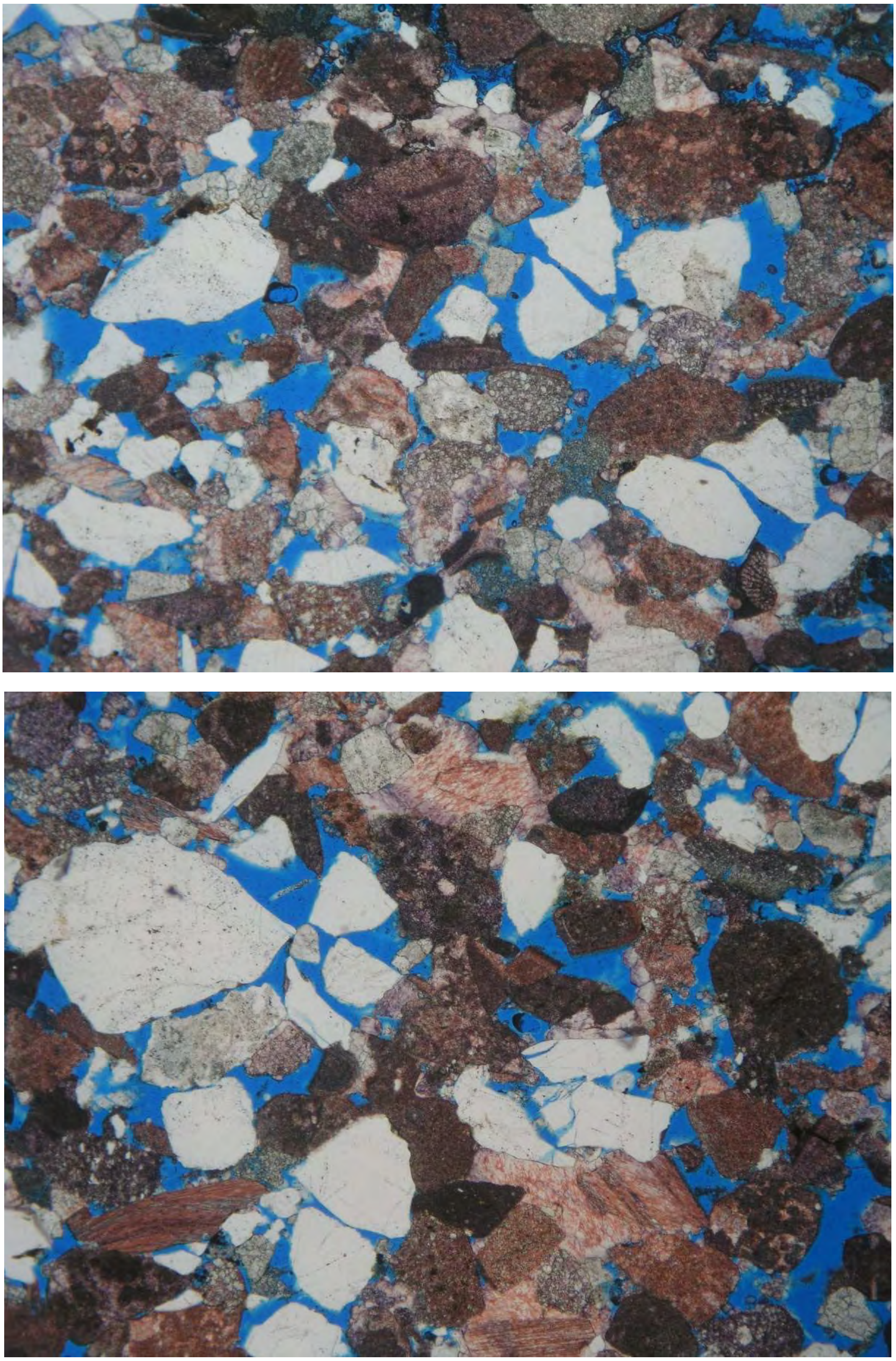


Figure 18. Thin section photographs of sample S6 (walling, Teviot Road).

Quartz grains appear white, while feldspar grains and carbonate-based ‘clasts’ appear light brownish grey, pink or dark pinkish brown (dependent on composition and consequent response to the dual carbonate stain). Iron oxide minerals appear black or almost black (in some cases, associated with carbonate-based ‘clasts’). Open pore space appears an intense sky blue colour. The images were taken in plane-polarised light, and the field of view is *c.* 3.3 mm wide.

A1.4. BATH STREET (WORK SECTION 7); SAMPLES S9 AND S10

Figure 19. Wall at sampling location, Bath Street (work section 7). Numbered stickers on the wall indicate the blocks each sample was collected from.

Figure 20. Samples S9 and S10, which were obtained from the copestones and walling, respectively, at the Bath Street sampling location (work section 7).

A1.4.1. Petrographic description of sample S9 (copestone, Bath Street)

See Appendix 3 for notes describing each numbered item below.

Hand specimen observations

Stone type [1] (general classification):	sandstone
Stone colour [2]:	greyish buff
Stone cohesion [3]:	strongly cohesive
Stone fabric [4]:	uniform
Distinctive features:	none

Thin section observations

Stone constituents [5]:

Granular (detrital) constituents		*Intergranular constituents*	
Quartz	72%	Silica (overgrowth)	2%
Feldspar	6%	Feldspar (overgrowth)	<<1%
Silicate rock fragments	2%	Carbonate	<1%
Carbonate debris	0%	Iron/manganese oxide	3%
Mica	<1%	Clay	3%
Opaque material	<1%	Hydrocarbon	0%
Other	<<1%	Intergranular pores	4%
Intragranular pores	6%		

Stone type [1] (detailed classification):	subfeldspathic-arenite
Grain-size [6]:	fine-sand-grade to coarse-sand-grade
Grain sorting [7]:	poorly sorted
Grain roundness [8]:	angular to subrounded
Stone permeability [9]:	moderate
Cement distribution [10]:	silica cement discontinuous, carbonate cement isolated
Supergene changes [11]:	strong dissolution of feldspar grains; moderate dissolution of rock fragments

Comments

1) The constituent rock fragments comprise a mix of metamorphic (predominantly quartzite) and sedimentary (predominantly mudstone) types. The feldspar grains include both potassic and sodic-calcic varieties; all of these are altered to a greater or lesser extent.
2) At least some of the constituent ‘clay’ has formed as a result of the natural chemical alteration of detrital feldspar grains and rock fragments, likely before the stone was quarried. This has been taken into account in the detailed classification of the stone (see ‘Stone Type’ above).
3) A very small amount (<1%) of carbonate is present, which appears as minute sparry crystals within the pore system of the stone. Most of the carbonate has ‘taken’ the dual carbonate stain, and is interpreted to be non-ferroan calcite as a result.
4) The detrital quartz grains show evidence of suturing where in contact with one another and have locally significant developments of associated quartz overgrowth cement. These observations provide an explanation for the strongly cohesive character of the stone.
5) Both biotite (‘brown’ mica) and muscovite (‘white’ mica) are present as small flakes, which often appear deformed (due to compaction during diagenesis). The grains show no particular alignment.
6) The minerals epidote and zircon are present in trace amounts (together accounting for <<1% of the total thin section area).
7) The sample shows no discernible reaction with dilute (10%) hydrochloric acid.

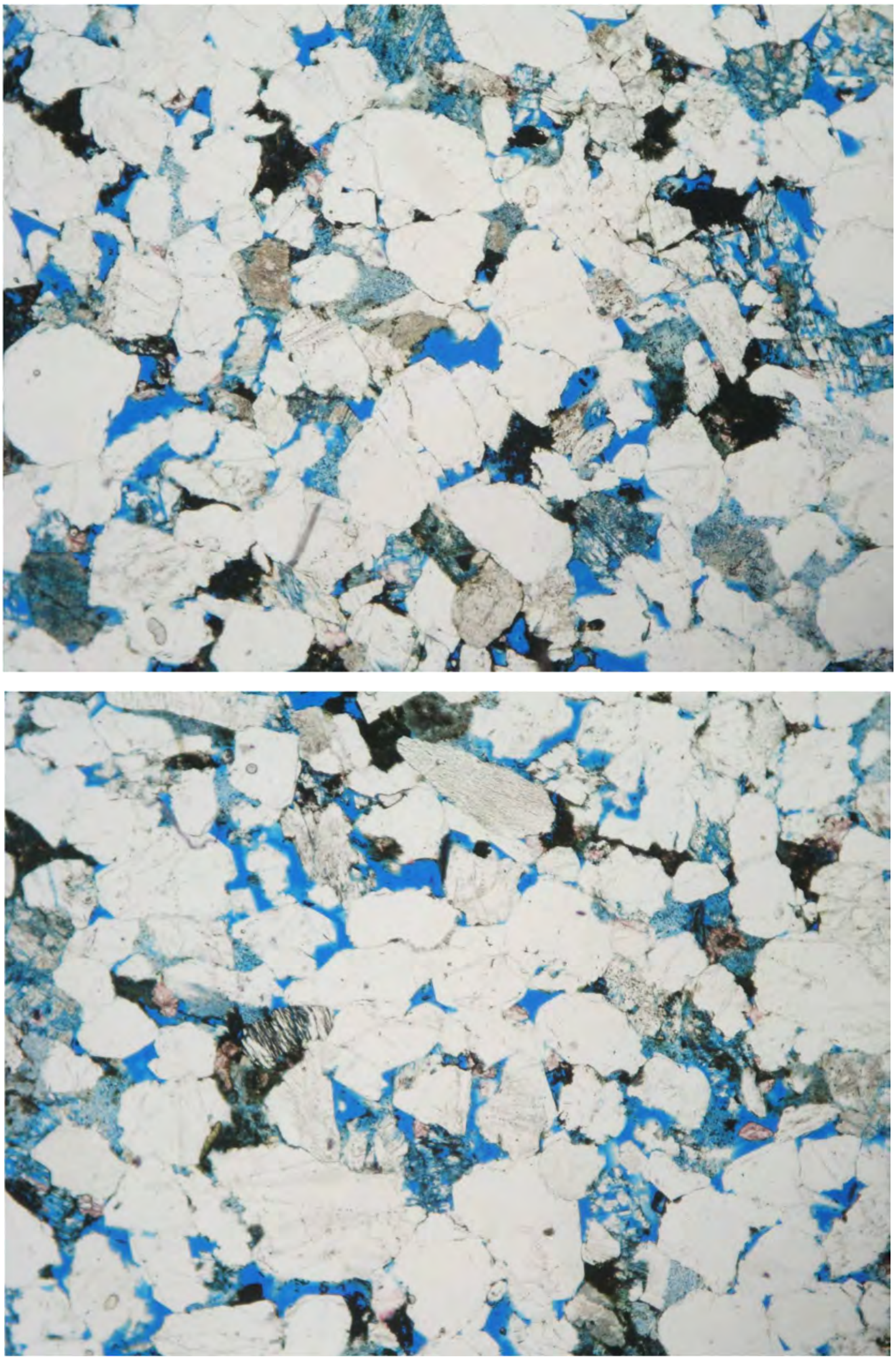


Figure 21. Thin section photographs of sample S9 (copestone, Bath Street).

Quartz grains appear white, while rock fragments display a range of grey to light brown colours. Iron oxide minerals appear black. Small, pinkish crystals within the pore system of the stone are carbonate (likely non-ferroan calcite). Open pore space appears sky blue, whereas pore space occupied by growths of clay minerals appears a lighter blue-grey colour. The images were taken in plane-polarised light, and the field of view is *c.* 3.3 mm wide.

A1.4.2. Petrographic description of sample S10 (walling, Bath Street)

See Appendix 3 for notes describing each numbered item below.

Hand specimen observations

Stone type [1] (general classification):	limestone
Stone colour [2]:	buff
Stone cohesion [3]:	strongly cohesive
Stone fabric [4]:	uniform
Distinctive features:	significant carbonate debris

Thin section observations

Stone constituents [5]:	*Granular (detrital) constituents*		*Intergranular constituents*	
	Quartz	25%	Silica (overgrowth)	<<1%
	Feldspar	<1%	Feldspar (overgrowth)	0%
	Silicate rock fragments	0%	Carbonate	9%
	Carbonate debris	42%	Iron/manganese oxide	<1%
	Mica	0%	Clay	<<1%
	Opaque material	<1%	Hydrocarbon	0%
	Other	<<1%	Intergranular pores	22%
	Intragranular pores	0%		

Stone type [1] (detailed classification):	silici-sandy calcarenite
Grain-size [6]:	fine-sand-grade
Grain sorting [7]:	moderately well sorted
Grain roundness [8]:	angular to subrounded
Stone permeability [9]:	high
Cement distribution [10]:	carbonate cement discontinuous
Supergene changes [11]:	weak dissolution of feldspar grains; weak dissolution of rock fragments

Comments

1) The detrital content consists essentially of carbonate-based debris and quartz grains.
2) The individual quartz grains are typically angular, in contrast to the carbonate-based debris, the grains of which normally show evidence of appreciable abrasion and rounding.
3) The carbonate-based debris comprises grains ('clasts') of various types and sizes. These include bioclasts (notably echinoderm and bivalve debris, together with foraminifera tests), peloids and reworked pieces of 'limestone'. Mineralogically, some of the 'clasts' are evidently calcitic, whereas others are dolomitic (based on their response to the dual carbonate stain). Micritization and/or impregnation with iron oxide minerals affect a proportion of the 'clasts'.
4) The detrital constituents collectively are held together by a discontinuous intergranular carbonate cement (mostly calcitic, but in part dolomitic). The calcite often forms conspicuous (syntaxial) overgrowths on specific bioclasts.
5) The sample reacts vigorously with dilute (10%) hydrochloric acid, reflecting the fact that the carbonate material present (including both the carbonate-based debris and intergranular carbonate cement) consists in large part of the mineral calcite.

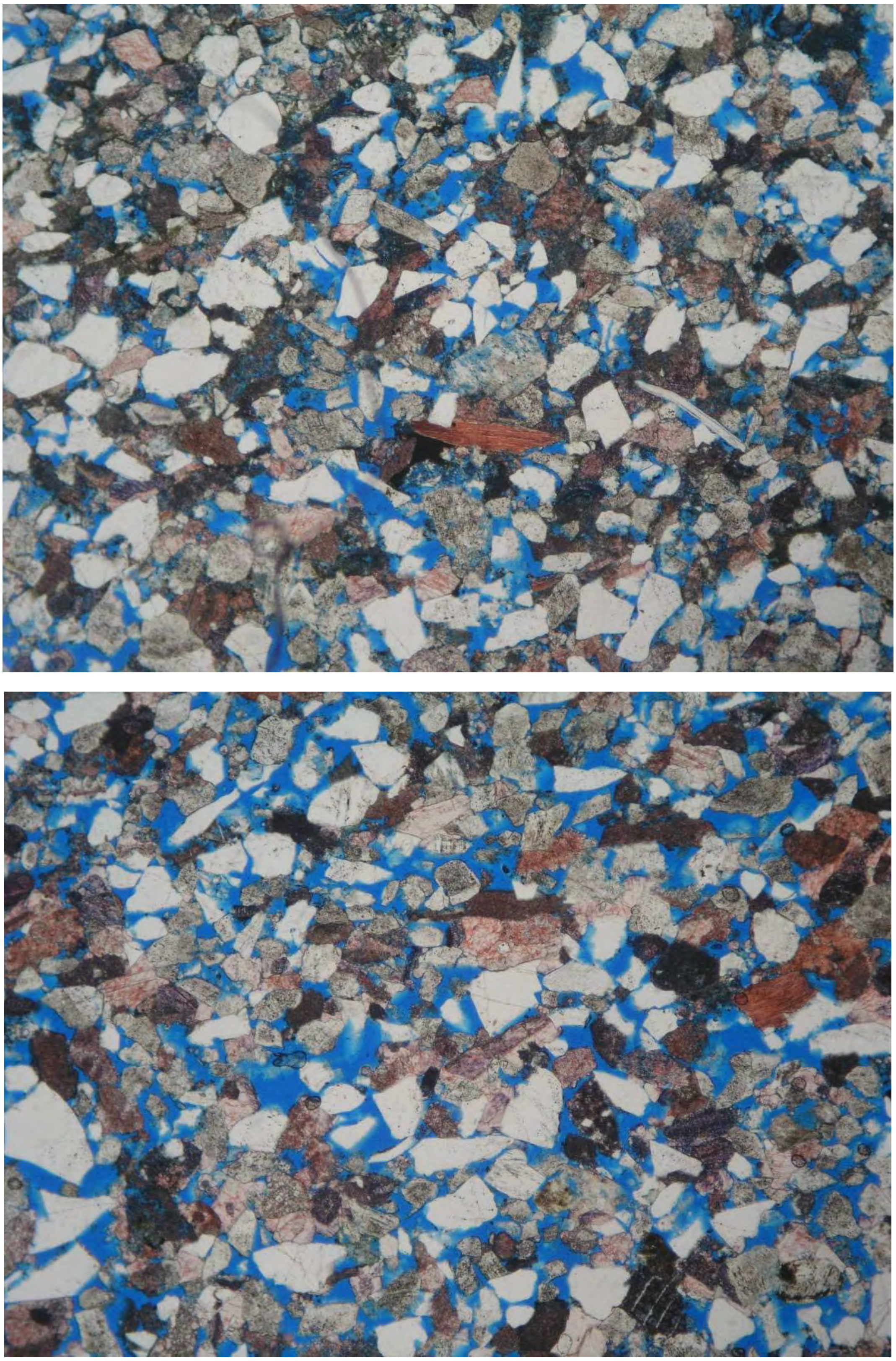


Figure 22. Thin section photographs of sample S10 (walling, Bath Street).

Quartz grains appear white, while carbonate-based 'clasts' appear light brownish grey, pink or dark pinkish brown (dependent on composition and consequent response to the dual carbonate stain). Iron oxide minerals appear black or almost black (in some cases, associated with carbonate-based 'clasts'). Open pore space appears an intense sky blue colour. The images were taken in plane-polarised light, and the field of view is *c.* 3.3 mm wide.

A1.5. MANSFIELD ROAD (WORK SECTION 9); SAMPLES S13 AND S14

Figure 23. Wall at sampling location, Mansfield Road (work section 9). Numbered stickers on the wall indicate the blocks each sample was collected from.

Figure 24. Samples S13 and S14, which were obtained from the copestones and walling, respectively, at the Mansfield Road sampling location (work section 9).

A1.5.1. Petrographic description of sample S13 (copestone, Mansfield Road)

See Appendix 3 for notes describing each numbered item below.

Hand specimen observations

Stone type [1] (general classification):	sandstone
Stone colour [2]:	greyish buff
Stone cohesion [3]:	strongly cohesive
Stone fabric [4]:	uniform
Distinctive features:	none

Thin section observations

Stone constituents [5]:

Granular (detrital) constituents		*Intergranular constituents*	
Quartz	74%	Silica (overgrowth)	2%
Feldspar	10%	Feldspar (overgrowth)	<<1%
Silicate rock fragments	1%	Carbonate	<1%
Carbonate debris	0%	Iron/manganese oxide	2%
Mica	1%	Clay	6%
Opaque material	<1%	Hydrocarbon	0%
Other	<<1%	Intergranular pores	5%
Intragranular pores	7%		

Stone type [1] (detailed classification):	subfeldspathic-arenite
Grain-size [6]:	fine-sand-grade to very coarse-sand-grade
Grain sorting [7]:	poorly sorted
Grain roundness [8]:	angular to subrounded
Stone permeability [9]:	moderate
Cement distribution [10]:	silica cement discontinuous
Supergene changes [11]:	strong dissolution of feldspar grains; moderate dissolution of rock fragments

Comments

1) The constituent rock fragments comprise a mix of metamorphic (predominantly quartzite) and sedimentary (predominantly mudstone) types. The feldspar grains include both potassic and sodic-calcic varieties; all of these are altered to a greater or lesser extent.

2) At least some of the constituent ‘clay’ has formed as a result of the natural chemical alteration of detrital feldspar grains and rock fragments, likely before the stone was quarried. This has been taken into account in the detailed classification of the stone (see ‘Stone Type’ above).

3) A very small amount (<1%) of carbonate is present, which appears as sparry crystals. Most of this carbonate has ‘taken’ the dual carbonate stain and is interpreted to be non-ferroan calcite as a result.

4) The detrital quartz grains show evidence of suturing where in contact with one another and have locally significant developments of associated quartz overgrowth cement. These observations provide an explanation for the strongly cohesive character of the stone.

5) Both biotite (‘brown’ mica) and muscovite (‘white’ mica) are present as small flakes, which often appear deformed (due to compaction during diagenesis). The flakes of mica show no preferred orientation.

6) The minerals epidote and zircon are present in trace amounts (together accounting for <<1% of the total thin section area).

7) The sample shows no discernible reaction with dilute (10%) hydrochloric acid.

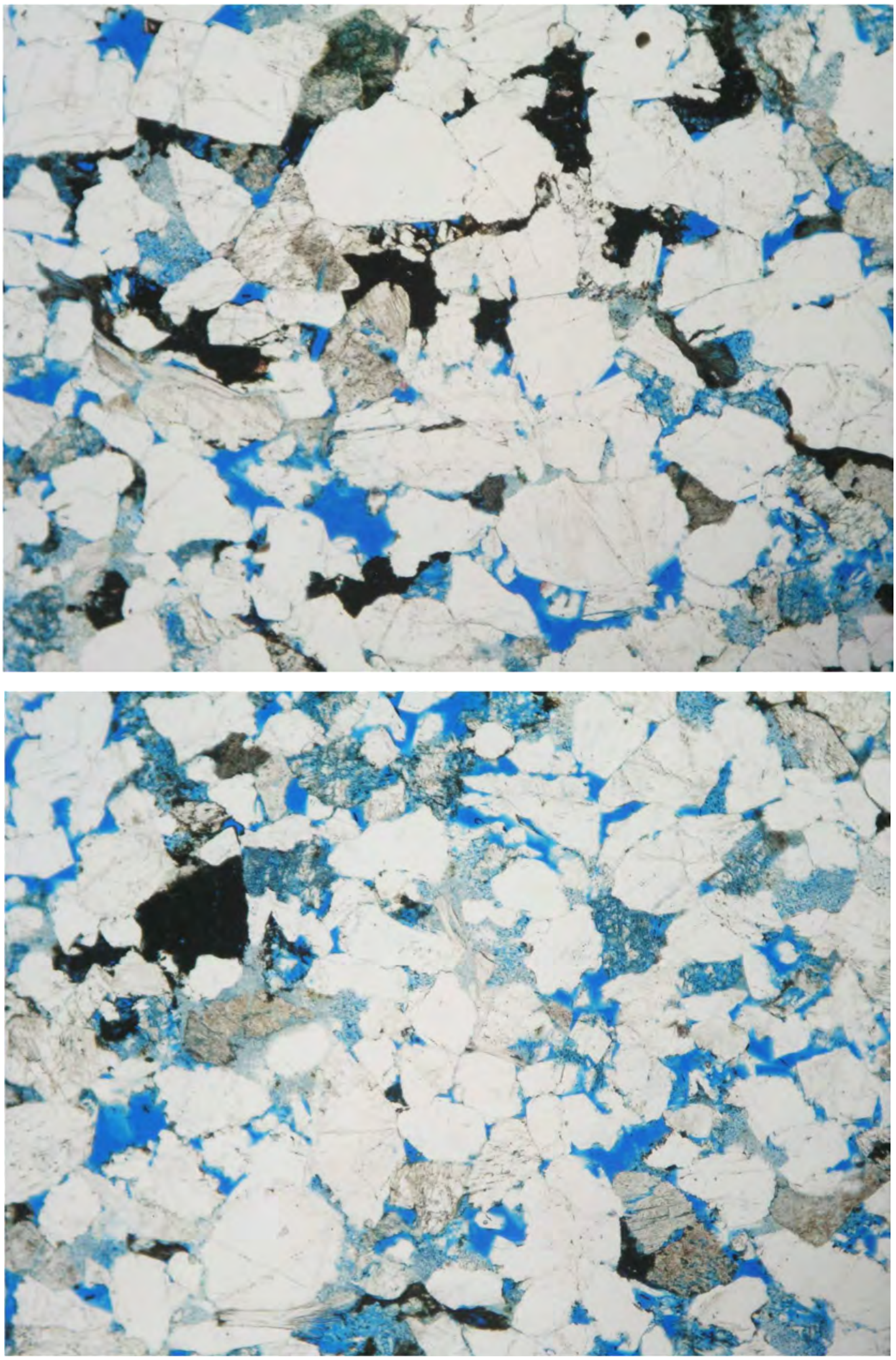


Figure 25. Thin section photographs of sample S13 (copestone, Mansfield Road).

Quartz grains appear white, while feldspar and rock fragments display a range of grey to light brown colours. Iron oxide minerals appear black. Open pore space appears sky blue, whereas pore space occupied by growths of clay minerals appears a lighter blue-grey colour. The images were taken in plane-polarised light, and the field of view is *c.* 3.3 mm wide.

A1.5.2. Petrographic description of sample S14 (walling, Mansfield Road)

See Appendix 3 for notes describing each numbered item below.

Hand specimen observations

Stone type [1] (general classification):	limestone
Stone colour [2]:	buff
Stone cohesion [3]:	strongly cohesive
Stone fabric [4]:	uniform
Distinctive features:	significant carbonate debris

Thin section observations

Stone constituents [5]:

Granular (detrital) constituents		*Intergranular constituents*	
Quartz	27%	Silica (overgrowth)	<<1%
Feldspar	<1%	Feldspar (overgrowth)	0%
Silicate rock fragments	1%	Carbonate	10%
Carbonate debris	40%	Iron/manganese oxide	<1%
Mica	0%	Clay	<<1%
Opaque material	<1%	Hydrocarbon	0%
Other	<<1%	Intergranular pores	20%
Intragranular pores	<1%		

Stone type [1] (detailed classification):	silici-sandy calcarenite
Grain-size [6]:	fine-sand-grade to medium-sand-grade
Grain sorting [7]:	moderately well sorted
Grain roundness [8]:	angular to subrounded
Stone permeability [9]:	moderate to high
Cement distribution [10]:	carbonate cement discontinuous
Supergene changes [11]:	weak dissolution of feldspar grains; weak dissolution of rock fragments

Comments

1) The detrital content consists essentially of carbonate-based debris and quartz grains. Also present are silicate-based rock fragments (in this case, chert and quartzite), although these are a comparatively minor component overall (accounting for *c.* 1% of the modal volume).

2) The individual quartz grains are typically angular, in contrast to the carbonate-based debris, the grains of which normally show evidence of appreciable abrasion and rounding.

3) The carbonate-based debris comprises grains ('clasts') of various types and sizes. These include bioclasts (notably echinoderm and bivalve debris, together with foraminifera tests), peloids and reworked pieces of 'limestone'. Mineralogically, some of the 'clasts' are evidently calcitic, whereas others are dolomitic (based on their response to the dual carbonate stain). Micritization and/or impregnation with iron oxide minerals affect a proportion of the 'clasts'.

4) The detrital constituents collectively are held together by a discontinuous intergranular carbonate cement (mostly calcitic, but in part dolomitic). The calcite often forms conspicuous (syntaxial) overgrowths on specific bioclasts.

5) The sample reacts vigorously with dilute (10%) hydrochloric acid, reflecting the fact that the carbonate material present (including both the carbonate-based debris and intergranular carbonate cement) consists in large part of the mineral calcite.

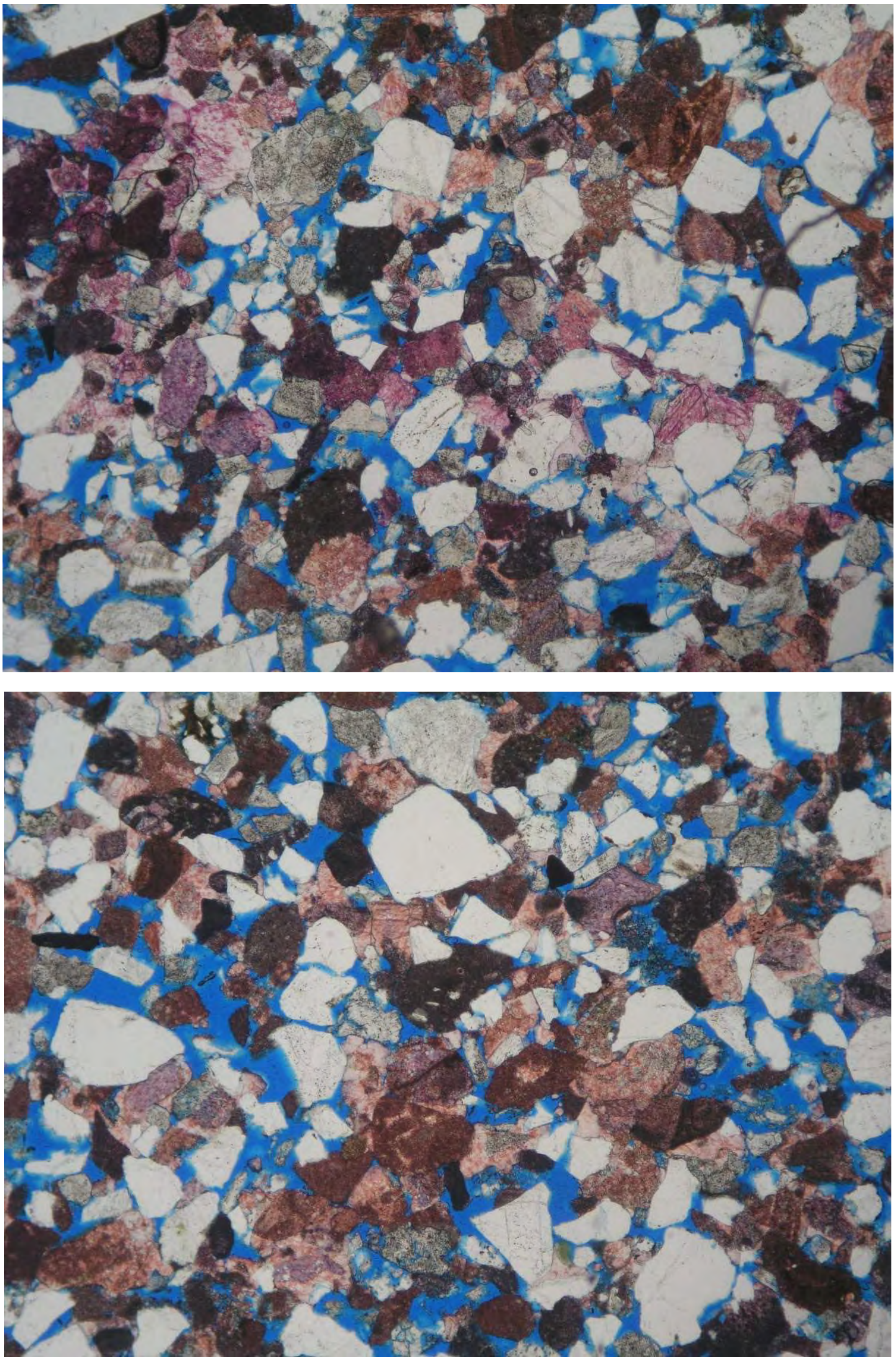


Figure 26. Thin section photographs of sample S14 (walling, Mansfield Road).

Quartz grains appear white, while feldspar grains, silicate rock fragments and carbonate-based ‘clasts’ appear light brownish grey, pink or dark pinkish brown (dependent on composition and consequent response to the dual carbonate stain). Iron oxide minerals appear black or almost black (in some cases, associated with carbonate-based ‘clasts’). Open pore space appears an intense sky blue colour. The images were taken in plane-polarised light, and the field of view is *c.* 3.3 mm wide.

Appendix 2 Sample descriptions: BGS reference specimens

A2.1. SAMPLE MC8768 – FLETCHER BANK SANDSTONE

Figure 27. Sample of Fletcher Bank sandstone held within the BGS Collection of Building Stones. The scale shown is in millimetres.

A2.1.1. Petrographic description of sample MC8768 (Fletcher Bank sandstone)

See Appendix 3 for notes describing each numbered item below.

Hand specimen observations

Stone type [1] (general classification):	sandstone
Stone colour [2]:	greyish buff
Stone cohesion [3]:	strongly cohesive
Stone fabric [4]:	uniform
Distinctive features:	none

Thin section observations

Stone constituents [5]:

Granular (detrital) constituents		*Intergranular constituents*	
Quartz	75%	Silica (overgrowth)	2%
Feldspar	9%	Feldspar (overgrowth)	<<1%
Silicate rock fragments	1%	Carbonate	<1%
Carbonate debris	0%	Iron/manganese oxide	2%
Mica	1%	Clay	6%
Opaque material	<1%	Hydrocarbon	0%
Other	<<1%	Intergranular pores	5%
Intragranular pores	7%		

Stone type [1] (detailed classification):	subfeldspathic-arenite
Grain-size [6]:	fine-sand-grade to very coarse-sand-grade
Grain sorting [7]:	poorly sorted
Grain roundness [8]:	angular to subrounded
Stone permeability [9]:	moderate
Cement distribution [10]:	silica cement discontinuous
Supergene changes [11]:	strong dissolution of feldspar grains; moderate dissolution of rock fragments

Comments

1) The constituent rock fragments comprise a mix of metamorphic (predominantly quartzite) and sedimentary (predominantly mudstone) types. The feldspar grains include both potassic and sodic-calcic varieties; all of these are altered to a greater or lesser extent.
2) At least some of the constituent 'clay' has formed as a result of the natural chemical alteration of detrital feldspar grains and rock fragments, likely before the stone was quarried. This has been taken into account in the detailed classification of the stone (see 'Stone Type' above).
3) A very small amount (<1%) of carbonate is present, which appears as sparry crystals. Most of this carbonate mineral has 'taken' the dual carbonate stain and is interpreted to be non-ferroan calcite as a result.
4) The detrital quartz grains show evidence of suturing where in contact with one another and have locally significant developments of associated quartz overgrowth cement. These observations provide an explanation for the strongly cohesive character of the stone.
5) Both biotite ('brown' mica) and muscovite ('white' mica) are present as small flakes, which often appear deformed (due to compaction during diagenesis). The flakes of mica show no preferred orientation.
6) The minerals epidote and zircon are present in trace amounts (together accounting for <<1% of the total thin section area).
7) The sample shows no discernible noticeable reaction with dilute (10%) hydrochloric acid.

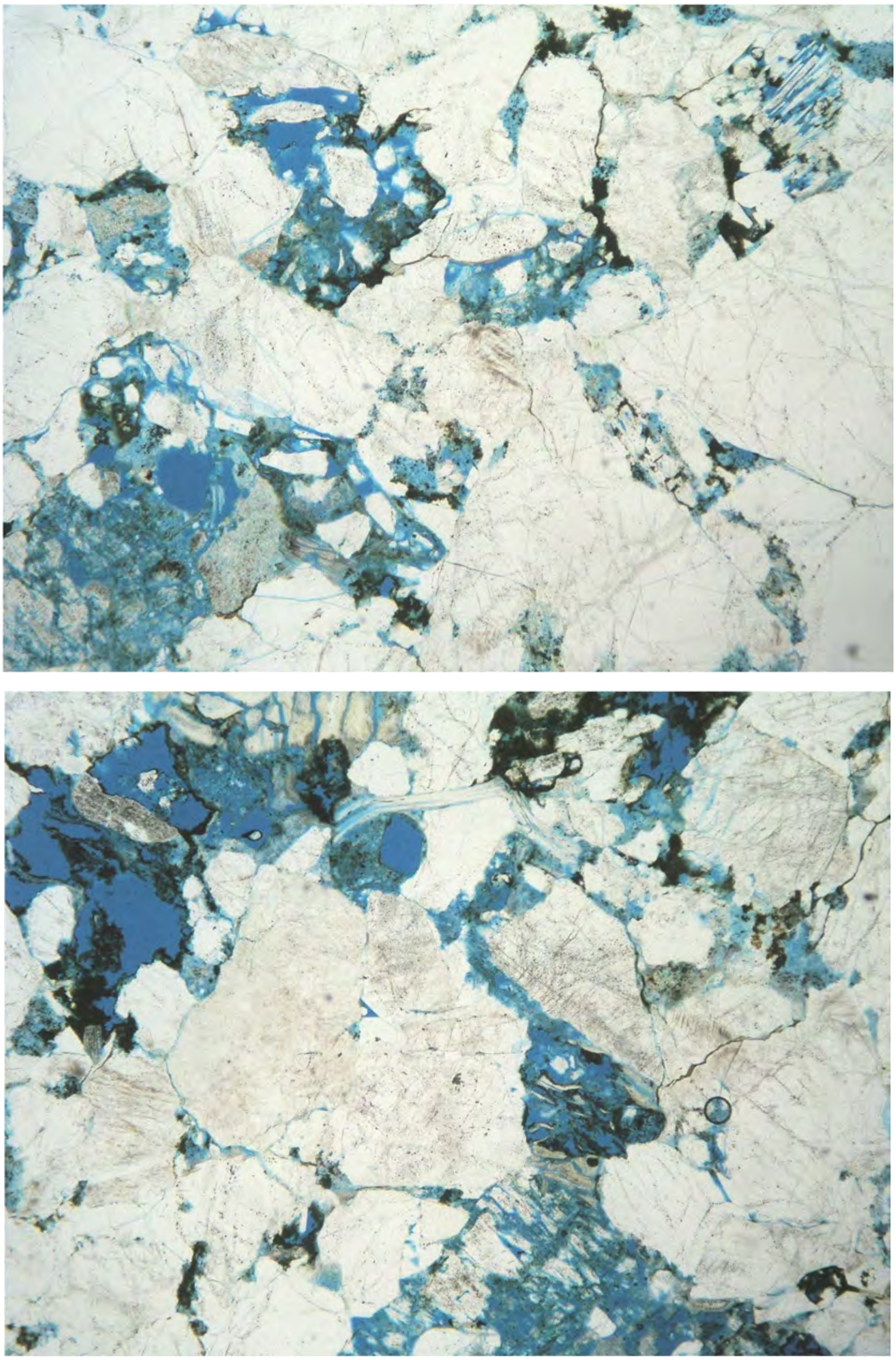


Figure 28. Thin section photographs of sample MC8768 (Fletcher Bank sandstone).

Quartz grains appear white, while feldspar and rock fragments display a range of grey to light brown colours. Iron oxide minerals appear black. Open pore space appears sky blue, whereas pore space occupied by growths of clay minerals appears a lighter blue-grey colour. The images were taken in plane-polarised light, and the field of view is *c.* 3.3 mm wide.

A2.2. SAMPLES EMC9058A AND EMC9058B – BEIGE PINAR CALCARENITE

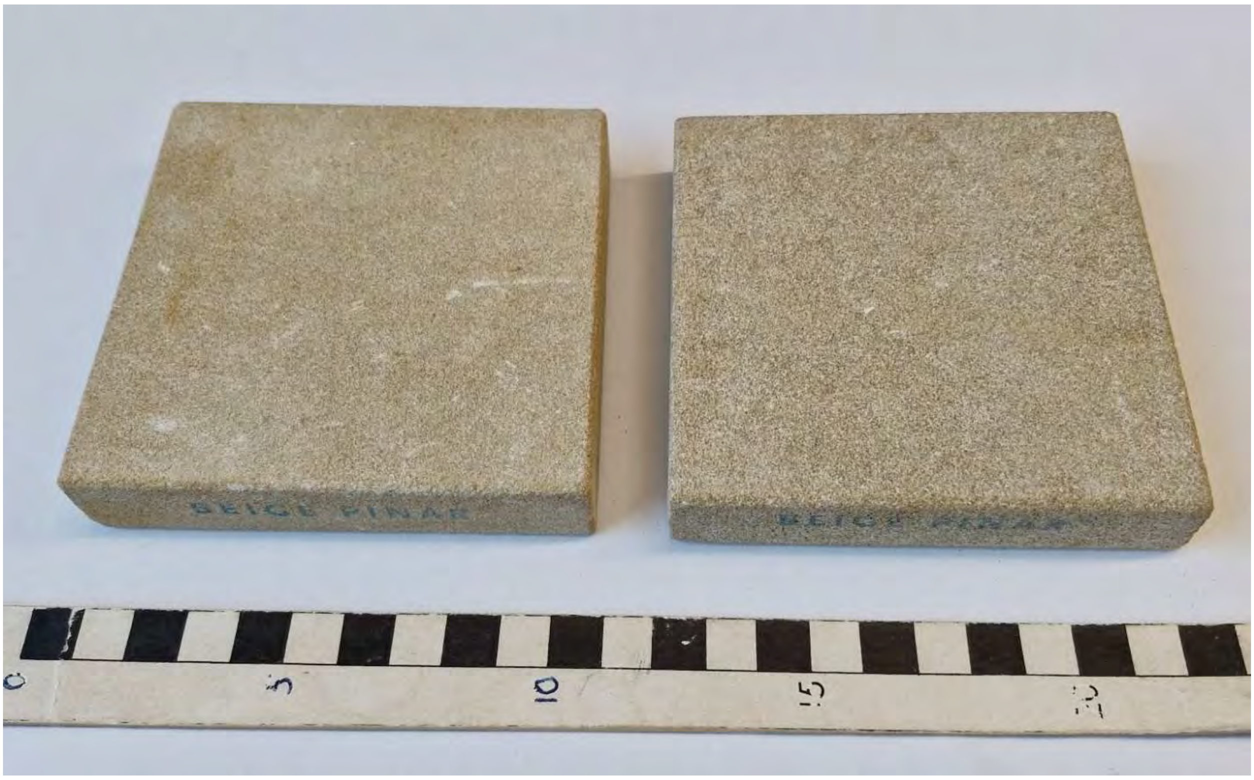


Figure 29. Samples of 'Beige Pinar' calcarenite held within the BGS Collection of Building Stones; these were supplied by the company "Areniscas". The sample to the left (EMC9058A) represents a fine-grained variant of this stone, whilst the sample to the right (EMC9058B) represents a medium-grained variant. The scale shown is in centimetres.

A2.2.1. Petrographic description of sample EMC9058A (Beige Pinar calcarenite)

See Appendix 2 for notes describing each numbered item below.

Hand specimen observations

Stone type [1] (general classification):	limestone
Stone colour [2]:	buff
Stone cohesion [3]:	strongly cohesive
Stone fabric [4]:	uniform
Distinctive features:	significant carbonate debris

Thin section observations

Stone constituents [5]:

Granular (detrital) constituents		*Intergranular constituents*	
Quartz	25%	Silica (overgrowth)	<<1%
Feldspar	1%	Feldspar (overgrowth)	0%
Silicate rock fragments	<1%	Carbonate	10%
Carbonate debris	41%	Iron/manganese oxide	<1%
Mica	<1%	Clay	<<1%
Opaque material	<1%	Hydrocarbon	0%
Other	<<1%	Intergranular pores	20%
Intragranular pores	1%		

Stone type [1] (detailed classification):	silici-sandy calcarenite
Grain-size [6]:	fine-sand-grade to medium-sand-grade
Grain sorting [7]:	moderately sorted
Grain roundness [8]:	angular to subrounded
Stone permeability [9]:	high
Cement distribution [10]:	carbonate cement discontinuous
Supergene changes [11]:	weak dissolution of feldspar grains; weak dissolution of rock fragments

Comments

1) The detrital content consists essentially of carbonate-based debris and quartz grains. Also present are silicate-based rock fragments as trace components, (accounting for *c.* <1% of the modal volume).
2) The individual quartz grains are typically angular, in contrast to the carbonate-based debris, the grains of which normally show evidence of appreciable abrasion and rounding.
3) The carbonate-based debris comprises grains (‘clasts’) of various types and sizes. These include bioclasts (notably echinoderm and bivalve debris, together with foraminifera tests), peloids and reworked pieces of ‘limestone’. Mineralogically, some of the ‘clasts’ are evidently calcitic, whereas others are dolomitic (based on their response to the dual carbonate stain). Micritization and/or impregnation with iron oxide minerals affect a proportion of the ‘clasts’.
4) The detrital constituents collectively are held together by a discontinuous intergranular carbonate cement (mostly calcitic, but in part dolomitic). The calcite often forms conspicuous (syntaxial) overgrowths on specific bioclasts.
5) The sample reacts vigorously with dilute (10%) hydrochloric acid, reflecting the fact that the carbonate material present (including both the carbonate-based debris and intergranular carbonate cement) consists in large part of the mineral calcite.

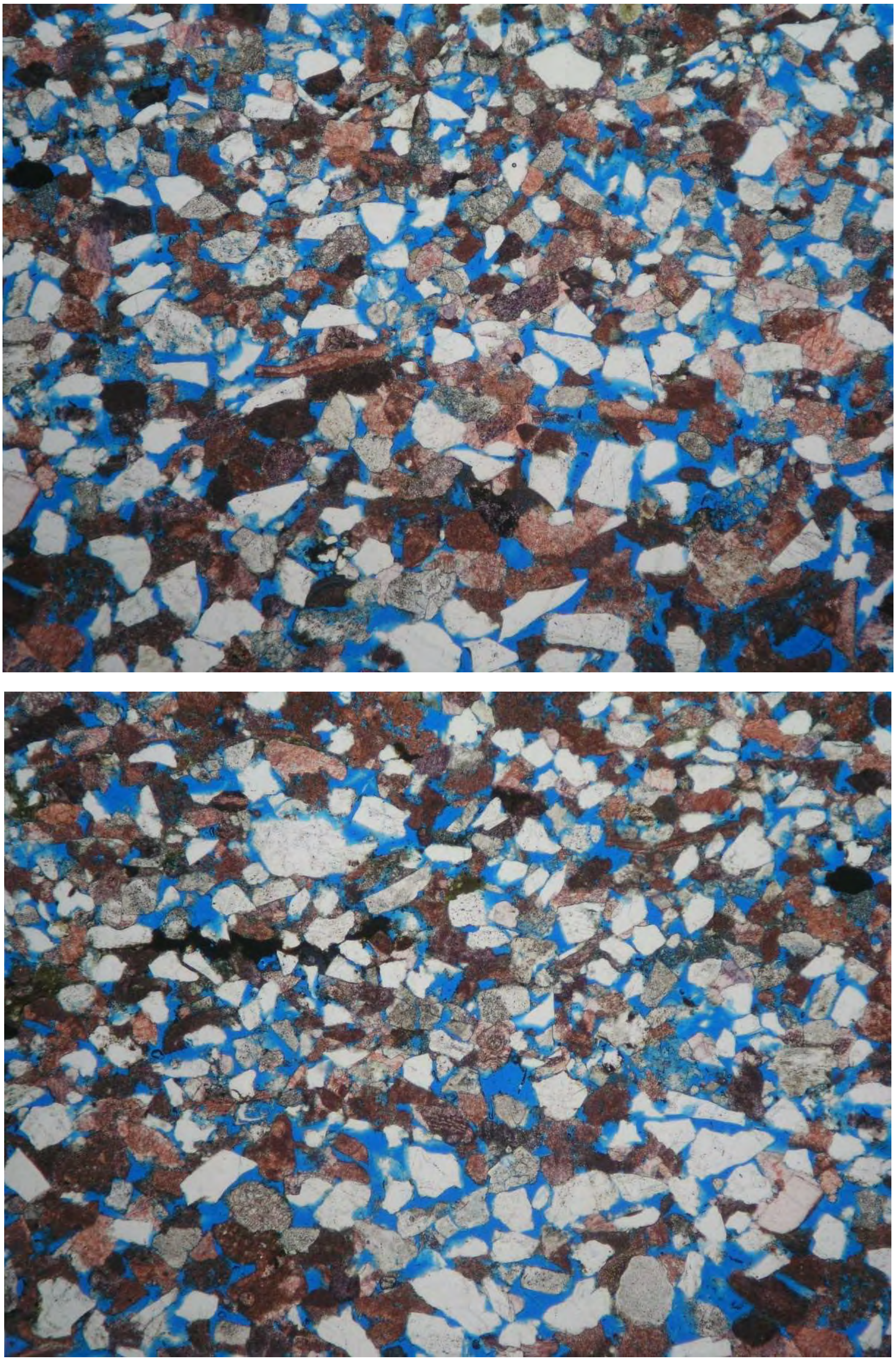


Figure 30. Thin section photographs of sample EMC9058A (Beige Pinar calcarenite).

Quartz grains appear white, while feldspar grains, silicate rock fragments and carbonate-based ‘clasts’ appear light brownish grey, pink or dark pinkish brown (dependent on composition and consequent response to the dual carbonate stain). Iron oxide minerals appear black or almost black (in some cases, associated with carbonate-based ‘clasts’). Open pore space appears an intense sky-blue colour. The images were taken in plane-polarised light, and the field of view is *c.* 3.3 mm wide.

A2.2.2. Petrographic description of sample EMC9058B (Beige Pinar calcarenite)

See Appendix 2 for notes describing each numbered item below.

Hand specimen observations

Stone type [1] (general classification):	limestone
Stone colour [2]:	buff
Stone cohesion [3]:	strongly cohesive
Stone fabric [4]:	uniform
Distinctive features:	significant carbonate debris

Thin section observations

Stone constituents [5]:

Granular (detrital) constituents		*Intergranular constituents*	
Quartz	25%	Silica (overgrowth)	<<1%
Feldspar	1%	Feldspar (overgrowth)	0%
Silicate rock fragments	<1%	Carbonate	7%
Carbonate debris	41%	Iron/manganese oxide	<1%
Mica	0%	Clay	<1%
Opaque material	<1%	Hydrocarbon	0%
Other	<<1%	Intergranular pores	23%
Intragranular pores	0%		

Stone type [1] (detailed classification):	silici-sandy calcarenite
Grain-size [6]:	medium-sand-grade
Grain sorting [7]:	moderately well sorted
Grain roundness [8]:	angular to subrounded
Stone permeability [9]:	very high
Cement distribution [10]:	carbonate cement discontinuous
Supergene changes [11]:	weak dissolution of feldspar grains; weak dissolution of rock fragments

Comments

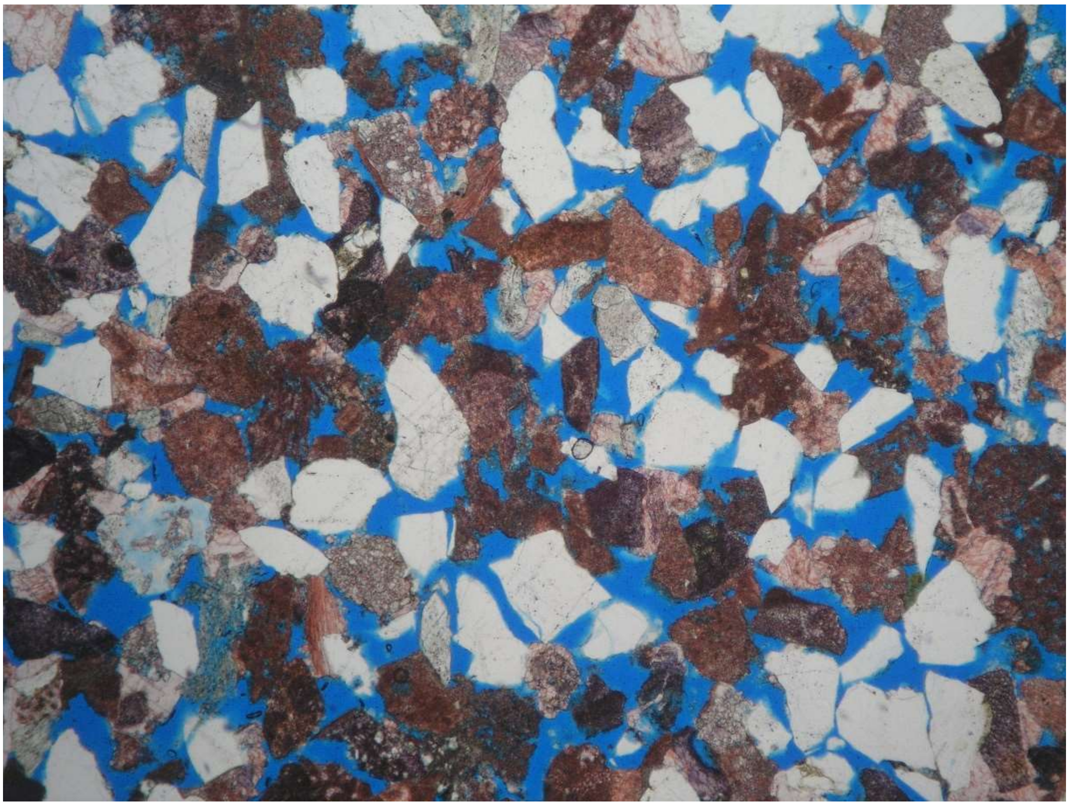
1) The detrital content consists essentially of carbonate-based debris and quartz grains. Also present are silicate-based rock fragments (in this case, chert and quartzite), although these are a comparatively minor component overall (accounting for *c.* 5% of the modal volume).

2) The individual quartz grains are typically angular, in contrast to the carbonate-based debris, the grains of which normally show evidence of appreciable abrasion and rounding.

3) The carbonate-based debris comprises grains ('clasts') of various types and sizes. These include bioclasts (notably echinoderm and bivalve debris, together with foraminifera tests), peloids and reworked pieces of 'limestone'. Mineralogically, some of the 'clasts' are evidently calcitic, whereas others are dolomitic (based on their response to the dual carbonate stain). Micritization and/or impregnation with iron oxide minerals affect a proportion of the 'clasts'.

4) The detrital constituents collectively are held together by a discontinuous intergranular carbonate cement (mostly calcitic, but in part dolomitic). The calcite often forms conspicuous (syntaxial) overgrowths on specific bioclasts.

5) The sample reacts vigorously with dilute (10%) hydrochloric acid, reflecting the fact that the carbonate material present (including both the carbonate-based debris and intergranular carbonate cement) consists in large part of the mineral calcite.



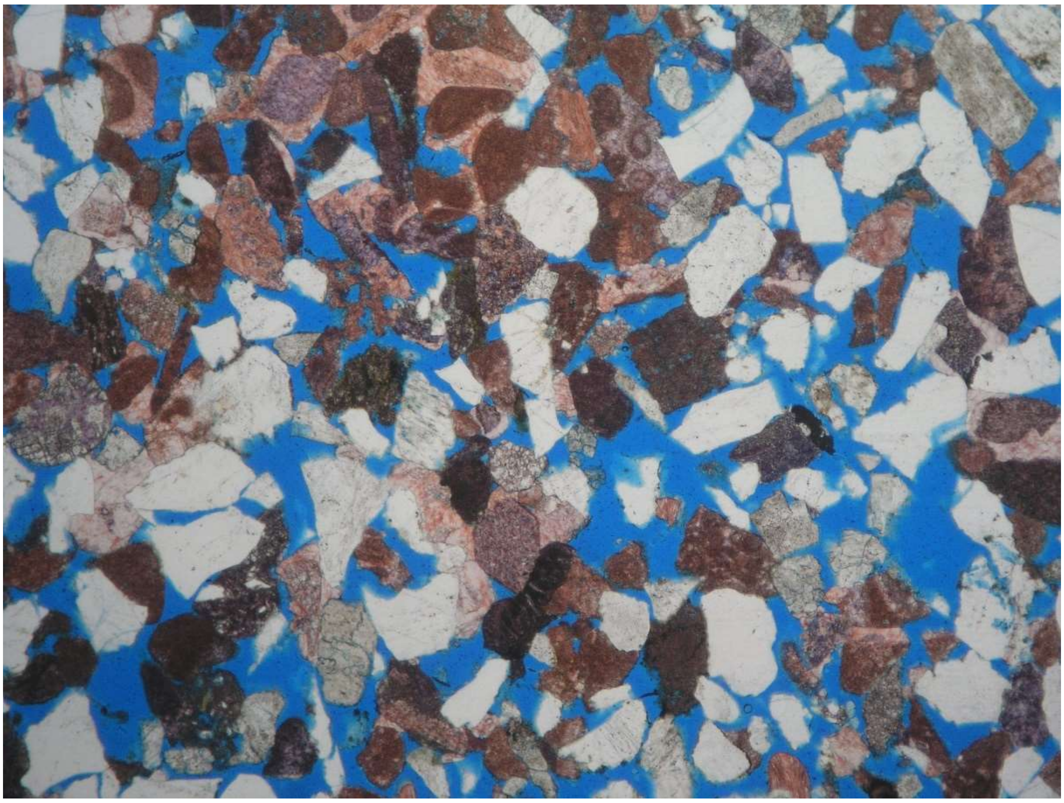


Figure 31. Thin section photographs of sample EMC9058A (Beige Pinar calcarenite).

Quartz grains appear white, while feldspar, silicate rock fragment grains and carbonate-based ‘clasts’ appear light brownish grey, pink or dark pinkish brown (dependent on composition and consequent response to the dual carbonate stain). Iron oxide minerals appear black or almost black (in some cases, associated with carbonate-based ‘clasts’). Open pore space appears an intense sky blue colour. The images were taken in plane-polarised light, and the field of view is *c.* 3.3 mm wide.

Appendix 3 Petrographic analysis: methodology

Petrographic examination

A macroscopic examination of a stone sample is performed with the unaided eye and using a binocular microscope. A microscope examination is performed on a thin section (a slice of the stone sample cut thin enough to be transparent), using a polarizing microscope.

The thin section is cut perpendicular to the bedding fabric of the stone (where this is visible) and is positioned to be as representative as possible of the sample. The thin section is typically cut to include the freshest part of the supplied stone sample, and also any weathered part and/or exposed (exterior) surface where these are present.

The thin sections were prepared to a standard thickness of 30 microns (30 μm) by the staff of the thin sectioning laboratories at the British Geological Survey, Keyworth, Nottingham, as follows:

- a representative portion of the supplied sample was impregnated (under vacuum) with blue-dye resin before further processing in order to facilitate identification and description of the stone's pore space characteristics
- the thin section was treated with a standard dual carbonate alizarin red-S and potassium ferricyanide chemical stain to help determine the composition of any carbonate minerals present. The staining differentiates non-ferroan calcite (pale pink) from ferroan calcite (mauve -> purple -> dark blue with increasing Fe-content), dolomite (no colour) and ferroan dolomite (pale to deep turquoise with increasing Fe-content)

Observations from these examinations are recorded on a Petrographic Description Form designed for building stones, to ensure the description is systematic and consistent with the procedures set out in British Standard BS EN 12407:2000 (*Natural stone test methods – Petrographic examination*). The completed Petrographic Description Form is included in this report, with a set of accompanying notes describing each of the recorded properties. The description is accompanied by one or more photographs illustrating the typical character of the stone as it appears in the thin section.

Supporting notes for petrographic descriptions

Each numbered note below relates to a superscript number in the Petrographic Description Forms (Appendix 1 and Appendix 2).

1 The determination of stone type follows the classification and nomenclature of the BGS Rock Classification Scheme.

2 The determination of stone colour is based on a simple assessment with the unaided eye in natural light. In stones displaying variable colour, the determination records the colour deemed by the geologist to be most representative. The determination of stone colour is made on a broken (not sawn), dry surface.

3 A simple, non-quantitative assessment of the degree to which the stone is cohesive. This property is recorded in terms of four conditions, each representing one segment of a continuum: *strongly cohesive*, *moderately cohesive*, *moderately friable*, and *very friable*. The grains in a *strongly cohesive* stone cannot be disaggregated by hand, whereas the grains in a *very friable* stone can be readily disaggregated by hand.

4 A record of whether the distribution of granular (detrital) constituents in the sample is essentially isotropic (uniform) or anisotropic (non-uniform). The type of anisotropic fabric is recorded.

5 A record of the identity and relative proportions of all granular (detrital) and intergranular (authigenic materials and pore space) constituents currently in the stone. The proportions are

estimates, expressed in %, which are based on a visual assessment of the whole thin section area.

6 The terms are those used for grain-size divisions in the BGS Rock Classification Scheme.

7 A simple, non-quantitative assessment of the degree to which detrital constituents display similarity in terms of physical characteristics (in particular the size and shape of grains).

8 A simple, non-quantitative assessment of the degree to which detrital constituents are abraded.

9 A simple, non-quantitative assessment of stone permeability, presented as one of five conditions (*very low*, *low*, *moderate*, *high*, *very high*) expressed relative to a nominal 'average' permeability in building stone sandstones. The assessment is based on: (i) a water bead test; (ii) the proportion of pore space in the stone; (iii) a visual assessment of the degree to which pore spaces appear connected in the thin section.

10 A record of the type and extent of authigenic mineral cement that acts to bind detrital grains, as observed in thin section. *Isolated* means the cement occurs in discrete locations (e.g. as overgrowths on individual detrital grains) that are typically not connected in the plane of the thin section. *Discontinuous* means the cement is formed in patches, each of which typically encloses several to many detrital grains. *Continuous* means the cement is more-or-less connected across the thin section.

11 A record of the evidence observed in thin section for mineral alteration that occurs in the stone when it is near the ground surface. Such alteration processes typically begin before stone is quarried, but some may continue, or be initiated, after stone is extracted from the ground.

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