Impact of Mineralogy, Texture and Fabric of the Maritime Canadian Sandstones on Deterioration of Ornamental Bridges in Central Park, NYC

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1. INTRODUCTION

The construction of Central Park in New York City took place between 1858 and 1873. Much of the olive-green and grey colored sandstone used for the construction and restoration of Bethesda Terrace and several ornamental arches and bridges came from the Maritime Canadian Provinces of New Brunswick and Nova Scotia. The Canadian 'freestones' were known for their durability, consistency of weathering, variety of earth-toned colors, fine-grained composition and easy workability.[1] Their ability to be carved in detail in any direction made them the preferred choice of the mid-19th century architects seeking picturesque 'naturalism'.[2] Nonetheless, they have displayed varying weathering behavior when exposed to the same environmental conditions.

While sandstones of the Maritime Provinces are similar in some respects, they vary in color, texture and character of their cementing material and thus have slightly different physical properties, which may help to understand why they are not deteriorating in the same manner in Central Park. Different sandstones exhibit different weathering characteristics when used as a building material. While softer sandstones such as the Dorchester sandstone are easy to work, they may exhibit granular disintegration after years of exposure to wind and rain as observed in Central Park.[3] Sandstone deterioration stems from the geological structure of the stone itself and also how the stone is laid up during building construction.[4] The bedding planes of the stone are set parallel to the plane of the wall during construction and this historic practice causes the sandstone layers to delaminate from the surface when subjected to weathering by water and/or wind. Other types of sandstone deterioration include blistering caused by crust formation from

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[1] Freestone is a fine-grained or uniform textured stone that can be worked equally in any direction.
[2] Deborah K. Dietsch, "Saving Sandstone: Bethesda Terrace Restoration, Central Park, New York City," *Architectural Record* 174, no. 6 (1986): 131.
[3] Jeanne Marie Teutonico, "The Conservation of the Bethesda Terrace in Central Park," *PreCIS* 3 (1981): 29.
[4] Dietsch, "Saving Sandstone," 131.

airborne chemicals or crystallized salts beneath the surface of the stone; formation of cavities on the surface (known as *alveolization*) due to inhomogeneities in physical and/or chemical properties of the stone; and differential erosion where the erosion does not proceed at the same rate from one area of the stone to the other.

While the type and degree of deterioration of the stone noted by former researchers at Central Park have been attributed largely to extrinsic factors rather than intrinsic factors, the aim of this research is to understand how different forms of deterioration observed may relate to the sandstone's mineralogy and texture and determine if weathering is dependent on the stone's source and utilization. Mineralogical composition and textural characteristics are important in any study of stone deterioration and treatment performance. They are useful to understand stone performance and weathering when the stone is used with other materials in a structure with complex environment such as of New York City.

For this study, the Maritime Canadian sandstones used in Central Park are fully characterized by determining their mineralogical composition and textural characteristics using x-ray diffraction (XRD), polarized light microscopy (PLM), scanning electron microscopy (SEM) and methylene blue index (MBI) of clay. Hygric dilation measurements were carried out to calculate the stress exerted during swelling when the expansion is constrained. This characterization helps to compare and contrast deteriorated, undeteriorated and current quarry samples; see differences among sandstones from different quarries; and understand how a particular stone characteristic may influence the sandstone's specific weathering behavior.

1.1 HISTORY OF THE MARITIME SANDSTONE QUARRIES OF CANADA

The Maritime dimension stone industry of Canada thrived in the mid-19th century as the 1854 Reciprocity Treaty took effect, eliminating the ten percent duty on building stones and the five percent duty on grindstones entering the United States from Canada.[5] New York and other eastern United States cities coincidentally entered their 'brownstone' era of architectural design just as this 19th century free-trade agreement took effect, luring Americans to invest in the provincial stone business.[6]

Figure 1.1: A Map of Canada and the United States
Google Maps, 2013

The Maritime Canadian Provinces of New Brunswick, Nova Scotia and Prince Edward Island are major sources of building and ornamental stones. These stones have been shipped throughout eastern North America with sandstone production reaching a peak between the 1840s

[5] The 1854 Canadian-American Reciprocity Treaty between Canada and the United States was in effect from 1854 to 1865. It admitted most Canadian raw materials and agricultural produce duty-free to the United States market by eliminating the 21% tariff. The Americans were given fishing rights off the east coast in exchange. The treaty was abrogated by the United States in 1866.

[6] Gwen L. Martin, *For Love of Stone*, vol 1 of *Miscellaneous Report No. 8* (Fredericton: New Brunswick Department of Natural Resources and Energy, Mineral Resources Division, 1990), 39.

and the 1890s.[7] About New Brunswick's stone industry, T. C. Webb, Industrial Minerals Geologist for New Brunswick Department of Natural Resources and Energy, wrote that while granite from the province gained an international reputation as a fine monumental stone, it was the sandstone resources that "provided the most visible and widespread testimonial to the New Brunswick's stone industry".[8] New Brunswick's impressive variety of geological terrains has offered a diverse variety of stone colors and textures; and its advantageous location with a tidewater access to global markets and one-day trucking distance to a regional market have created a 'solid framework' for its dimension stone industry.[9] The olive-green, blue, brown and red colored sandstones of the Maritime Provinces have been used for construction of both public and private buildings and structures in Canada and the United States.

The 'Golden Age' of sandstone slowly came to an end at the turn of the 20th century and was precipitated by some of the same factors that originally contributed to the industry's rise. Trade protectionism in the United States after 1866 lead to the implementation of restrictive tariff barriers and drove many New Brunswick quarries to oblivion.[10] The 1854 Reciprocity Treaty was abrogated by the United States in 1866 and caused escalation of import duties on stone "from being nonexistent in 1860 to ten percent in 1870, twenty percent in 1883 [and] a staggering forty percent in 1890".[11] Change of taste in architectural style, development of cost-effective concrete blocks, transportation costs and inadequate labor supply were other important factors that contributed to decline of the industry. The story of the Maritime sandstone industry of Canada did not end here, however. Preference for using an 'original' stone for restoration,

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[7] Martin, *For Love of Stone*, vol 1, 1.
[8] T.C. Webb, *Developing New Brunswick's Stone Resource: a Down-to-Earth Approach* (Fredericton: New Brunswick Department of Natural Resources and Energy, Mineral Resources Division, 2000), 2.
[9] Webb, *Developing New Brunswick's Stone Resource*, 1.
[10] Martin, *For Love of Stone*, vol 1, 39-40; Webb, *Developing New Brunswick's Stone Resource*, 2.
[11] Ibid., 39-40.

renovation and repair has resulted in the re-opening of quarries in New Brunswick and Nova Scotia including revival of the historic Dorchester quarries and the Wallace quarries in the late 1900s.[12]

The majority of the information about geological formations and the sandstone quarries in this chapter is received from William A. Parks's *Report on the Building and Ornamental Stones of Canada* (1914), Gwen L. Martin's *For Love of Stone* (1990) and G. B. Dickie's *Building Stone in Nova Scotia* (1993).

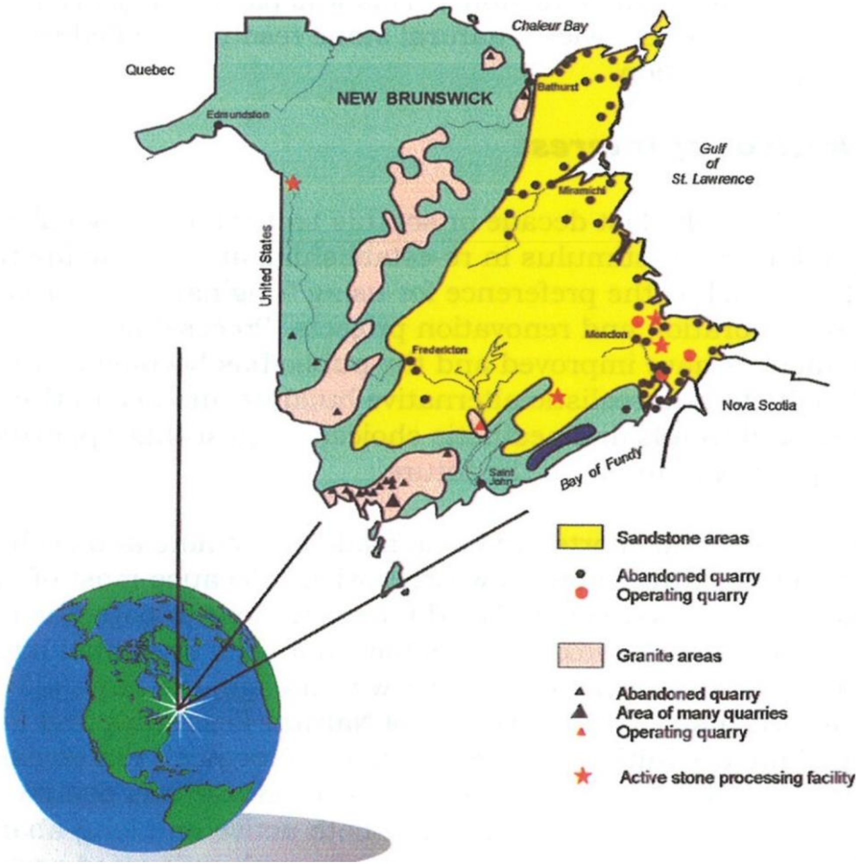


Figure 1.2: Abandoned and operating sandstone quarries in New Brunswick as of 2000
Webb, *Developing New Brunswick's Stone Resource*, 1.

[12] Sandstones from the Dorchester and Wallace quarries are used in Central Park and both quarries are currently in operation.

Geological Formations of the Maritime Provinces

The bedrock geology of the Maritime Provinces ranges from 1 billion years to 200 million years old. The present region "lies on a line of weakness in the earth's crust [and] extends in a general northeast and southwest direction".[13] Extensive uplifting and folding of the rocks at several different times throughout history have caused twisting of the formations into ridges with a general northeast direction. The rocks have been thrown out of their original position due to intense pressure and their mineralogical composition has also been changed. The intense pressure has altered originally sedimentary rocks into members of the metamorphic rocks. Parks noted the complex character of certain areas to "have further increased by enormous masses of igneous rocks which have invaded or broken through the sedimentary strata of earlier date".[14]

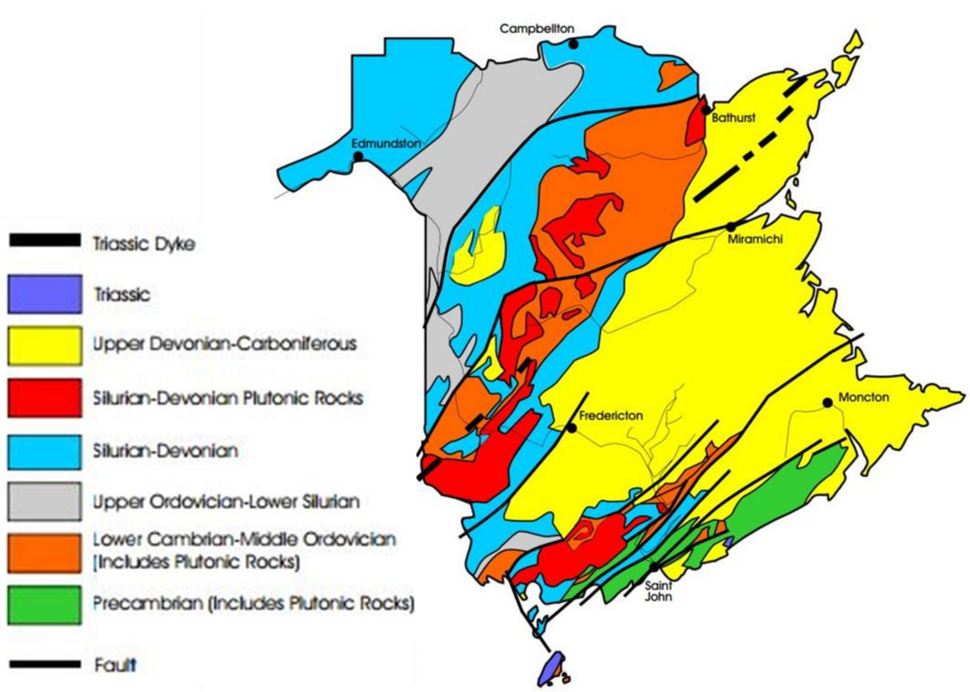


Figure 1.3: Generalized geology map of New Brunswick
Pronk and Allard, *Landscape Map of New Brunswick*, Map NR-9.

[13] William A. Parks, *Report on the Building and Ornamental Stones of Canada*, vol 2 (Ottawa: Government Printing Bureau, 1914), 11.
[14] Ibid., 11.

The geological formations of the Maritime Provinces are classified as following beginning with the oldest and proceeding to the youngest formation: Paleozoic (Pre-Cambrian, Cambrian, Cambro-Silurian, Silurian, Devonian, Carboniferous and Permian) and Mesozoic (Triassic). The strata of the Carboniferous, or coal-bearing formation, are abundant in the Maritime Provinces and all the sandstone of the Provinces is obtained from its different members. The Carboniferous formations are divided into three series: lower Carboniferous, middle Carboniferous, and upper or Permo-Carboniferous.

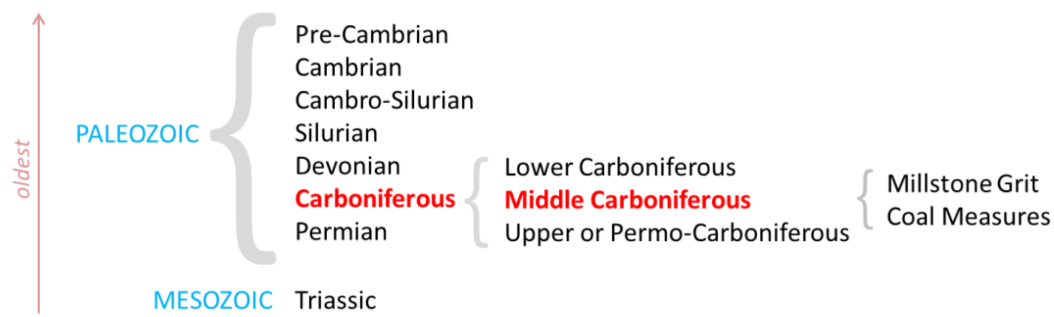


Figure 1.4: Geological formations of the Maritime Provinces

The lower Carboniferous series consists chiefly of coarse conglomerates and shales and some bands of limestone. In New Brunswick, the series occupies a considerable part of the Carboniferous formations; however, it is of lesser relative extent in Nova Scotia. Parks attributed the chief importance of the series to be due to the presence of gypsum beds and noted the beds "to possess a distinct value as ornamental material".[15]

The middle Carboniferous series includes the Millstone Grit and the Coal Measures layers. The Millstone Grit layer has produced a large amount of fine building stone and practically all the grindstones and pulp stones of the Provinces. The Coal Measures layer has produced stone mainly for structural purposes.

[15] Ibid., 16.

The upper or Permo-Carboniferous series includes conglomerates and coarse sandstones. It furnished the bulk of the building stone quarried in the 1900s.

While sandstone has been quarried from all the subdivisions, the Permo-Carboniferous and the Millstone Grit layers were noted by Parks to have produced practically all the stone used for building construction.[16] The Shepody Bay quarries, which include the historic Dorchester quarries, are in the Millstone Grit series and the Wallace quarry in Nova Scotia is in the upper Carboniferous series.

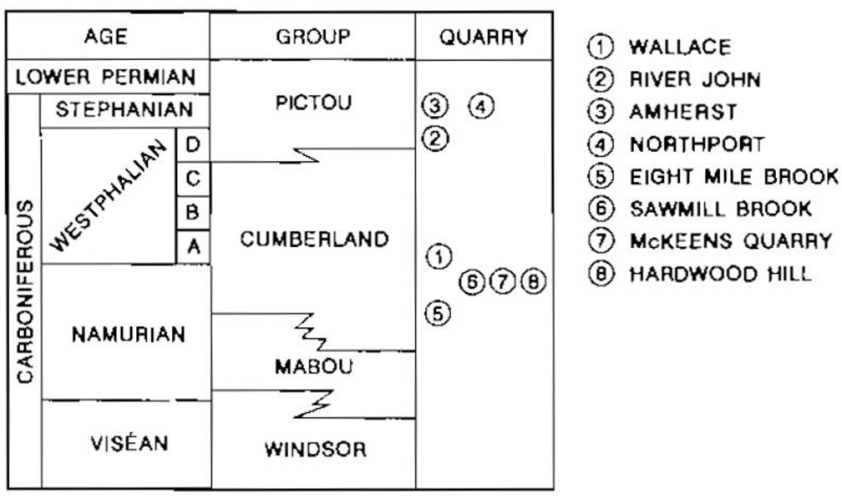


Figure 1.5: Approximate positions of Nova Scotia sandstone quarries in the Carboniferous stratigraphic succession
Dickie, *Building Stone in Nova Scotia*, 3rd ed., 9.

Maritime Sandstone Quarries of Canada

The Maritime Provinces of New Brunswick, Nova Scotia and Prince Edward Island historically produced the most important sandstone quarries. Sandstone quarries in New Brunswick are distributed around Chaleur Bay, Miramichi, Buctouche, Shediac, Fredericton, Shepody Bay and Cumberland Basin. In Nova Scotia they are located around Cumberland Basin, Wallace, John River, Pictou, Monk Head, Boularderie, Sydney, Whycocomagh and Port

[16] Ibid., 19.

Hood. Parks noted sandstones from these areas to be similar in some respects but different in color, texture and the character of the cementing material.[17] Parks organized the Maritime sandstones into two groups according to their color – olive-green and grey sandstones, and red and brown sandstones. Shepody Bay quarries have produced both olive-green, and red and brown sandstones and the Wallace quarry has produced chiefly 'grey' and 'blue' color sandstones.[18] This research solely focuses on the quarries in Shepody Bay area in New Brunswick, and the Wallace quarries in Nova Scotia. (Physical properties, mineralogical composition and textural characteristics of sandstones from different quarries are discussed in Chapter 3.)

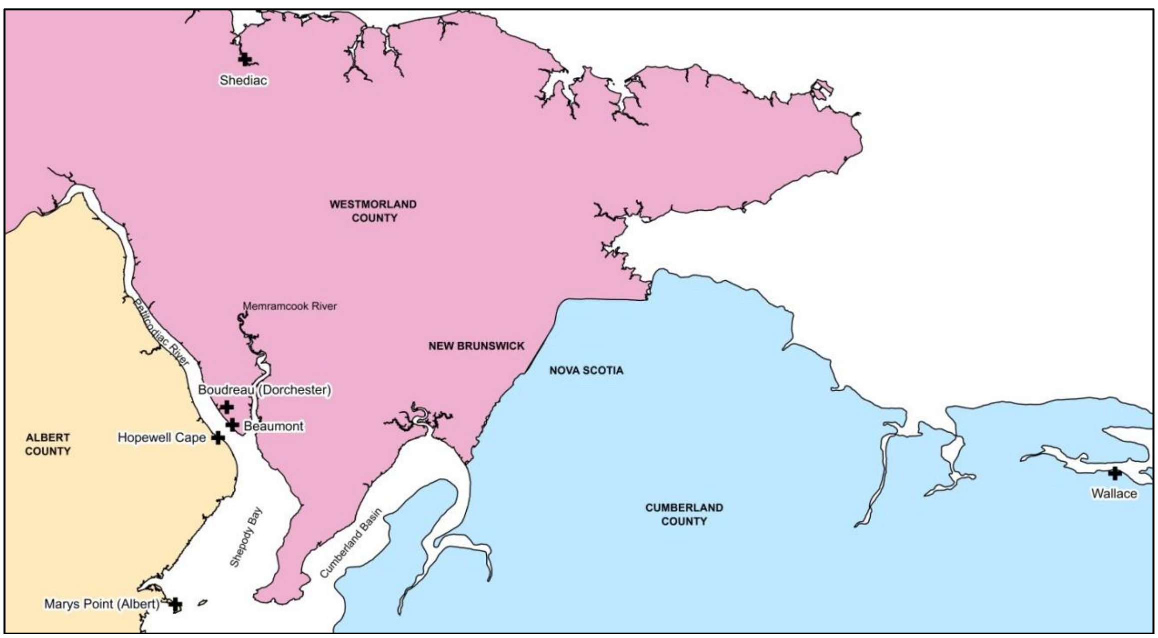


Figure 1.6: A Map showing the Beaumont, Boudreau (Dorchester), Marys Point (Albert), Wallace, Shediac and Hopewell Cape quarries

Shepody Bay Quarries, New Brunswick

Quarrying activity began around 1800 in New Brunswick with sandstone quarries distributed predominantly in the province's southeast region. According to Parks, the quarries in

[17] Ibid., 20.
[18] Ibid.

Shepody Bay area fell into three groups in Albert and Westmorland counties – a group at Marys Point and Grindstone Island, a group centering around Curryville on Demoiselle creek and a group between the Petitcodiac and Memramcook rivers.[19]

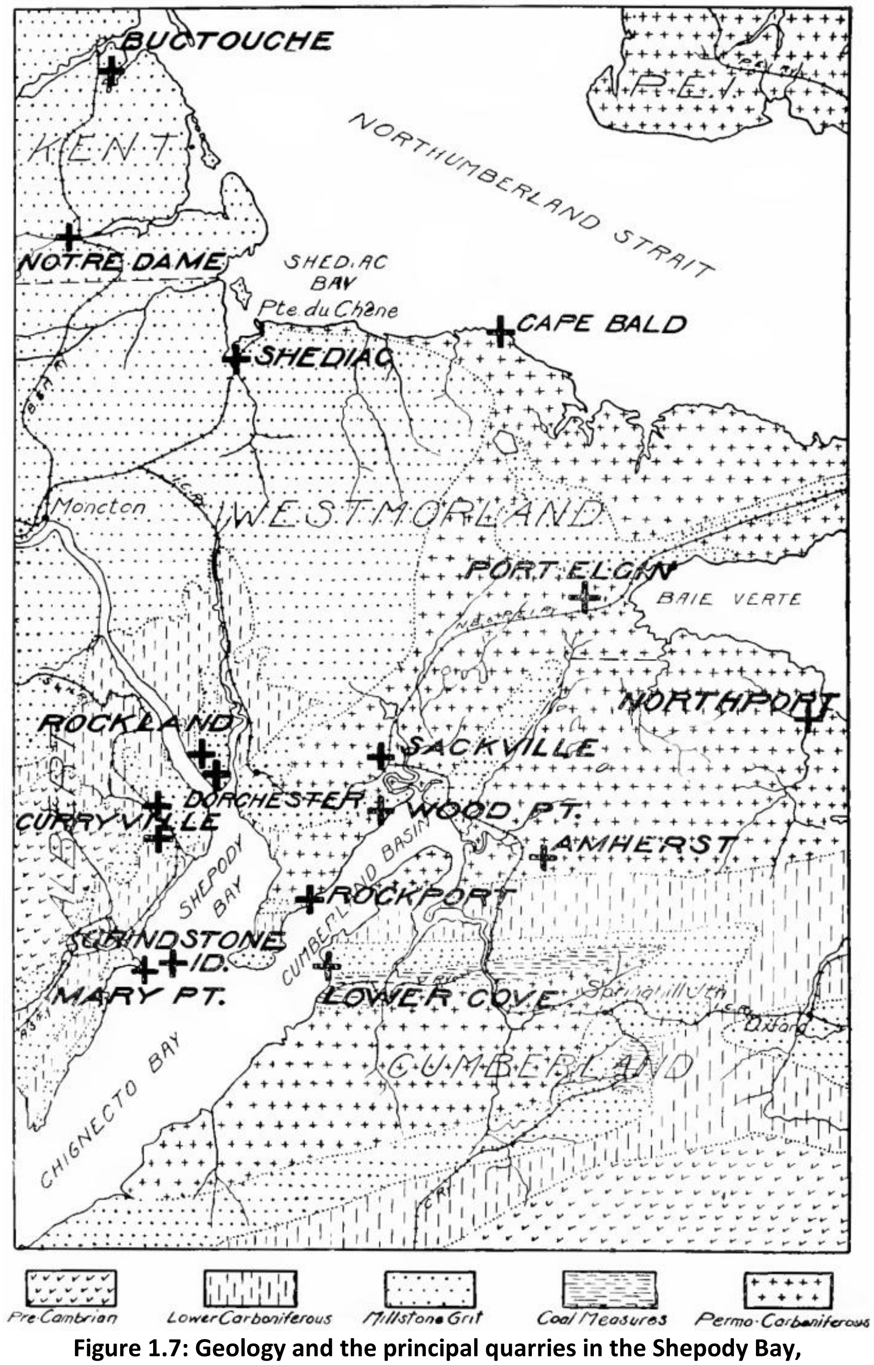


Figure 1.7: Geology and the principal quarries in the Shepody Bay, Cumberland Basin, Shediac and Buctouche Sandstone areas
Parks, *Report on the Building and Ornamental Stones of Canada*, 46.

[19] Ibid., 60.

Beaumont Quarry

The Beaumont quarry was opened to the south of the former Boudreau quarries near the extremity of the point between the Petitcodiac and Memramcook rivers in Westmorland County. This quarry, unlike the Boudreau quarries (discussed next), is situated at a much lower level with the bottom of the excavation being below the high water level. The Beaumont quarry was owned by the Dorchester Manufacturing Company originally and was later transferred to the Dorchester Union Freestone Company via Sir Albert J. Smith. The Dorchester Manufacturing Company was incorporated in 1855 in New York City and operated the quarry until 1858 when it went bankrupt.[20] The Beaumont quarry was active during the periods from 1860 to 1872 and from the 1890s to the 1920s.[21]

Boudreau (Dorchester) Quarries

The Boudreau quarries are located on the east bank of the Petitcodiac River, south of the Boudreau village on the west side of Fort Folly Peninsula, in Westmorland County. Regular stone production began here under the auspices of the Dorchester Olive Freestone Company of New York, which first introduced the Boudreau sandstone to the New York and New England markets. A large quantity of the rock was removed during the four decades of activity that followed since its opening in 1856.[22] The company became debt-ridden as markets for New Brunswick stone dropped due to an economic depression in 1862 and the American Civil War and owed money to at least four creditors by 1862.[23] Sir Albert J. Smith foreclosed the company in 1863 for $3000 and acquired its holdings. He transformed portions of the land to a second company called the Dorchester Union Freestone Company of New York in 1865.

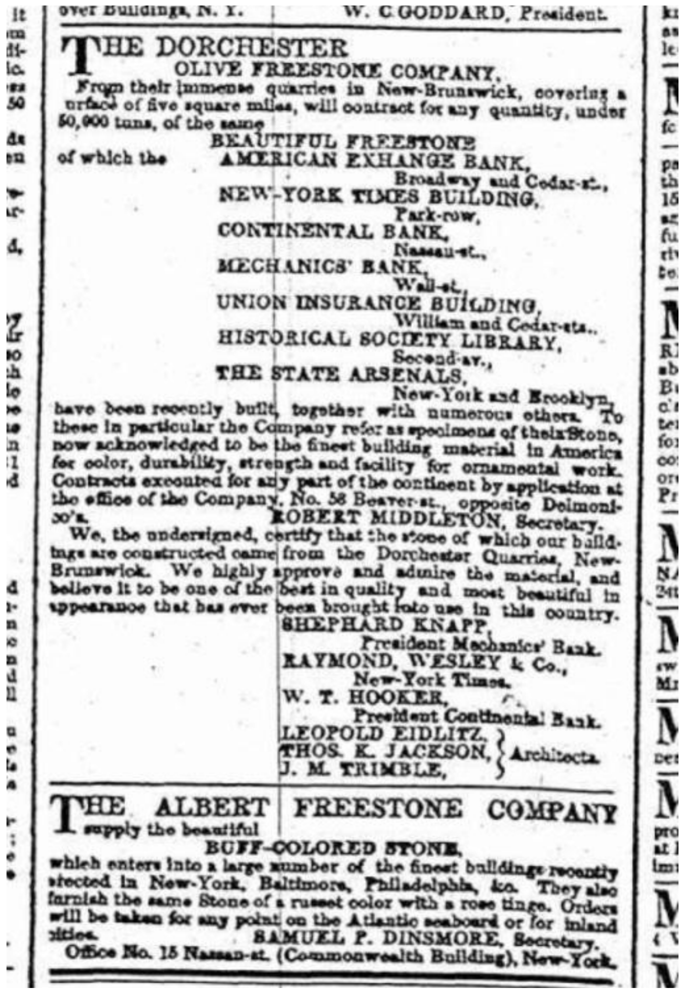
[20] George W. Burbidge, *A General Index to the Statues of New Brunswick* (Fredericton, 1878), 21.
[21] Martin, *For Love of Stone*, vol 1, 43.
[22] Parks, *Report on the Building and Ornamental Stones of Canada*, 57.
[23] Martin, *For Love of Stone*, vol 1, 50-51.

The Dorchester Union Freestone Company accumulated numerous land holdings covering much of southern Fort Folly Peninsula between 1866 and 1880. Despite the annulment of the Free Trade agreement between Canada and the United States, records from this time indicate that the company was shipping between 5,000 and 7,000 tons of stone annually to other Canadian parts as well as to the United States.[24] According to Martin, G.P. Sherwood, former President of the New York Stone Association had assured a favored place for the company in New York by creating a monopoly.[25] "The association charged quarry owners a $500 membership fee and blacklisted anyone attempting to sell non-membership stone in [New York C]ity."[26] Martin noted that it was difficult to be part of the association even with the $500 fee. The company sold most of its property to John Furlong and John Deery of G. P. Sherwood and Company of New York City in 1895. They operated the quarries until 1906. They both are also listed as the owners of the Wallace Stone Co. (the Wallace quarries) in Parks's report.

History of the Boudreau quarries from 1906 to 1989 is not well-documented. Fred Pellerin purchased the property in 1989 and re-opened it for both new construction and restoration purposes under the name of Bee Stone Company Inc. Pellerin renamed the Boudreau quarries as the Dorchester quarries based upon their historical name association. The Bee Stone Company Inc. now operates as Atlantic Sandstone Company.

The Dorchester quarries today comprise an area of 560 acres and 8 different stone quarry sites. These quarries are by far the largest and most important sandstone quarries in the eastern Canada employing up to 600 men during their peak operation periods.[27]

[24] Ibid., 52.
[25] Ibid., 53.
[26] Ibid., 53.
[27] Bees Stone Company Inc., "Central Park Restoration Revives Dorchester Quarries," *Brownstone Bits* 1, no. 1 (1991): 1.


over Buildings, N. Y. W. C. GODDARD, President.

THE DORCHESTER
OLIVE FREESTONE COMPANY,
From their immense quarries in New-Brunswick, covering a urface of five square miles, will contract for any quantity, under 50,000 tuns, of the same
BEAUTIFUL FREESTONE
of which the AMERICAN EXHANGE BANK,
Broadway and Cedar-st.,
NEW-YORK TIMES BUILDING,
Park-row,
CONTINENTAL BANK,
Nassau-st.,
MECHANICS' BANK,
Wall-st.,
UNION INSURANCE BUILDING,
William and Cedar-sts.,
HISTORICAL SOCIETY LIBRARY,
Second-av.,
THE STATE ARSENALS,
New-York and Brooklyn,
have been recently built, together with numerous others. To these in particular the Company refer as specimens of their Stone, now acknowledged to be the finest building material in America for color, durability, strength and facility for ornamental work. Contracts executed for any part of the continent by application at the office of the Company, No. 58 Beaver-st., opposite Delmonico's.
ROBERT MIDDLETON, Secretary.
We, the undersigned, certify that the stone of which our buildings are constructed came from the Dorchester Quarries, New-Brunswick. We highly approve and admire the material, and believe it to be one of the best in quality and most beautiful in appearance that has ever been brought into use in this country.
SHEPHARD KNAPP,
President Mechanics' Bank.
RAYMOND, WESLEY & Co.,
New-York Times.
W. T. HOOKER,
President Continental Bank.
LEOPOLD EIDLITZ,
THOS. K. JACKSON, } Architects.
J. M. TRIMBLE,

THE ALBERT FREESTONE COMPANY
supply the beautiful
BUFF-COLORED STONE,
which enters into a large number of the finest buildings recently erected in New-York, Baltimore, Philadelphia, &c. They also furnish the same Stone of a russet color with a rose tinge. Orders will be taken for any point on the Atlantic seaboard or for inland cities.
SAMUEL P. DINSMORE, Secretary.
Office No. 15 Nassau-st. (Commonwealth Building), New-York.

Figure 1.8: 1858 advertisements for the Dorchester Olive Freestone Company and Albert Freestone Company
New-York Daily Tribune, September 4, 1858.

Marys Point (Albert) Quarries

The Albert quarries are located on Marys Point in Albert County. William Crane of Sackville mortgaged the land at Marys Point in the mid-1830s from Alva Andrew of New York. London entrepreneur Charles Archibald mortgaged Marys Point in 1847 and when Andrew went bankrupt five years later, Archibald acquired full title to the property. Archibald and five other men incorporated the Albert Freestone Company in 1855 with the United States being their intended market.[28] The company operated the quarry until 1862 and produced about 4000 tons of stone annually. The quarries were operated by other companies until operations ceased in 1883. Since then, Marys Point quarries have been reopened briefly on three occasions for restoration projects.

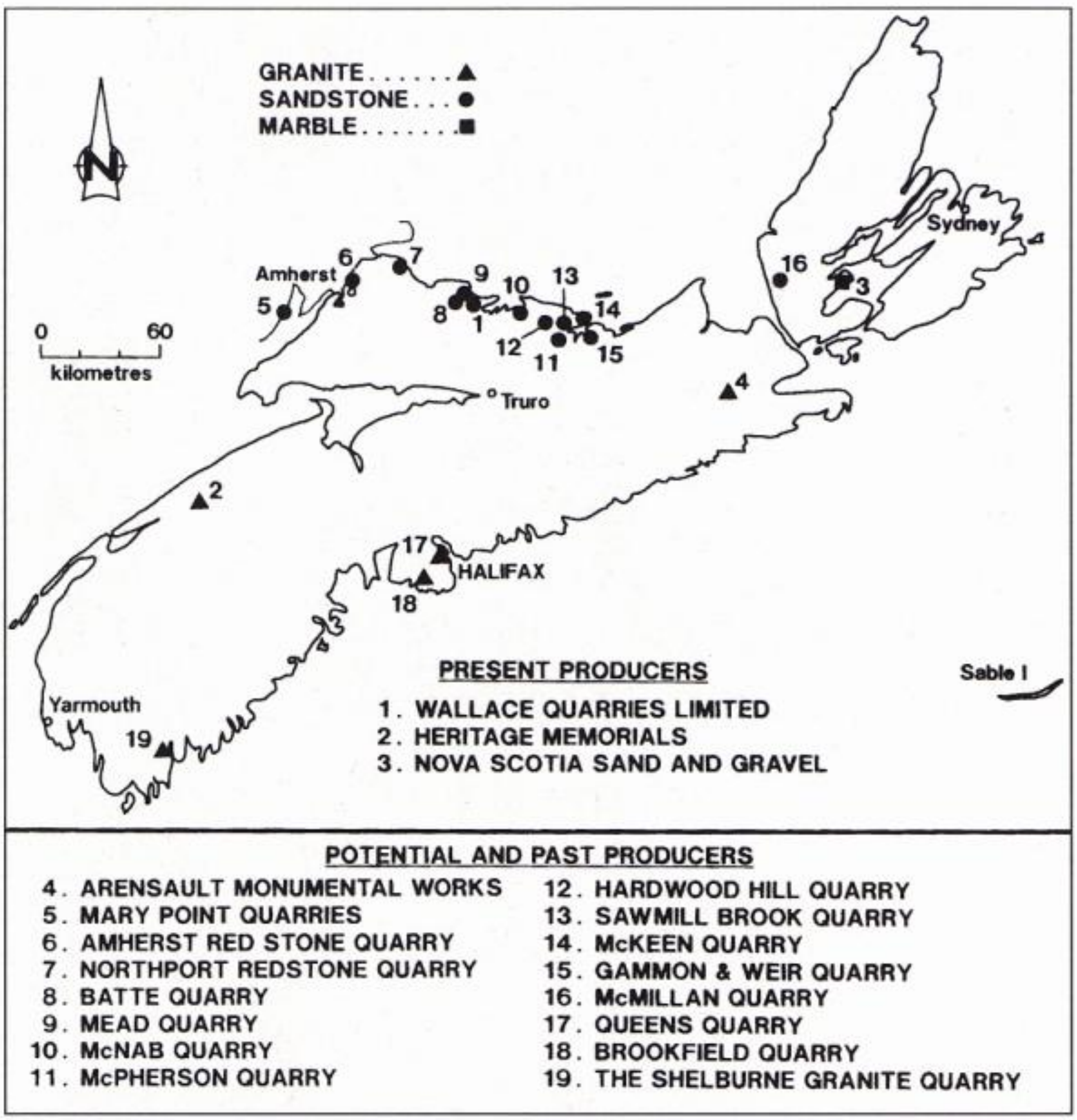


Figure 1.9: Major present and past producing Nova Scotia building stone quarries as of 1993
Dickie, *Building Stone in Nova Scotia*, 3rd ed., 5.

[28] *Acts of the General Assembly of Her Majesty's Province of New Brunswick* (Fredericton: J. Simpson, Printer to the Queen's Most Excellent Majesty, 1855), 231.

Wallace Quarries, Nova Scotia

The region about Wallace harbor in Cumberland County in Nova Scotia is an important producer of building stone and ranks as one of the chief districts in the Maritime Provinces.[29] There were as many as 75 sandstone quarries in Nova Scotia during the mid- to late 1800s. While many of the sandstone quarries produced only enough stone for the basement course of local buildings, the Wallace quarry has produced stone for both domestic and international consumption.[30] A total of 1,000,000 tons of stone production in the province was recorded with the Nova Scotia Department of Mines for the period between 1873 and 1973, of which 90.1 percent was sandstone.[31] The Wallace quarry produced approximately 50 percent of the total dimension stone and was by far the largest single stone producer in the region during that time.[32]

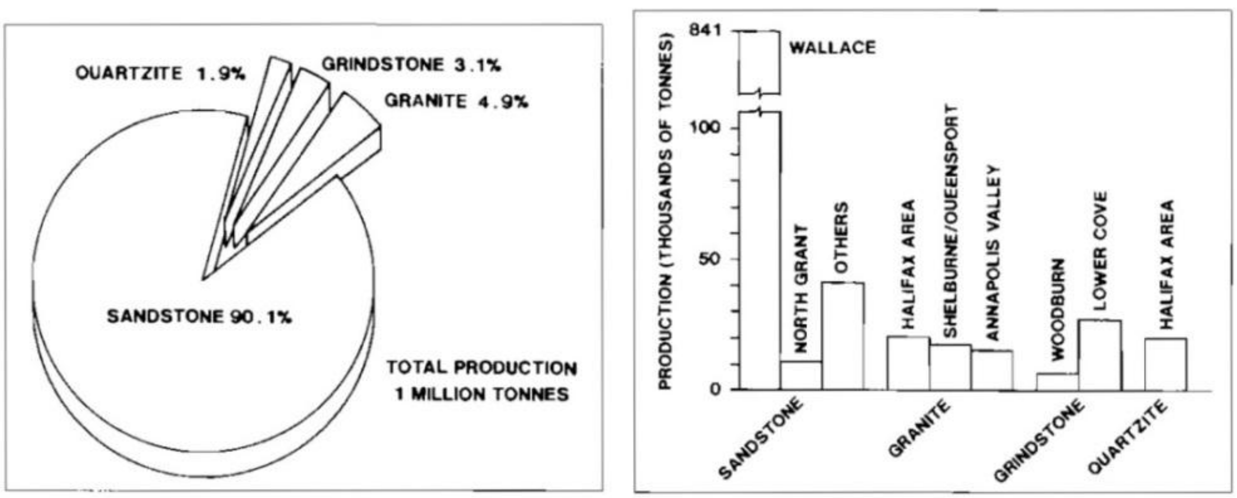


Figure 1.10: Nova Scotia building stone production between 1873 and 1973
Dickie, *Building Stone in Nova Scotia*, 3rd ed., 8.

The Wallace quarries are located 750 meters southeast of the intersection of Route 6 and the road to Wallace Station from Wallace. The presence of stone here was first discovered by a

[29] Parks, *Report on the Building and Ornamental Stones of Canada*, 77.
[30] G.B. Dickie, *Building Stone in Nova Scotia*, 3rd ed. (Halifax: Nova Scotia Department of Natural Resources, Mines and Energy Branches, 1993), 4.
[31] Ibid., 6.
[32] Ibid.

farmer digging post holes and the quarry was opened by a local man named William McNab in 1863.

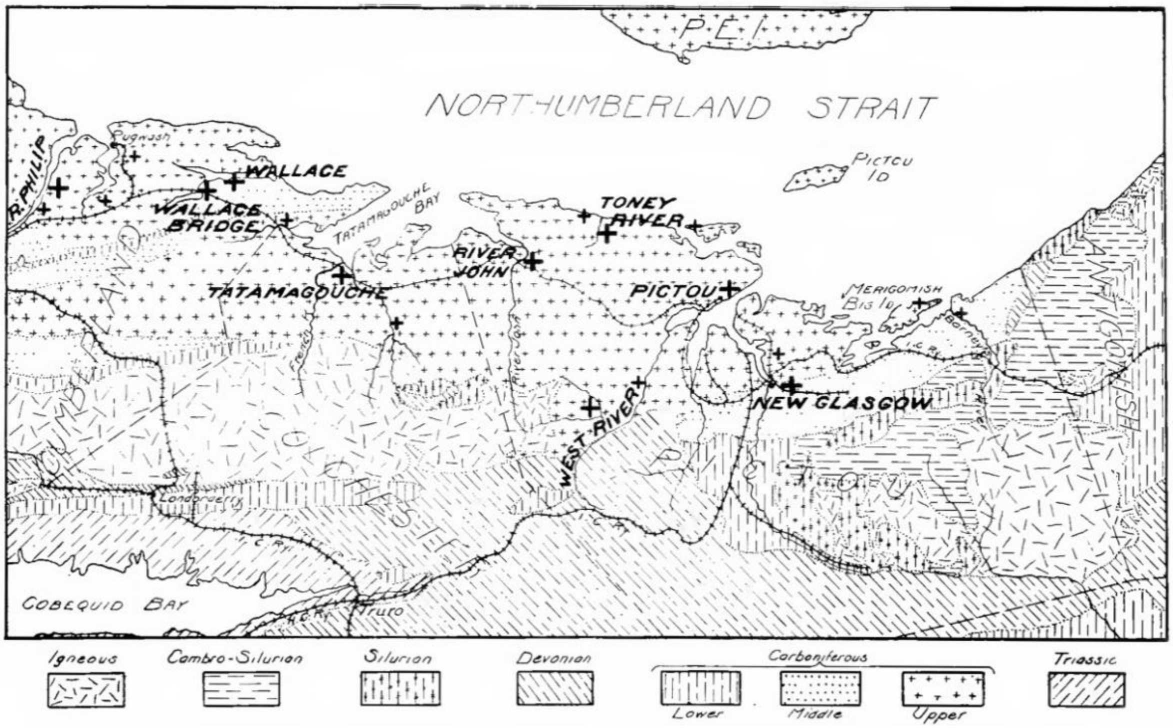


Figure 1.11: Geology and the chief quarries in the Wallace, River John and Pictou areas
Parks, *Report on the Building and Ornamental Stones of Canada*, 78.

Beginning in 1872, the Wallace Heustis Greystone Company and the Wallace Greystone Company operated the quarry. At some point between 1872 and 1905, the nearby Dobson Quarry was incorporated with the Wallace quarries. In 1885, the quarry was sold to G. P. Sherwood & Co. In 1912, P. Lyall & Sons purchased the quarry and modernized the operations with a steam mill for sawing, a large electric crane and shovels. The quarry employed 100 employees at one point including quarriers, stone carvers, masons and laborers and operated with this many people until the mid-1900s. By then, demand for the sandstone had begun to shrink steadily. The quarry remained relatively inactive throughout the 1970s. It was reopened in the 1980s when demand for the sandstone was picked up for restoration projects. Wallace Quarries Ltd. is now the sole owner and operator of all quarries in Wallace and vicinity.

1.2 USES OF THE MARITIME CANADIAN SANDSTONES IN CENTRAL PARK

Sandstones of the Maritime Canadian Provinces became popular in the United States during the mid-19th century as New York and other eastern United States cities made a transition to brownstone. This change in taste was encouraged by availability of good sources of colored sandstones, easy transportation via water and rail, and improvements in quarrying methods that made the stone cheaper. The architectural use of sandstone in New York City reached its peak by the 1870s and the 1880s and of all the buildings with stone fronts, 89.4 percent consisted of sandstone.[33] Different stones were used in the following proportion during the decade: brown sandstone, 78.6 percent; Nova Scotia sandstone, 9.0 percent; marble, 7.9 percent; granite, 1.8 percent; Ohio sandstone, 1.6 percent; foreign sandstone, 0.1 percent; and bluestone and limestone, 0.1 percent.[34] Import of marble and other stone from Nova Scotia, New Brunswick and Prince Edward Island was highest for the year ending on June 30, 1881.[35]

While the use of sandstone in Central Park coincided with the 'brown decades' in America, a question of interest is to learn why the sandstones from New Brunswick were used in a large quantity in Central Park over brown sandstone and sandstone from elsewhere.[36] In *Villas and Cottages*, Calvert Vaux, one of the architects of Central Park, wrote,

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[33] U. S. Census Office, *Report on the Building Stones of the United States and Statistics of the Quarry Industry for 1880* (Washington: U.S. Census Office 10th Census, 1880), 314.

[34] "The Decay of Building Stones in New York City." *The Manufacturer and Builder* 15, no. 2 (1883): 43. It should be noted that the percent value for Nova Scotia sandstone probably accounted for all the Maritime Canadian sandstone including the Dorchester stone. The Dorchester sandstone from New Brunswick was known throughout New England markets as 'Nova Scotia' sandstone in the 1800s. The full 95 percent of the imported material was, in reality, from Albert and Westmorland Counties in New Brunswick (probably 85 percent from Dorchester) and the remainder from Nova Scotia and other points. This was noted by both George Perkins Merrill and Alexis A. Julien in the late 1880s.

[35] U. S. Census Office, *Report on the Building Stones of the United States and Statistics of the Quarry Industry for 1880*, 398.

[36] The 'brown decades' in America refers to a period between about 1865 and 1895 after the American Civil War. During this time, architects favored the use of brown color sandstones for facings of buildings in New York and other eastern United States cities. Brown color reflected the somber mood of the country and Americans' adaptation to "visible smut of early industrialism".

> "Houses that are built of squared brown stone have a melancholy, dingy, monotonous, and uninteresting look…Marble is too white to be agreeable in the country. Squared blue stone is cold, prison-like, and repellant for ten or twelve years…Granite is still colder and more expressionless than blue stone, with the additional disadvantage that it is wholly uninfluenced by time. Stone from Caen, in Normandy, has lately been introduced into New York, and is used to some extent. It is a beautiful material, and very delicate in color, but unequal in quality, unless specially imported from well-known firms. It seems, however, a little unnatural for a continent like this to seek building materials in Europe, and there can be little doubt but that a strict geological examination will, after a time, supply us with many new varieties of building-stone. A capital free-stone, of a pleasant, soft tint, has lately come into use, brought from the Dorchester quarries, Westmorland County, New Brunswick."[37]

And about the use of stone in Central Park, it was written in the *1858 Central Park Architect Report*,

> "I have seen some fine specimens of stone from the neighborhood of Kingston, Hudson River; the color is good, and the stone very durable. Brown stone, I cannot recommend, either for its color or its durability. Whatever is built in the Park, must be as nearly imperishable as possible; for pedestals, large granite blocks should be employed. The copings of the bridges and terraces should be of Nova Scotia stone, or the Kingston, before mentioned."[38]

Ornamental Arches and Bridges of Central Park

Ornamental arches and bridges of Central Park are elaborate grade separations of traffic with Bethesda Terrace being the most elaborate of them all.[39] These include bridges for the carriage roads, bridle paths and walks in the Park. The Park Commissioners complained about Frederick Law Olmsted and Vaux's original bridle path design being inadequate and ordered both to extend paths throughout the already narrow landscape.[40] Instead of removing even an

[37] Calvert Vaux, *Villas and Cottages* (New York: Harper & Brothers Publishers, 1857), 69-70.
[38] Board of Commissioners of the Central Park, *1858 Central Park Architect Report* (New York: Charles W. Baker, 1859), 14.
[39] Bethesda Terrace was originally referred to as Terrace Bridge, No. 1, as it carries the 72nd Street Drive and serves as an underpass between the Mall and the lower terrace.
[40] Sara Cedar Miller, *Seeing Central Park* (New York: Abrams, 2009), 19.

inch of wood, water or turf for an additional thoroughfare, Olmsted and Vaux came up with a series of ornamental arches and bridges that allowed intersecting routes to pass over and under one another to separate different modes of traffic and allow for horses and pedestrians to enjoy the Park together. Arches and bridges were originally numbered in the order of their design sequence and were later renamed to their current names. (The historic designation numbers are in Appendix A.)

While the ornamental arches and bridges were constructed in about the same manner as the other bridges in the Park, the exteriors were formed of different kinds of selected stone and brick. Facings of the bridges are of stones of different quality, texture and degree of hardness.

Original Sandstone

The widespread use of the Canadian sandstones for constructing parts of the perimeter wall, ornamental arches and bridges, and Bethesda Terrace increased the stones' popularity in America. A large quantity of the original sandstone that came from the Boudreau (Dorchester) quarries was supplied by the Dorchester Olive Freestone Company. The *1858 Central Park Commissioners Annual Report* listed two payments made to the Dorchester Olive Freestone Company on December 22, 1858. The *1861 Central Park Commissioners Annual Report* mentioned use of olive-colored freestone from Albert, Dorchester and Weston quarries in New Brunswick.

Table 1.1 lists areas on the arches and bridges in Central Park where New Brunswick sandstone was used originally.

Table 1.1: Original uses of New Brunswick sandstone in Central Park[41]

Name of Structure	Location	Date of Completion	Areas of Use
Balcony Bridge	West Side at 77th Street and West Drive	1859	New Brunswick sandstone trimmings and balustrades
Bethesda Terrace	Mid-Park at 72nd Street	1863	New Brunswick sandstone face-work, trimmings and balustrades; a slightly harder greyer variant of the same stone was used for capstones and finials[42]
Dalehead Arch	West Side at 64th Street and West Drive	1860	New Brunswick sandstone facings of ends and fronts of bridge, trimmings and balustrades
Denesmouth Arch	East Side just north of the Central Park Wildlife Conservation Center at 65th Street and Fifth Avenue	1860	New Brunswick sandstone facings throughout, balustrades and trimmings
Driprock Arch	Mid-Park at 63rd Street	1859	New Brunswick sandstone trimmings and balustrades
Glade Arch	East Side between 77th and 87th Streets just east of Cedar Hill	1860	New Brunswick sandstone facings throughout and balustrades
Green Gap Arch	East Side at 63rd Street and East Drive	1860	New Brunswick sandstone facings throughout and balustrades
Greyshot Arch	West Side between 61st and 62nd Streets	1860	New Brunswick sandstone trimmings and balustrades
Willowdell Arch	East Side at 67th Street	1860	New Brunswick sandstone trimmings and balustrades
Winterdale Arch	West Side at 82nd Street	1861	New Brunswick sandstone trimmings

It is important to note that the sandstone used for the original construction came from New Brunswick and not from Nova Scotia. It was not until the mid-1900s when the sandstone from Nova Scotia began being used for restoration and repair in the Park.

Restoration Sandstone

Smith Cut Stone & Quarries Ltd. supplied sandstone for repair work of Bethesda Terrace during the 1950s and the 1960s; however, the stone that this Shediac, New Brunswick, quarry

[41] Board of Commissioners of the Central Park, *Fifth Annual Report* (New York: William C. Bryant & Co., 1862), 87.
[42] Jean Parker Murphy and Kate Burns Ottavino, "The Rehabilitation of Bethesda Terrace: The Terrace Bridge and Landscape, Central Park, New York," *Bulletin of the Association for Preservation Technology* 18, no. 3 (1986): 28.

supplied to Central Park was in fact the Wallace sandstone.[43] The Wallace sandstone was sold to the Smiths beginning around 1954 and most of the stone cut at the Smiths was in fact Wallace material.[44] Wallace rock was described by Martin to be similar in color and generally superior in grain size and consistency to the Shediac material. Additionally, the Wallace beds are more massive and yield larger blocks. (I have not located additional information about this repair work outside of Martin's writings.)

The replacement sandstone for the 1980s restoration of Bethesda Terrace was obtained from the Wallace quarries in Nova Scotia by Can-Stone Inc. The restoration team visited the only quarry at Wallace that was able to match the original sandstone used in Central Park and ended up using large blocks of stone that had been quarried years before and were lying near the road.[45] Some blocks were weathered or cracked and the team did not have an option to select freshly quarried pieces. Acceptable sandstone was fabricated by the Bybee Stone Company Inc. in Indiana.

When the Central Park Conservancy decided to restore some of the ornamental arches and bridges in 1989, sandstone was purchased from the historic Dorchester quarries that were reopened by Bee Stone Company the same year. The company fabricated and supplied the Conservancy with over 1100 cubic feet of carved sandstone.[46]

Table 1.2 is a list of New Brunswick and Nova Scotia quarries, whose sandstone was noted to have been used in Central Park.

[43] Martin, *For Love of Stone*, vol 2, 152.
[44] Ibid.
[45] Murphy and Ottavino, "The Rehabilitation of Bethesda Terrace," 28.
[46] Bee Stone Company Inc., "Central Park Restoration Revives Dorchester Quarries," 3.

Table 1.2: New Brunswick and Nova Scotia sandstone quarries and their use in Central Park

Province	County	Locality	Examples in Central Park[47]
NB	Albert	Marys Point (Albert)	Parts of the perimeter wall, ornamental arches and bridges, Bethesda Terrace, most of the freestone masonry in the Park
NB	Albert	Shepody Mountain, Hopewell	Parts of the perimeter wall, ornamental arches and bridges
NB	Albert	Surface quarries of Hillsboro	Ornamental arches and bridges
NB	Westmorland	Boudreau (Dorchester)	Parts of the perimeter wall, ornamental arches and bridges, Bethesda Terrace
NB	Information not available	Weston	Parts of the perimeter wall, ornamental arches and bridges, Bethesda Terrace
NS	Cumberland	Wallace	Bethesda Terrace

Performance of the Maritime Canadian Sandstones in Central Park

The Maritime Canadian sandstones are not the only sedimentary rocks used in Central Park; however, they are deteriorating significantly poorly and displaying various modes of decay in comparison to New Jersey sandstone and Hudson River 'Mountain Greywacke' when exposed to the same set of environmental conditions. Weathering of the Canadian stones in the Park has been attributed to its geological structure, construction techniques, and extreme climatic changes and pollution by the former researchers.

A complex set of natural and human induced causes has resulted in widespread differential weathering of sandstone elements in Central Park. Some of the causes include air pollutants; biological growth; rising damp; exposure to chloride containing soil; full exposure to rain and wind; continuous running of water over the surface of the stone during rain; varying climates of wet/dry and freeze/thaw cycling; and accumulation of water in certain areas due to uneven ground, from rising ground water or blocked drainage. The environment of the Bethesda arcade and almost all the ornamental arches and bridges is also sufficiently different from the

[47] Board of Commissioners of the Central Park, *Fifth Annual Report*, 87; U. S. Census Office, *Report on the Building Stones of the United States and Statistics of the Quarry Industry for 1880*, 361, 368.

exterior as many structures are both above and below grade in certain areas. The Bethesda arcade displays lower temperatures and higher relative humidity than the surrounding landscape most of the year, due in part to its subterranean areas.[48] The arches and bridges also act as a wind tunnel through which atmospheric pollution, rain and snow are rapidly carried deep into the interior.[49]

Some issues that are unique to Bethesda Terrace include flooding of the structure in the past caused by the Lake at the end of the terrace, infiltration of water through the failed waterproof membrane of the bridge, and spalls and stains from the use of iron anchors to fasten the kitchen equipment to the stonework of the arcade between 1967 and 1974.

The sandstone elements in the Park have also suffered damage by human activity and interventions that include graffiti, physical abuse and alteration, structural modifications, de-icing activity during snow and failed structural mechanics. The majority of the structures are frequently visited by transients, who use them as urinals and which can deposit harmful nitrates. Bird's heads and other finials at Bethesda Terrace, now repaired, were once knocked off completely. Vehicular traffic including snowplows caused significant damage to arches and balustrades in the past. Furthermore, inappropriate repair interventions have resulted in use of cast-stone with coarse aggregates for fine-grained sandstone as noticed at Balcony Bridge (Figure 1.12).

[48] Christopher John Gembinski, "Bethesda Terrace: Conditions Assessment and Evaluation of Previous Stone Conservation Treatments" (MSc Thesis, University of Pennsylvania, 1998), 14.
[49] Ibid.

Figure 1.12: Eastern balustrade of Balcony Bridge showing use of cast-stone for replacement

Central Park's environment is crucial in understanding how sandstone structures have survived today; however, as previously mentioned, the core of this research is to investigate the role of sandstone's mineralogical composition and textural characteristics towards its weathering in Central Park if any. The Canadian sandstones used in the Park came from multiple quarries and depending on the location and geological age of a quarry, stones may differ in mineralogical composition and physical characteristics and may deteriorate differently. Even within a same stone block, deterioration occurs at a different rate from one area to another as noticed on diaper-patterned stone panels on walls of the central staircase at Bethesda Terrace (Figure 1.13). Certain portions of the stone surface are severely disintegrated that stone carvings are no longer readable while others are in a perfectly sound condition as if the stone was carved yesterday.

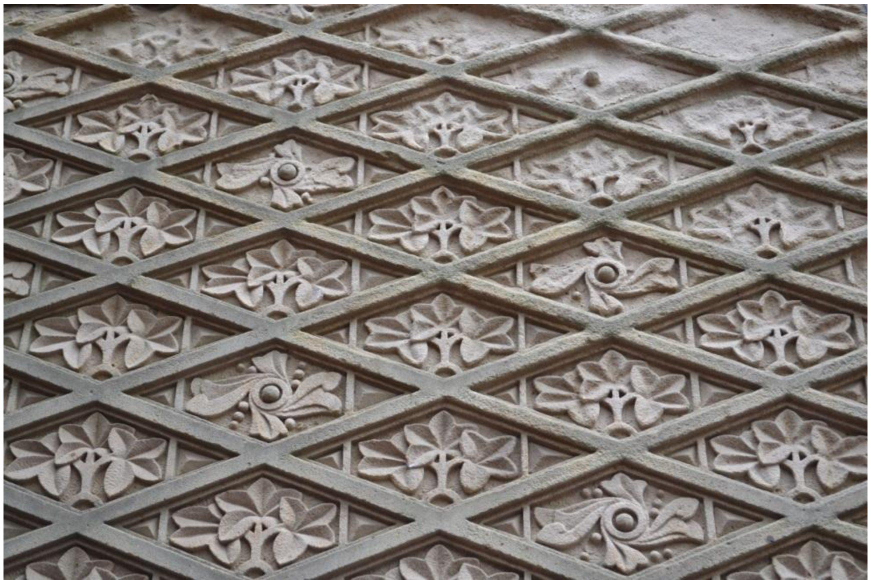

Figure 1.13: A diaper-patterned stone panel at Bethesda Terrace showing differential erosion

Figure 1.14: Denesmouth Arch showing deterioration conditions

The Dorchester sandstone gained a reputation for early deterioration within years of installation and the conditions of weathering at Bethesda Terrace were noted as early as 1883 by Alexis A. Julien who reported freestone moldings being repeatedly recut at the Terrace in 1883.[50] (Julien was hired by the Building Stone Commission of the Census Department to report on the decay of building stones in New York City in the 1880s.)

[50] "The Decay of Building Stones: What Dr. Alexis A. Julien Says on the Subject," New York Times, January 30, 1883, Miscellaneous City News.

Various modes of sandstone decay have been noted at Central Park, which include granular disintegration, delamination, alveolization, scaling and blistering. (A list of deterioration conditions that refer to any chemical or physical modification of the intrinsic stone properties resulting in worsening or lowering of quality, value or character is in Appendix B.)

While the sandstone elements have weathered to a varying degree in Central Park, sandstone, where unaffected by decay, retains its color, sharp edges and crisp details. The highly carved areas have weathered the most as the sandstone used is generally soft and easily carved.

2. METHODOLOGY

The Maritime Canadian sandstones are fully characterized by determining their mineralogical composition and textural characteristics, which are useful in understanding their performance and weathering when used with other materials in a structure with complex environment. The characterization of the stones was done using x-ray diffraction (XRD), polarized light microscopy (PLM), scanning electron microscopy (SEM) and methylene blue index (MBI) of clay. Additionally, the stress exerted during swelling when the expansion is constrained is calculated from hygric dilation results. The overall characterization is used to compare and contrast deteriorated, undeteriorated and current quarry samples; see differences among sandstones from different quarries; and understand how a particular stone characteristic may influence sandstone's specific weathering behavior.

Field and Quarry Samples

Cylindrical core samples of approximately 14 mm in diameter and 50 mm in length were extracted from 10 ornamental arches and bridges in Central Park including Bethesda Terrace. Various factors were taken into consideration when selecting areas for sampling such as exposure to rain, sun and wind; type and level of deterioration; location, interior or exterior; distance from the ground; type of use; and original vs. restoration sandstone. (Details about field sampling are in Appendix A.)

Samples were also acquired from Atlantic Sandstone Co., current owner of the historic Dorchester quarries, and Wallace Quarries Ltd., current owner of the Wallace quarries. The Dorchester sandstone block received from the company is 15 cm wide, 15 cm long and 15 cm tall. The sample is of an olive color and fine-grained composition. It has no visible bedding planes. The Wallace sandstone blocks received from the quarries are 5 cm wide, 5 cm long and

5 cm tall each. All 6 samples are of a light blue to grey color and fine-grained composition. They have no visible bedding planes.

X-ray Diffraction (XRD)

X-ray diffraction is a method used to identify the chemical composition of crystalline materials. Test specimens were prepared by grinding representative portion of a sample into fine powder. The ground sample (usually about 250 mg) was then scanned using a Phillips PW1835 X-ray Diffractometer with a copper x-ray tube set at a voltage of 40 kV and a current of 30 mA measuring between 5^{o} to 65^{o} for 50 minutes. Analysis was conducted using JCPDS minerals database and Search–Match program uPDSM. (X-ray diffraction on the field samples from Central Park and two quarry samples was performed with the assistance of George Wheeler at the Metropolitan Museum of Art, who also helped to identify minerals in stone samples.)

Polarized Light Microscopy (PLM)

Polarized light microscopy uses slides of materials cut to a thickness where light can be transmitted through the sample (thin section). Transmitted light is polarized before passing through the sample. This is called plane-polarized light (PPL). If the light is polarized again after passing through the sample, then it is called cross-polarized light (XPL). These two light types create different effects as they pass through the sample and highlight differences in the minerals present. (Thin sections for PLM characterization were prepared by National Petrographic Services, Inc. in Houston, TX and American Petrographics in Roslyn Heights, NY. Samples were grounded in oil and impregnated with blue epoxy in order to highlight pore space.)

Scanning Electron Microscopy (SEM)

In scanning electron microscopy, an image of the sample is scanned with a beam of electrons in a raster scan pattern. The electrons interact with the atoms that make up the sample producing signals that contain information about the sample's surface topography and composition. SEM on the stone samples was performed using Hitachi TM3000 Tabletop Microscope.

Methylene Blue Index (MBI) of Clay

Methylene blue index of clay measures the adsorption of methylene blue dye by clay minerals. The test generally indicates a straight-line relationship between MBI and fundamental clay properties such as cation exchange capacity, dry bond strength and casting rate. MBI is useful in understanding impact of the cation exchange capacity of clays present in sandstone.

Test specimens were prepared by grinding representative portion of the sample to separate sand particles from binding cementing material. 1.2 g of grounded sample was mixed with 25 ml of de-ionized water in a volumetric flask. 0.1 ml of methylene blue solution was added to the flask. The concentration of the methylene blue solution was 10 g unhydrate methylene blue per liter solution. The contents inside the flask were agitated before letting the flask set for 24 hours. The next day, each flask was visually analyzed to compare amount of methylene blue dye absorbed by clay particles in the stone sample. A control was prepared by adding 0.1 ml of methylene blue solution in 25 ml of de-ionized water.

Hygric Dilation

Clays in sandstone that dilate with changes in humidity and during wetting/drying cycles can lead to deterioration of the stone and cause destruction of consolidants.[51] This test was carried out to calculate the stress exerted during swelling when the expansion is constrained.

Swelling of the stone, perpendicular to the bedding planes, was quantified using a Perkin-Elmer Differential Mechanical Analyzer (DMA 7e). Samples with a maximum height of 10 mm and diameter of no more than 14 mm were placed in the sample holder and then immersed in de-ionized water. The height of the sample was continuously monitored before, during and after immersion for 90 minutes at 20 ºC and static force of 500 mN.

[51] Inmaculada Jimenez Gonzalez, Megan Higgins, and George W. Scherer, "Hygric Swelling of Portland Brownstone," *MRS proceedings* 712 (2002): 21.

3. DESCRIPTION OF THE MARITIME CANADIAN SANDSTONES OF CENTRAL PARK

Sandstone is a type of sedimentary rock in which individual grains of sand, consisting mainly of the minerals quartz and feldspar, are cemented together by silica, iron oxide, calcite or clay. Since the rock is formed from layers of sand held together by natural cements, it has "inherent areas of weakness, where each layer, or bedding plane, comes into contact with adjacent layers".[52] The loss of adhesion between the strata can cause sandstone to delaminate. Durability of sandstone is related to its matrix; and thus, the stronger the matrix, the more durable the stone.

Sandstone forms in a wide range of colors, grain sizes and texture. It can form in colors ranging from light grey to buff to orange-red depending upon the relative trace amounts of carbon and/or iron oxide compounds.[53] The color is mainly due to iron containing minerals such as hematite, limonite and pyrite and composition of the stone's matrix. The grains of more or less rounded in form may vary in size ranging from impalpable dust to small pebbles. In texture, sandstone can be of fine texture with almost no particles visible to the naked eye or coarse conglomerates wherein the individual grains dominate.[54] The stone can be hard or extremely soft and porous.

This chapter provides an overview of description of the Maritime Canadian sandstones, used in Central Park, by geologists and quarry owners. The purpose is to illustrate variance in color, grain size, texture and physical properties among sandstones from a single quarry and from different quarries. Diversity in stone characteristics is vital in understanding different

[52] Dietsch, "Saving Sandstone," 131.
[53] Martin, *For Love of Stone*, vol 1, 4.
[54] Teutonico, "The Conservation of the Bethesda Terrace in Central Park," 29.

modes of decay observed at Central Park and determining the stone's durability and capacity to resist different weathering agents.

3.1 GENERAL DESCRIPTION

Sandstones of the Maritime Canadian Provinces range in color from olive-green to grey, red and brown. While quarries in Shepody Bay area has produced both olive-green, red and brown color sandstones, the Wallace quarries, Nova Scotia, has produced chiefly 'grey' and 'blue' color sandstones. According to Parks, the olive-green and grey color sandstones from Shepody Bay area and the Wallace quarries vary from fine- to coarse-grained in texture with the general average texture of the typical olive-green stones being rather coarse.[55] Table 3.1 is an overview of physical characteristics, such as color and texture/bedding by geologists and quarry owners, of the Maritime Canadian sandstones that were noted to have been used in Central Park.

Table 3.1: Physical characteristics of the Maritime Canadian sandstones used in Central Park

Province	County	Locality	Geological age	Color	Texture/bedding
NB	Albert and Westmorland	General	Lower Carboniferous	Light grey, buff-yellow, olive-green, red and brown	Fine-grained, even textured with more or less distinct laminations
NB	Albert	Marys Point (Albert)	Lower Carboniferous	Salmon, olive and dark brown	Fine- to medium-grained
NB	Albert	Shepody Mountain, Hopewell	Millstone Grit	Pale olive-green	Medium-grained and uniform texture
NB	Albert	Surface quarries of Hillsboro	Information not available	Information not available	Information not available
NB	Westmorland	Boudreau (Dorchester)	Millstone Grit/ Upper Carboniferous[56]	Olive-green to grey, Yellow-brown	Homogeneous, fine-grained, uniform, even texture
NB	Information not available	Weston	Lower Carboniferous	Information not Available	Information not available
NS	Cumberland	General	Upper Carboniferous	Light grey, yellow and olive-green, bright red	Fine-grained, even textured
NS	Cumberland	Wallace	Upper Carboniferous	Fresh olive and blue grey, weathered olive to buff and grey, uniform to variable	Medium-grained, uniform texture

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[55] Parks, *Report on the Building and Ornamental Stones of Canada*, 21.

[56] Parks listed the bedrock geology for the quarry to be Millstone Grit, while the Bee Stone Company Inc. listed it to be upper Carboniferous.

Parks also noted the sandstones having varying physical properties. In specific gravity, they ranged from 2.64 to 2.69. The pore space was greater than 10 percent with the highest result being 18.489 percent and the average of 21 samples being 13.73 percent. Average weight per cubic foot of 21 samples was 143 lbs. All the samples were found to suffer a considerable loss in compressive strength when saturated with water according to him. Compressive strength ranged from 8869 psi to 17893 psi and an average of 26 tests was 13000 psi. Transverse strength ranged from 809 to 1700 psi. Parks concluded from the coefficient of saturation experiment "that the direct action of frost on the stones was not to be seriously apprehended".[57] Table 3.2 is a list of physical properties of the Marys Point (Albert), Beaumont and Wallace sandstones reported by Parks in 1914.

Table 3.2: Physical properties of the Marys Point (Albert), Beaumont and Wallace sandstones reported by William A. Parks in 1914

Locality	Transverse strength (psi)	Compressive strength (psi)			Specific gravity	Weight per cubic foot (lbs)	Pore space (%)	Ratio of absorption (%)	Coefficient of Saturation		Loss on treatment with carbonic acid and oxygen (grams per sq in)
		Dry	Wet	Wet and frozen					One hour	Two hours	
Marys Point (Albert)	1638	17817	9099	5728	2.665	144.387	13.271	5.749	0.60	0.61	0.0062
Beaumont	1447	17800	8418?	5920	2.657	146.795	10.897	4.604	0.58	0.68	0.00343
Wallace 'Grey'	1838	13681	10075	8754	2.687	144.808	13.688	5.902	0.61	0.63	0.0057
Wallace 'Blue'	1534	15633 17680	12235		2.687	145.869	13.038	5.58	0.62	0.63	0.00164

[57] Parks, *Report on the Building and Ornamental Stones of Canada*, 21.

Table 3.3 is a list of physical properties of the Boudreau (Dorchester) and Nova Scotia sandstones published by Julien in 1890.

Table 3.3: Physical properties of the Boudreau (Dorchester) and Nova Scotia sandstones published by Dr. Alexis A. Julien in 1890[58]

Locality	Specific gravity	Weight per cubic foot (lbs)	Ratio of absorption	Heated at 600 ˚F	Heated at 800 ˚F	Heated at 900 ˚F	Heated at 1000 ˚F
Boudreau (Dorchester)	2.363	147.7	1+26	Not injured	Cracks	Cracks and crumbles	Cracks and crumbles
Nova Scotia	2.424	151.5	1+240	Not injured	Not injured	Cracks	Friable

Table 3.4 is a list of physical properties of the Boudreau (Dorchester) sandstone published by Bee Stone Company Inc. in 1991.

Table 3.4: Physical properties of the Boudreau (Dorchester) sandstone published by Bee Stone Company Inc. in 1991[59]

Locality	Density (lbs/cf) (ASTM C97)	Water absorption (%) (ASTM C97)	Transverse strength (psi) (ASTM C99)	Compressive strength (psi) (ASTM C170)	Flexural strength (psi) (ASTM C880)	Hardness (H_a) (ASTM C241)
Boudreau (Dorchester)	141	515	420	9404	696	8

Table 3.5 is a list of testing data published by National Research Council (NRC), NS, in 1967.

Table 3.5: Physical properties of the Wallace sandstone published by National Research Council, NS, in 1967[60]

Locality	Ratio of absorption (%) (after 24 hours)	Coefficient of saturation	Weight per cubic foot (lbs)	Pore Space (%)	Compressive strength (psi)	Freeze/thaw test
Wallace	4.0	0.644	141 to 145 (for 12 specimens)	14.3	11,154 to 14,759 (for 4 specimens)	50 freeze/thaw test was completed on four samples with no failures. The avg. weight loss at the end of cycling was 0.06%.

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58 Alexis A. Julien, "The Decay of the Building Stones of the City of New York and Vicinity," *The Manufacturer and Builder* 22, no. 11 (1890): 248.
59 Bees Stone Company Inc., "Central Park Restoration Revives Dorchester Quarries," 4.
60 "Wallace Quarries – Test Data," Wallace Quarries Ltd., accessed May 8, 2013, http://www.wallacequarries.com/test-data.html.

Relative hardness and relative specific gravity of sandstones from Marys Point (Albert), Boudreau (Dorchester) and Weston quarries from *the Fifth Annual Report of the Board of Commissioners of the Central Park* is listed in Table 3.6. The report mentioned that

> "[t]he qualities of strength and durability are not governed exclusively by hardness and specific gravity or density, being dependent also upon the cohesion of the particles of the stone by the natural cement contained, freedom from metallic oxides, etc. No experiments have been tried in these respects, as the general character of the most of the stones has been long well known, and a reputation derived from long actual use is considered the safest and best."[61]

Table 3.6: Relative hardness and relative specific gravity of New Brunswick sandstones used in Central Park[62]

Locality	Relative Hardness	Relative Specific Gravity
Marys Point (Albert)	Hardest	Higher
Boudreau (Dorchester)	Harder	Highest
Weston	Hard	High

Overall, testing data on the Wallace sandstone published by Parks, Julien and NRC were nearly similar. Parks reported compressive strength (psi) to be between 13,681 and 17,680; and NRC reported it to be lower in range between 11,154 and 14,759. Weight per cubic foot (lbs) of the stone noted by Parks, Julien and NRC was between 141 and 151.5. Specific gravity value reported by Julien and Parks was as follows: 2.424 and 2.687. Parks reported pore space (%) of Wallace 'Grey' and Wallace 'Blue' to be 13.688 and 13.038, and NRC reported it to be 14.3. Ratio of absorption (%) by NRC was 4.0 and by Parks, it was between 5.58 and 5.902. Coefficient of saturation reported by Parks and NRC was between 0.61 and 0.64.

[61] Board of Commissioners of the Central Park, *Fifth Annual Report*, 88.
[62] According to the Fifth Annual Report of the Board of Commissioners of the Central Park "[t]he relative degrees of hardness [was] ascertained in the dressing the stone and [was] stated according to the judgment of the stone-cutters employed. The relative specific gravity [was] ascertained by the weight of equal bulks of stone of the several kinds."

Beaumont Sandstone

Parks described the upper stone at the Beaumont quarry to be similar to the stone from the Boudreau quarries and the lower stone to be distinctly blue-grey and different from the average stone of the district. He reported the blue-grey color of the stone to retain under action of the weather and the stone to remain durable under the oxidation test.

Boudreau (Dorchester) Sandstone

Majority of the sandstone from the Boudreau quarries was of fine grains and a lighter and more greenish color, with a considerable variation in texture according to Parks's description. Out of two sandstone samples he collected, one was a homogeneous, even and fine-grained stone of medium texture and second was medium-grained stone of more distinctly greenish color. He noted the stone to lose its brownish cast and turn grey on short exposure and darken considerably later.

The 1989 New Brunswick stone brochure listed Boudreau 'Tan' and Boudreau 'Grey' sandstones. The 'Tan' sandstone was described to be yellow-brown in color and have uniform medium-grained texture with some fine-grained and coarse-grained areas. The 'Grey' sandstone was described to be grey-brown in color and have a fairly uniform medium-grained texture with some fine-grained and coarse-grained areas locally. The brochure noted that the 'Grey' type was a color variation within a large quarry that was dominated by yellow-brown sandstone.

In the 1991 publication by Bee Stone Company Inc., the sandstone was described as a "homogeneous, fine-grained sedimentary stone of uniform, even texture with an average grain size of .35 mm".[63] The stone is of a yellowish-brown color, "which in natural, rocked and split cleft displays a golden ochre color [and] in sawn, tooled, honed and rubbed finish displays a

[63] Bees Stone Company Inc., "Central Park Restoration Revives Dorchester Quarries," 4.

paler buff color".[64] The quarry claimed the stone to weather well and be durable in varied urban environments.

Marys Point (Albert) Sandstone

Marys Point sandstone from Albert County could be quarried in blocks of the largest size required for building purposes and was noted to resist influence of the atmosphere and frost as well as any freestone in North America.[65] Martin described the stone to be well suited for structures built in a maritime environment. She listed that the stone has proven to be 'very durable', in comparison to the Connecticut brownstone, in coastal New England.[66] The sandstone was "pronounced equal, if not superior" to the Connecticut brownstone by the New Brunswick government in 1847.[67]

Surface Quarries of Hillsboro Sandstone

About surface quarries of Hillsboro, New Brunswick, it was written that the sandstone was apt to be of bad and varying color, more or less full of iron and other defects since they were obtained from outcropping ledges and boulders.[68]

Wallace Sandstone

Parks tested two samples of the Wallace sandstone from the chief quarry and noted the upper stone, known locally as the 'grey' stone, to be yellow-grey in color, and the lower stone, referred to as the 'blue' stone, to be of a true grey color.[69] According to him, the 'grey' stone was rather yellow in color to be classified as a grey stone. From corrosion study, he concluded

[64] Ibid.
[65] Martin, *For Love of Stone*, vol 1, 44.
[66] Ibid., 45.
[67] Ibid.
[68] U. S. Census Office, *Report on the Building Stones of the United States and Statistics of the Quarry Industry for 1880*, 368.
[69] Wallace 'grey' is referred to as 'olive' in G. B. Dickie's *Building Stone in Nova Scotia.*

the stone to become distinctly more yellowish and lose appreciably in weight.[70] Under the freezing test, the stone showed a slight disintegration at the corners only. Unlike the 'grey' stone, the 'blue' stone became a little more yellowish and lost far less in weight during his corrosion test. The stone stood well under the freezing test but became somewhat darker in color according to his notes.

In grain and in structure, the difference from the grey type is scarcely to be noted under the microscope according to Parks's description, except for the lighter color of the cement. While the properties of the two were very much alike as noted in Table 3.2, the blue stone was somewhat stronger.

About sandstones from New Brunswick and Nova Scotia, it was noted in *Report on the Building Stones of the United States and Statistics of the Quarry Industry for 1880* that the stones varied in character and that the quarries produce both good and bad stones. The sandstones were noted to weather by exfoliating and falling off pieces due to incoherency of the particles and also by rusting of the iron in the stone uniformly or in patches. The Nova Scotia sandstone was reported to have remained unchanged in some buildings where it was used for more than 20 years. However, in 1991, John C. Smock reported some of the sandstone in New York City to have badly weathered through scaling and exfoliation triggered by combination of readily soluble binding material in the granular rock and frost.[71] Regarding the Dorchester sandstone's performance, the report mentioned that a little exfoliation was noticed near the ground line and on the sides and posts of stoops in many cases. Additionally, the stone disintegrated slightly

[70] Parks's corrosion study involved soaking 1" stone cubes in distilled water and drying them at 110 ^{0}C before weighing. Then the cubes were suspended in water through which a stream of CO_2 and O_2 were conducted. After keeping the stones under this treatment for three weeks, they were removed, rubbed gently with the fingers, dried, weighed and color changes were observed.

[71] John C. Smock, "Causes of Decay in Building Stones," *The Manufacturer and Builder* 23, no. 8 (1891): 182.

over the surface in panels, under heavy projecting moldings, and cornices, where the sun had no chance to reach and dry up the dampness. In her master's thesis, *A Conservation Study of the Bethesda Terrace, Central Park*, Eileen Grand Pre Brown noted that "of all the stones used in the construction of Central Park, Dorchester Olive Freestone ha[d] proven the least durable".[72] When listing 'life' of various stones in years, Julien estimated the Nova Scotia sandstone to survive for 50 to 200 years before "the incipient decay of the variety becomes sufficiently offensive to the eyes to demand repair or renewal" (Figure 3.1).[73]

decay of the variety becomes sufficiently offensive to the eye to demand repair or renewal.

	Life, in Years.
Coarse brownstone	5—15
Laminated fine brownstone	20—50
Compact fine brownstone	100—200
Bluestone	Untried, probably centuries.
Nova Scotia stone	Untried, perhaps 50—200
Ohio sandstone, (best siliceous variety)	perhaps from 1 to many centuries.
Limestone, coarse fossiliferous	20—40
Limestone, fine oolitic (French)	30—40
Limestone, fine oolitic (American)	Untried here.
Marble (Dolomite,) coarse	40
Marble (Dolomite,) fine	60—80
Marble, fine	50—200
Granite	75—200
Gneiss	50 years to many centuries.

Within a very few years past, it has become common to introduce rude varieties of rusticated work

Figure 3.1: 'Life' of a stone according to Alexis A. Julien

Julien, "The Decay of the Building Stones of the City of New York and Vicinity," (1891): 56.

[72] Eileen Grand Pre Brown, "A Conservation Study of the Bethesda Terrace, Central Park" (MSc Thesis, Columbia University, 1991), 11.

[73] Alexis A. Julien, "The Decay of the Building Stones of the City of New York and Vicinity," *The Manufacturer and Builder* 23, no. 3 (1891): 56.

3.2 MINERAL DESCRIPTION

The sandstones from New Brunswick and Nova Scotia generally consist of grains of quartz and feldspar in greenish-yellow argillaceous cement.[74] Detailed mineral composition of the Beaumont, Boudreau (Dorchester), Wallace 'Grey' and Wallace 'Blue' sandstones described by geologists and quarry owners is as follows.

The Beaumont sandstone was noted by Parks to consist largely of quartz fragments of rounded outline and medium size, 1/5 to 1/2 mm in diameter. The grains are bounded together in clay, with a very small amount of calcium carbonate and magnesium carbonate. Its ferrous oxide content is about 4.11%.

Mineralogy of the Dorchester sandstone reported by Bee Stone Company Inc. was as follows: quartz, 5%, quartzite, 10%, greywacke, 10%, feldspar, 5%, volcanic rock, 5%, argillite, 5%, opaque, 2%, unidentified fragments, 8%, and pore volume, 5%.[75]

Thin section microscopy of the New Brunswick sandstone used at Bethesda Terrace by Gembinski noted the stone to be densely packed with well-sorted grains of quartz. Plagioclase feldspar, biotite, albite and ferro-magnesium particles were identified under polarized light microscopy. The ferro-magnesium particles appeared as anisotropic inclusions ranging in color from dark browns to black depending on the level of alteration of the iron magnesium due to geologic water, high pressure and temperature during formation.[76] Gembinski noted oxidation of the particles to have caused them to shrink and create voids in the rock.

The Wallace 'Grey' was made up of uniform quartz grains of about 1/4 mm in diameter and feldspar of about the same size in far less abundance according to Parks. The grains were

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[74] Frank G. Matero and Jeanne M. Teutonico, "The Use of Architectural Sandstone in New York City in the 19th Century," *Bulletin of the Association for Preservation Technology* 14, no. 2 (1982): 17.
[75] Bees Stone Company Inc., "Central Park Restoration Revives Dorchester Quarries," 4.
[76] Gembinski, "Bethesda Terrace: Conditions Assessment and Evaluation of Previous Stone Conservation Treatments," 70.

rounded in outline and fitted closely together with only a small amount of greenish-yellow argillaceous cement. Its ferrous oxide content was 3.60% and ferric oxide content was 1.14%. Parks noted that the absence of dirty matter in the stone and greater relative amount of quartz "should render this stone more durable than most of the New Brunswick sandstones of the olive-green class".[77]

The mineral composition of Wallace 'Blue' by Parks was similar to that of the Wallace 'Grey'; however, its argillaceous cement was of a lighter color. Its ferrous oxide content was 4.88% and the stone had trace amount of ferric oxide.

Chemical analysis of the Wallace sandstone done by Mineral Engineering Center, NS in 2001 showed the following results: silicon dioxide, 82%; aluminum oxide, 8.12%, ferric oxide, 3.19%; sodium oxide, 1.67%; potassium oxide, 1.13%; magnesium oxide, 0.72%; calcium oxide, 0.81%; titanium oxide, 0.29%; and manganese oxide, 0.10%.[78]

[77] Parks, *Report on the Building and Ornamental Stones of Canada*, 72.
[78] "Wallace Quarries – Test Data," Wallace Quarries Ltd., accessed May 8, 2013, http://www.wallacequarries.com/test-data.html.

3.3 ANALYSIS

3.3.1 X-RAY DIFFRACTION (XRD)

27 samples (25 field samples and 2 quarry samples) were analyzed to identify their general mineral composition. The samples are primarily composed of quartz with other minerals consisting of feldspars (albite, microcline and orthoclase), muscovite, illite and clinochlore. Table 3.7 lists all the identified minerals using XRD for each sample. (The x-ray diffractograms for each sample along with a list of chemistry of identified minerals are included in Appendix D.)

Illite, a non-expanding clay mineral, and muscovite, a mica mineral, are structurally similar and cannot be distinguished using XRD. Their presence in the samples is confirmed using PLM and SEM. Similarly XRD is unable to distinguish between the four feldspar groups due to a similarity in their structures and each group is accurately identified using PLM.

Three field samples, Bethesda Terrace 6 and 9, and Balcony Bridge 1, contain gypsum. Parks noted the lower Carboniferous series to have gypsum beds, which may be responsible for the presence of gypsum in these samples.

7 samples including the current Dorchester quarry sample is identified to have clinochlore. This chlorite mineral occurs in green, olive-green and yellow colors in nature and is attributed for olive-green to yellow colors of the Maritime Canadian sandstones.

Bethesda Terrace 6 is the only sample identified to have akaganeite. Akaganeite, an iron (III) oxide-hydroxide/chloride mineral, is a weathering product of FeS. It occurs in yellowish to rusty brown color and has a metallic luster.

Table 3.7: X-ray diffraction analysis of the Dorchester, Wallace and field samples from Central Park

	Akaganeite	Clinochlore	Gypsum	Quartz	Feldspar				Mica	
					Albite	Anorthoclase	Microcline	Orthoclase	Muscovite	Illite
Dorchester		X		X				X		X
Wallace				X	X			X	X	
Balcony Bridge 1		X	X	X				X		X
Balcony Bridge 2				X	X	X				X
Bethesda Terrace 1				X	X					
Bethesda Terrace 2		X		X				X	X	
Bethesda Terrace 6	X		X	X					X	
Bethesda Terrace 9		X	X	X	X					
Bethesda Terrace 10				X				X		X
Dalehead Arch 1				X			X			X
Dalehead Arch 4				X	X			X		X
Dalehead Arch 5				X			X		X	
Denesmouth Arch 4				X	X				X	
Denesmouth Arch 5				X			X			X
Driprock Arch 1				X				X	X	
Driprock Arch 2				X				X		X
Glade Arch 4		X		X	X				X	
Glade Arch 5				X	X			X	X	
Green Gap Arch 2				X	X				X	
Green Gap Arch 3				X	X			X	X	
Greyshot Arch 1				X	X		X		X	
Greyshot Arch 2				X			X			
Willowdell Arch 2				X	X				X	
Willowdell Arch 4				X	X			X	X	
Willowdell Arch 5		X		X	X		X			X
Winterdale Arch 2				X						X
Winterdale Arch 3		X		X				X		X

3.3.2 POLARIZED LIGHT MICROSCOPY (PLM)

Twenty five thin sections of the field and current quarry samples were analyzed through PLM to identify their mineralogical composition and textural characteristics.

The samples are typically of sub-rounded to angular grains of fine to coarse size (Figure 3.2 and 3.3). In porosity, they range from low to high and evenly or unevenly distributed (Figure 3.4 and 3.5). The sandstones are poorly sorted on average; and compaction and distribution of different grain sizes vary from a sample to a sample. (Detailed textural and mineral analysis of each sample is in Table 3.8 and 3.9.)

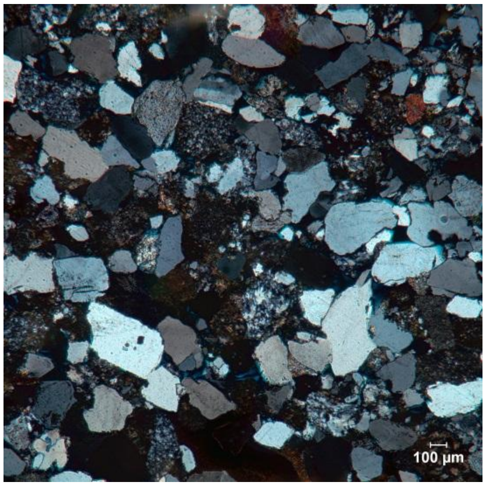

Figure 3.2: Dalehead Arch 4
[5X, cross-polarized light (XPL)]

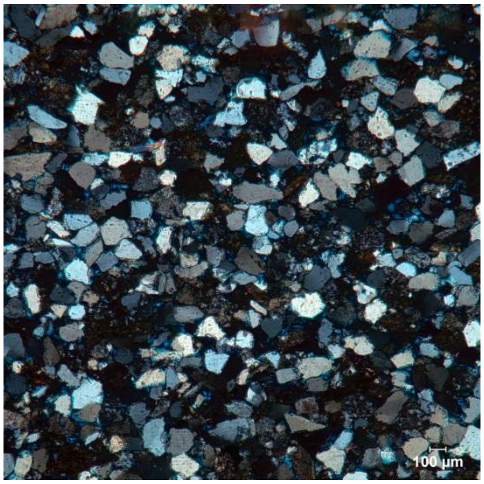

Figure 3.3: Dalehead Arch 5 (5X, XPL)

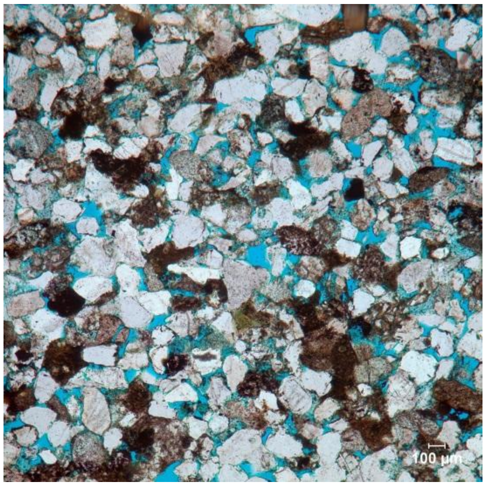

Figure 3.4: Bethesda Terrace 9
[5X, plane-polarized light (PPL)]

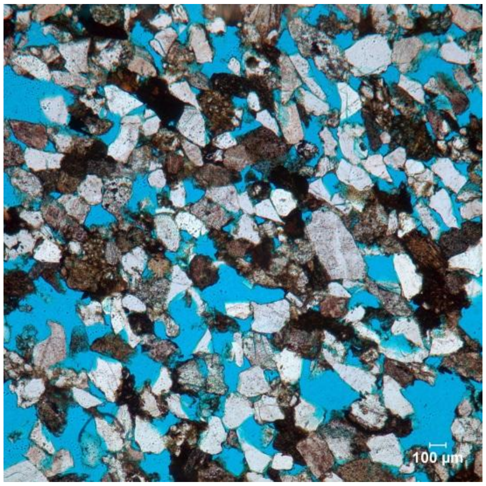

Figure 3.5: Willowdell Arch 4 (5X, PPL)

Quartz crystals are sub-rounded to sub-angular in morphology and form about 65 percent of the sandstones, feldspar averaging about 15 to 20 percent, mica averaging about 2 to 5 percent and other minerals averaging about 10 percent. Quartz of four different textural features is identified during the analysis: monocrystalline, polygonized, polycrystalline and microcrystalline. Monocrystalline refers to a quartz grain with a single crystal (Figure 3.6 and 3.8). Polygonized refers to two or three subcrystals in a single grain which are large enough to be identified as quartz (Figure 3.6). Polycrystalline refers to more than three subcrystals in a single grain, which are large enough to be identified as quartz. Finally, microcrystalline refers to quartz aggregate in which individual grains are less than 0.03 mm in size (Figure 3.7).

All the quartz crystals in the samples show undulose extinction with some being unstrained quartz. Undulose extinction is a complete extinction of the grain in a wave fashion rather than all at once due to over more than five degrees of microscope stage rotation (Figure 3.8). An unstrained quartz grain becomes fully extinct as a unit during the rotation. Outgrowth on the original quartz grains is noticed in almost all the samples (Figure 3.9). In some of the samples, it caused transformation of previously rounded grains into sub-angular grains. Mica and zircon inclusions are also found in some of the quartz grains (Figure 3.8).

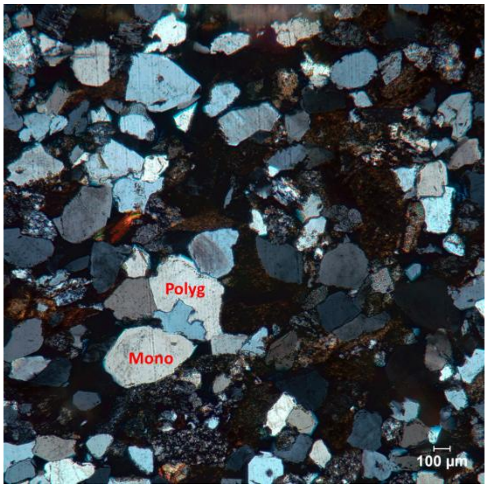

Figure 3.6: Balcony Bridge 2 (5X, XPL) showing monocrystalline and polygonized quartz

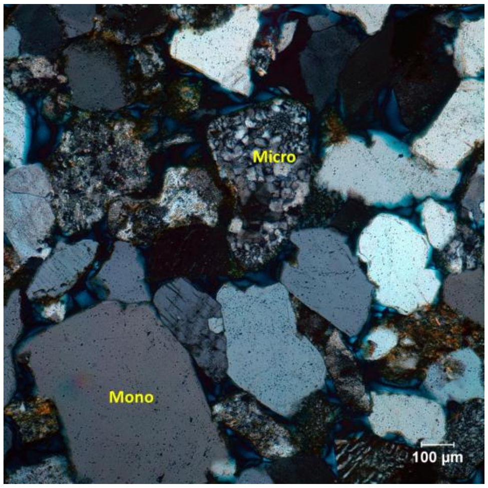

Figure 3.7: Driprock Arch 1 (10X, XPL) showing monocrystalline and microcrystalline quartz

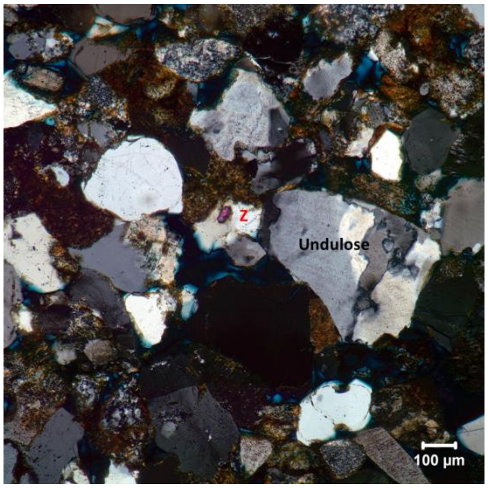

Figure 3.8: Winterdale Arch 3 (10X, XPL) showing undulose extinction and zircon inclusion

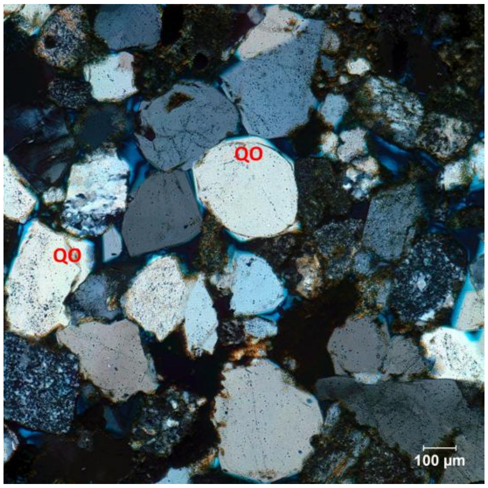

Figure 3.9: Winterdale Arch 3 (10X, XPL) showing quartz outgrowth

Most of the sandstones (field samples from Central Park) are supported structurally mainly by the framework of quartz, feldspar and microcrystalline rock mass with almost no matrices (Figure 3.10). However, deformation of argillaceous rock fragments in the stones appears to have resulted in the 'clay' matrix. Iron oxide is another cementing material in the stones besides chlorite. Distribution of chlorite and iron oxides is non-uniform and their amount varies in the samples (Figure 3.11 and 3.12).

Both plagioclase and K-feldspars are in the samples and are differentiated through their characteristic twinning. Albite, a plagioclase feldspar, has polysynthetic twinning recognized by the parallelism between the composition planes and the cleavage; and Microcline, a K-feldspar, has cross-hatched twinning (Figure 3.13 and 3.14).

The amount of mica minerals is very low in comparison to the amount of feldspar in the sandstones. Illite, biotite and muscovite of varying sizes are noticed unevenly distributed (Figure 3.15).

Volcanic rock fragments, schist, gneiss and vacuoles (transparent bubbles that are often filled with liquid) are also in some of the samples.

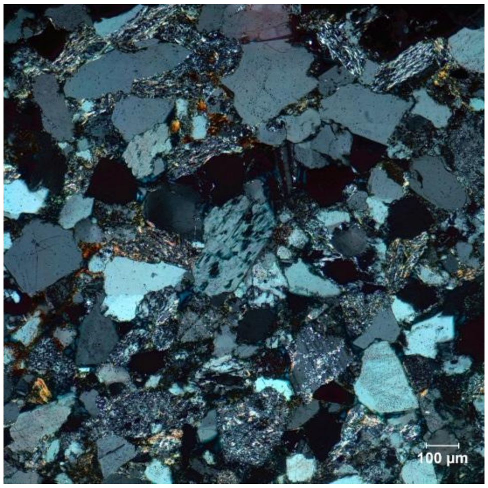

Figure 3.10: Bethesda Terrace 10 (10X, XPL) showing framework of quartz, feldspar and microcrystalline rock mass

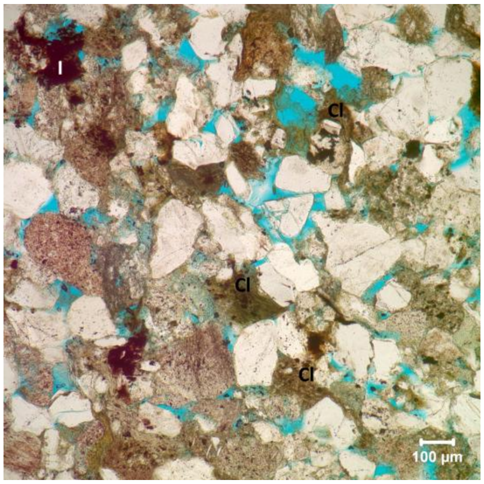

Figure 3.11: Glade Arch 5 (10X, PPL) showing chlorite and iron oxides

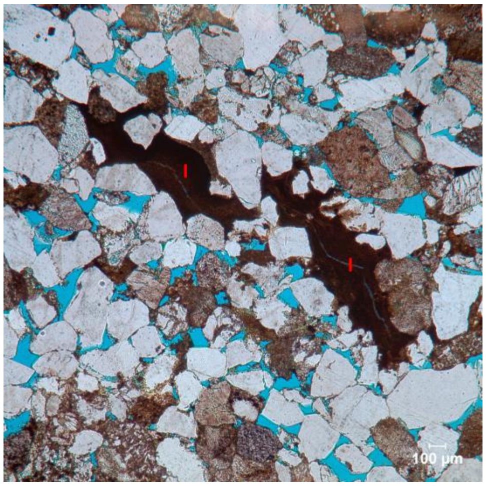

Figure 3.12: Dalehead Arch 4 (5X, PPL) showing iron oxides

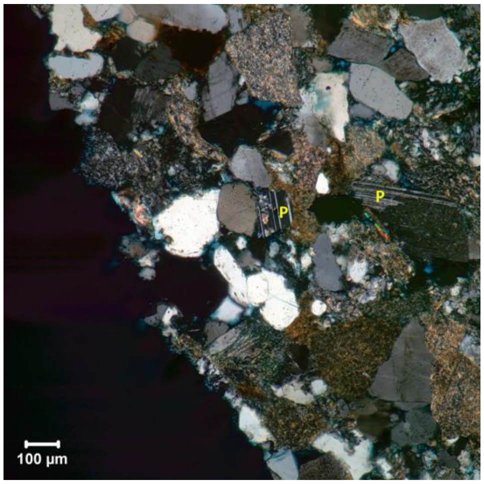

Figure 3.13: Glade Arch 5 (10X, XPL) showing plagioclase feldspar

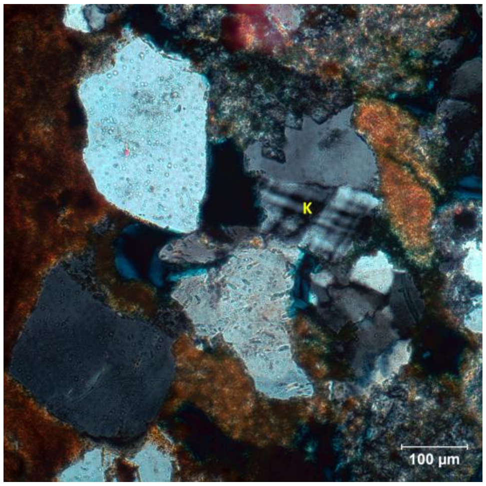

Figure 3.14: Dalehead Arch 4 (20X, XPL) showing K-feldspar

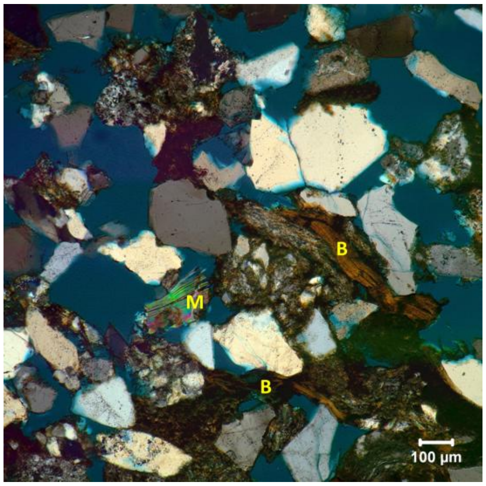

Figure 3.15: Willowdell Arch 4 (10X, XPL) showing muscovite and biotite

In texture, porosity, and chlorite and iron oxides content, the current Dorchester and Wallace quarry sandstones vary greatly. The Dorchester sandstone is of medium to coarse, sub-rounded to angular grains with very low to low porosity (Figure 3.16 and 3.18). In contrast, the Wallace sandstone is of fine to medium, angular grains with low to medium porosity (Figure 3.17 and 3.19). The amount of chlorite and iron oxides is greater in the Dorchester sandstone than in the Wallace sandstone.

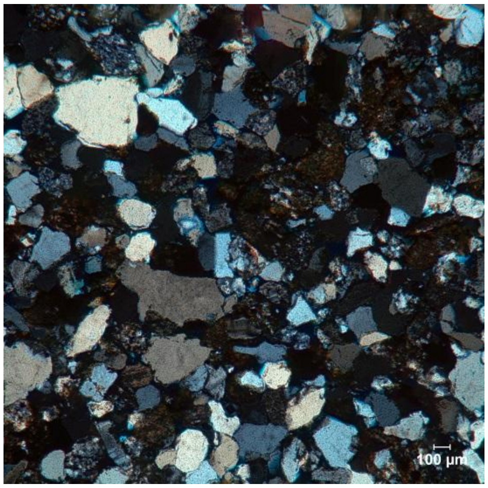

Figure 3.16: Dorchester (5X, XPL)

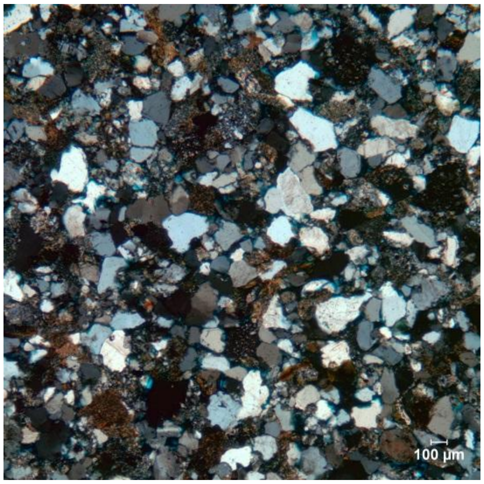

Figure 3.17: Wallace (5X, XPL)

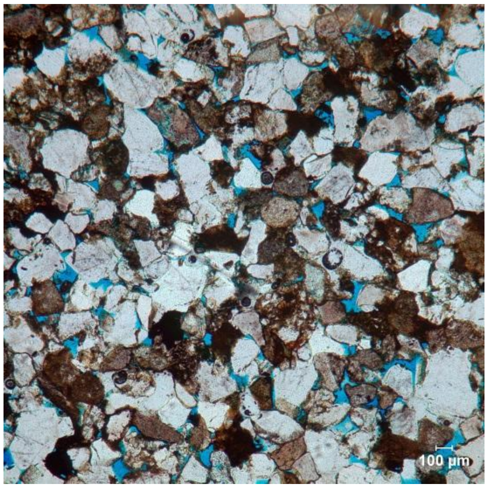

Figure 3.18: Dorchester (5X, PPL) showing chlorite and iron oxides

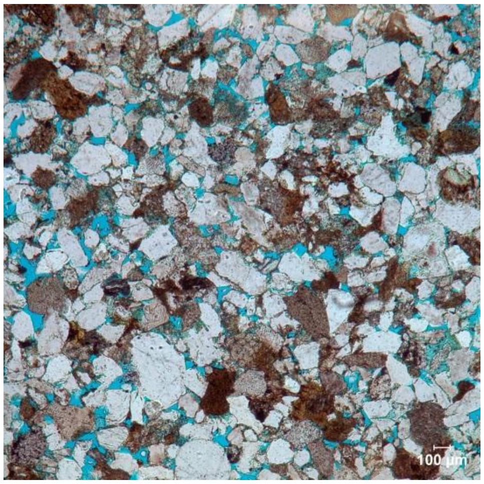

Figure 3.19: Wallace (5X, PPL) showing chlorite and iron oxides

It is difficult to identify exactly which sandstone blocks in Central Park are from the Dorchester quarries and which are not by comparing thin section of the Dorchester sandstone and thin sections of the field samples taken from Central Park. While majority of the field samples match the Dorchester sandstone in grain size and morphology, variance in grain compaction and porosity makes it difficult to make exact connections. Field samples are generally higher in porosity than the current quarry stones indicating that the greater porosity might have been due to loss of some of the soluble cementing material. (Additional images of the thin-sections are in Appendix E.)

Table 3.8: Textural characteristics of the Dorchester, Wallace and field samples from Central Park

Stone sample	Grain size *Fine* *Medium* *Coarse*	Morphology[79] *Well-rounded* *Rounded* *Sub-rounded* *Sub-angular* *Angular* *Very angular*	Degree of sorting *Well-sorted* *Moderately sorted* *Poorly sorted* *Very poorly sorted*	Grain compaction *Poorly compacted* *Moderately compacted* *Well compacted* *Very well compacted*	Porosity *Very low porosity* *Low porosity* *Medium porosity* *High porosity* *Very high porosity*
Dorchester	Medium to coarse, few fine	Sub-rounded to angular	Moderately sorted	Well compacted; non-uniform distribution of grain sizes	Very low to low porosity, overall evenly distributed
Wallace	Fine to medium, mostly medium, few coarse	Angular	Poorly to moderately sorted	Moderately compacted, uniform distribution of grain sizes	Low to medium porosity, unevenly distributed
Balcony Bridge 1	Medium to coarse	Sub-rounded to angular	Poorly sorted	Moderately compacted; grains fused together in some areas	Medium to high, evenly distributed
Balcony Bridge 2	Medium to coarse	Sub-rounded to angular	Poorly sorted	Moderately compacted	Medium, unevenly distributed
Bethesda Terrace 1	Medium to coarse, few fine	Sub-angular	Poorly sorted	Smaller grains pushing into larger grains	Medium porosity, almost evenly distributed
Bethesda Terrace 2	Fine to coarse, mostly medium	Sub-angular to angular	Moderately sorted	Some areas are well compacted and some are poorly compacted	Low to medium, unevenly distributed
Bethesda Terrace 6	Fine to coarse, mostly coarse	Sub-rounded to angular	Well-sorted	Well compacted	Low to medium, unevenly distributed
Bethesda Terrace 9	Medium, few coarse	Rounded to sub-angular	Poorly sorted	Compaction varies but overall well compacted	Medium, evenly distributed; few areas have large pores
Bethesda Terrace 10	Fine to coarse	Sub-rounded to angular	Very poorly sorted	Well compacted	Low, evenly distributed

[79] It refers to the shape and degree of roundness.

Stone sample	Grain size *Fine* *Medium* *Coarse*	Morphology[79] *Well-rounded* *Rounded* *Sub-rounded* *Sub-angular* *Angular* *Very angular*	Degree of sorting *Well-sorted* *Moderately sorted* *Poorly sorted* *Very poorly sorted*	Grain compaction *Poorly compacted* *Moderately compacted* *Well compacted* *Very well compacted*	Porosity *Very low porosity* *Low porosity* *Medium porosity* *High porosity* *Very high porosity*
Dalehead Arch 4	Fine to coarse, mostly coarse	Rounded to sub-angular	Very poorly sorted	Poorly compacted; non-uniform distribution of different grain sizes	Medium to very high, unevenly distributed
Dalehead Arch 5	Medium, few coarse	Angular	Poorly sorted	Poorly compacted; uniform distribution of grain sizes	Medium to high, evenly distributed; small pores overall
Denesmouth Arch 4	Coarse, few medium	Rounded to angular	Very poorly sorted	Some areas are very well compacted and some are poorly compacted	Medium to high, evenly distributed
Denesmouth Arch 5	Medium to coarse	Sub-angular to angular	Poorly sorted	Moderately compacted; less uniform distribution of grain sizes	Medium, evenly distributed
Driprock Arch 1	Medium to coarse	Rounded to angular	Poorly sorted	Poorly compacted	High, evenly distributed
Driprock Arch 2	Medium to coarse	Sub-rounded to sub-angular	Poorly sorted	Some areas very well compacted and some are poorly compacted; non-uniform distribution of grain sizes	Low to medium, evenly distributed
Glade Arch 4	Coarse	Sub-rounded to sub-angular	Moderately sorted	Poorly compacted	Very high, evenly distributed
Glade Arch 5	Fine to medium, few coarse	Sub-rounded to angular	Moderately sorted	Moderately compacted	Low to medium, evenly distributed porosity
Green Gap Arch 2	Medium to coarse	Sub-angular to angular	Poorly sorted	Moderately compacted	Medium to very high, unevenly distributed
Green Gap Arch 3	Medium to coarse, mostly coarse	Sub-rounded to angular	Poorly sorted	Some areas very well compacted and some are poorly compacted	Low to medium, unevenly distributed
Greyshot Arch 1	Fine to coarse, mostly coarse	Sub-rounded to angular	Very poorly sorted	Well compacted; non-uniform distribution of grain sizes	Low, evenly distributed porosity

Stone sample	Grain size *Fine* *Medium* *Coarse*	Morphology[79] *Well-rounded* *Rounded* *Sub-rounded* *Sub-angular* *Angular* *Very angular*	Degree of sorting *Well-sorted* *Moderately sorted* *Poorly sorted* *Very poorly sorted*	Grain compaction *Poorly compacted* *Moderately compacted* *Well compacted* *Very well compacted*	Porosity *Very low porosity* *Low porosity* *Medium porosity* *High porosity* *Very high porosity*
Greyshot Arch 2	Medium to coarse	Rounded to angular	Poorly sorted	Moderately compacted	High, unevenly distributed porosity
Willowdell Arch 4	Medium	Angular	Very poorly sorted	Poorly compacted	Very high, unevenly distributed
Willowdell Arch 5	Medium to coarse	Rounded to sub-angular	Poorly sorted	Well compacted	Medium to high, unevenly distributed
Winterdale Arch 2	Medium, few coarse	Rounded to sub-angular	Poorly sorted	Poorly compacted; uniform distribution of grain sizes	Medium to high, evenly distributed
Winterdale Arch 3	Fine to coarse, mostly medium	Sub-rounded to angular	Moderately sorted	Poorly to well compacted	Medium, unevenly distributed

Table 3.9: Mineralogical analysis of the Dorchester, Wallace and field samples from Central Park

Stone sample	Quartz characteristics	Cementing materials	Feldspar and mica	Other
Dorchester	Quartz with monocrystalline, polygonized and microcrystalline crystals Undulose extinction with unstrained crystals Quartz overgrowth	Fairly good amount of Chlorite (clinochlore) and Iron oxides Microcrystalline rock mass	Plagioclase feldspar K-feldspar (microcline) Very little mica (illite)	Schist Vacuole
Wallace	Quartz with monocrystalline, polygonized, polycrystalline and microcrystalline crystals Undulose extinction with both strained and unstrained crystals Quartz outgrowth caused transformation of previously rounded grains into sub-angular grains	Lower amount of chlorite and Iron oxides Microcrystalline rock mass	Fairly good amount of plagioclase feldspar Very little mica	Few zircons

Stone sample	Quartz characteristics	Cementing materials	Feldspar and mica	Other
Balcony Bridge 1	Quartz with monocrystalline, polygonized, polycrystalline and microcrystalline crystals Undulose extinction Quartz grains fusing into one another Mica and zircon inclusion into quartz	Chlorite (clinochlore) Iron oxides	Plagioclase feldspar Very little mica	Multiple Vacuoles
Balcony Bridge 2	Quartz with monocrystalline, polygonized and microcrystalline crystals Undulose extinction Straight inclusion Quartz outgrowth	Chlorite Iron oxides	Plagioclase feldspar Very little mica (illite)	Schist Gneiss Vacuole
Bethesda Terrace 1	Quartz with monocrystalline and polycrystalline crystals Undulose extinction with both strained and unstrained crystals Quartz outgrowth	Chlorite Iron oxides	Plagioclase feldspar K-feldspar (microcline) Little mica (illite)	Schist Zircons
Bethesda Terrace 2	Quartz with monocrystalline, polycrystalline and microcrystalline crystals Undulose extinction with unstrained crystals Quartz outgrowth	Chlorite (clinochlore) Microcrystalline rock mass	Some weathered feldspar Plagioclase feldspar K-feldspar (microcline) Mica (Illite)	Schist Vacuole
Bethesda Terrace 6	Quartz with monocrystalline, polygonized, polycrystalline and microcrystalline crystals Undulose extinction with unstrained crystals Quartz outgrowth Fusion of multiple grains together Microcrystalline rocks with mica intrusion	Chlorite Iron oxides Microcrystalline rock mass	Weathered feldspar K-feldspar (microcline) Mica (illite and muscovite)	Gneiss
Bethesda Terrace 9	Quartz with monocrystalline and microcrystalline crystals Undulose extinction with unstrained crystals Quartz outgrowth	Chlorite (clinochlore) Some iron oxides	Plagioclase feldspar Very little mica (illite)	Volcanic rock
Bethesda Terrace 10	Quartz with monocrystalline and microcrystalline crystals Undulose extinction with unstrained crystals Quartz outgrowth	Chlorite Some iron oxides	Plagioclase feldspar Fairly good amount of mica (biotite)	Schist

Stone sample	Quartz characteristics	Cementing materials	Feldspar and mica	Other
Dalehead Arch 4	Quartz with monocrystalline, polycrystalline and microcrystalline crystals Undulose extinction with unstrained crystals	Chlorite Iron oxides Microcrystalline rock mass	Plagioclase feldspar K-feldspar (microcline) Mica (biotite)	Schist Gneiss Zircon Vacuoles
Dalehead Arch 5	Quartz with monocrystalline and microcrystalline crystals Undulose extinction with unstrained crystals	Chlorite (clinochlore) Iron oxides	Plagioclase feldspar Fairly good amount of mica (illite and muscovite)	Volcanic rock
Denesmouth Arch 4	Quartz with monocrystalline and microcrystalline crystals Undulose extinction with both strained and unstrained crystals Mica fused into few quartz grains	Chlorite Lots of Iron oxides	Plagioclase feldspar Little Mica	Schist Gneiss
Denesmouth Arch 5	Quartz with monocrystalline and microcrystalline crystals Undulose extinction with unstrained crystals Quartz outgrowth and grains fusing into one another Straight inclusion	Chlorite Iron oxides	Plagioclase feldspar Fairly good amount of K-feldspar (microcline) Very little mica	Volcanic rock
Driprock Arch 1	Quartz with monocrystalline, polygonized and microcrystalline crystals Undulose extinction Metamorphic quartz Straight inclusion	Chlorite (clinochlore) Iron oxides	Plagioclase feldspar	Volcanic rock Schist Vacuoles
Driprock Arch 2	Quartz with monocrystalline, microcrystalline crystals Undulose extinction with strained and unstrained crystals Straight inclusion	Chlorite Iron oxides	Plagioclase feldspar Mica (illite and biotite)	Gneiss
Glade Arch 4	Quartz with monocrystalline, polycrystalline and microcrystalline crystals Undulose extinction with unstrained crystals Quartz outgrowth and grains pushing into one another Quartz with Zircon inclusion	Chlorite Iron oxides Very little microcrystalline rock mass	Fairly good amount of feldspar Weathered feldspar Plagioclase feldspar K-feldspar (microcline) Very little mica	Schist Gneiss

Stone sample	Quartz characteristics	Cementing materials	Feldspar and mica	Other
Glade Arch 5	Quartz with monocrystalline, polycrystalline and microcrystalline crystals Undulose extinction with unstrained crystals Quartz outgrowth	Chlorite Iron oxides Microcrystalline rock mass	Plagioclase feldspar K-feldspar (microcline) Mica (muscovite)	Volcanic rock
Green Gap Arch 2	Quartz with monocrystalline, polycrystalline and microcrystalline crystals Undulose extinction with unstrained crystals Quartz outgrowth	Chlorite Iron oxides Microcrystalline rock mass of quartz and mica	Plagioclase feldspar Mica (illite and muscovite)	Vacuoles
Green Gap Arch 3	Quartz with monocrystalline and polycrystalline crystals Undulose extinction with unstrained crystals Metamorphic quartz Quartz with lots of mica inclusions	Chlorite Iron oxides Microcrystalline rock mass	Plagioclase feldspar K-feldspar (microcline) Mica (muscovite)	Schist Gneiss
Greyshot Arch 1	Quartz with monocrystalline, polycrystalline and microcrystalline crystals Undulose extinction with unstrained crystals Quartz outgrowth and grains pushing into one another Quartz with Zircon inclusion	Chlorite (clinochlore) Iron oxides Microcrystalline rock mass of quartz and mica	Plagioclase feldspar Mica	
Greyshot Arch 2	Quartz with monocrystalline, polycrystalline and microcrystalline crystals Undulose extinction with unstrained crystals Straight inclusion	Chlorite Iron oxides	Feldspar weathering Plagioclase feldspar K-feldspar (microcline) Mica	Schist Vacuoles
Willowdell Arch 4	Quartz with monocrystalline and polycrystalline crystals Undulose extinction with unstrained crystals Quartz with mica inclusion	Chlorite Iron oxides	Plagioclase feldspar Mica (muscovite and biotite)	
Willowdell Arch 5	Quartz with monocrystalline and polycrystalline crystals Undulose extinction with unstrained crystals Quartz with mica inclusion	Chlorite (clinochlore) Iron oxides Microcrystalline rock mass	Plagioclase feldspar K-feldspar (microcline) Mica (muscovite)	Volcanic rock Schist Zircon Vacuoles

Stone sample	Quartz characteristics	Cementing materials	Feldspar and mica	Other
Winterdale Arch 2	Quartz with monocrystalline, polycrystalline and microcrystalline crystals Undulose extinction with unstrained crystals Quartz outgrowth Microcrystalline mass of mica surrounding some quartz crystals	Chlorite (clinochlore) Iron oxides	Weathered feldspar Plagioclase feldspar Mica (illite and biotite)	
Winterdale Arch 3	Quartz with monocrystalline and polycrystalline crystals Undulose extinction with unstrained crystals Mica surrounding some quartz crystals Quartz outgrowth and grains pushing into one another	Chlorite Iron oxides	Weathered feldspar Plagioclase feldspar Mica (illite)	Schist

3.3.3 SCANNING ELECTRON MICROSCOPY (SEM)

Field samples taken from Central Park and current quarry samples were observed under a scanning electron microscope to note their visible characteristics and binding cementing materials in their matrix.

Quartz crystal with kaolinite, a layered silicate clay mineral, is observed in the current Dorchester quarry sample (Figure 3.20). Kaolinite is produced by the chemical weathering of feldspar. Elemental analysis of the region containing both quartz, kaolinite and other minerals shows presence of Na, Mg, K, Ca, Al, Si, O and Cl. The layered structure of a kaolinite mineral is observed in the Denesmouth Arch 2 sample (Figure 3.21). Deformed sheets minerals (perhaps clay) are in the Denesmouth Arch 5 sample (Figure 3.22). Elemental analysis of the region with clay sheets shows presence of Na, Mg, K, Al, Fe, Si and O.

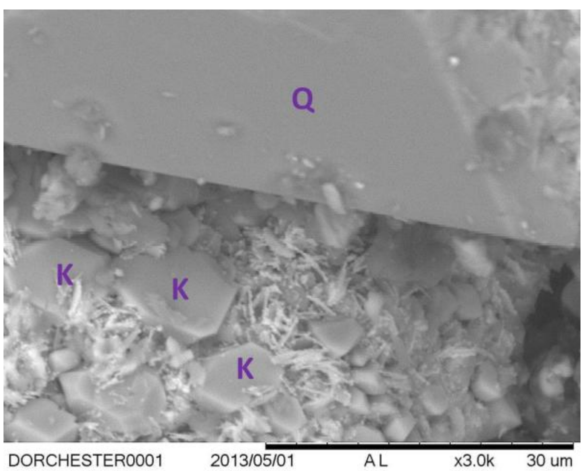

Figure 3.20: Dorchester (3,000X) showing quartz crystal, kaolinite and other minerals

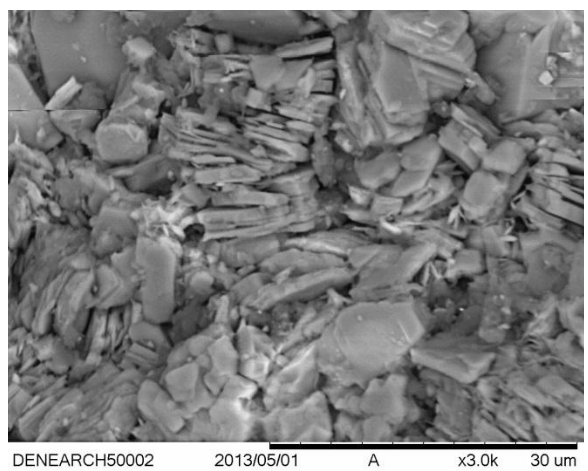

Figure 3.21: Denesmouth Arch 2 (3,000X) showing the layered structure of kaolinite

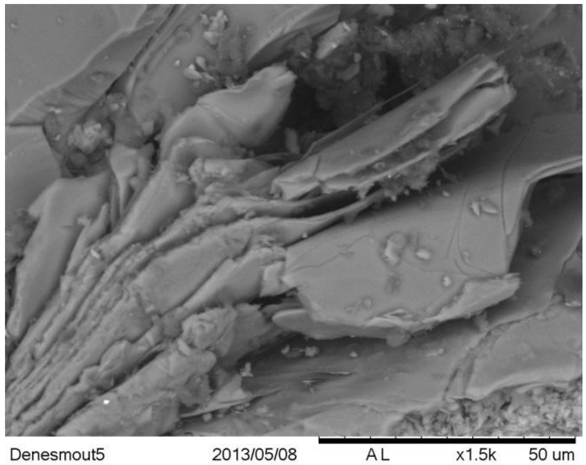

Figure 3.22: Denesmouth Arch 5 (1,500X) showing deformed sheets of minerals (clay)

The current Wallace quarry sample shows feldspar, kaolinite and chlorite minerals in its matrix (Figure 3.23 and 3.24).

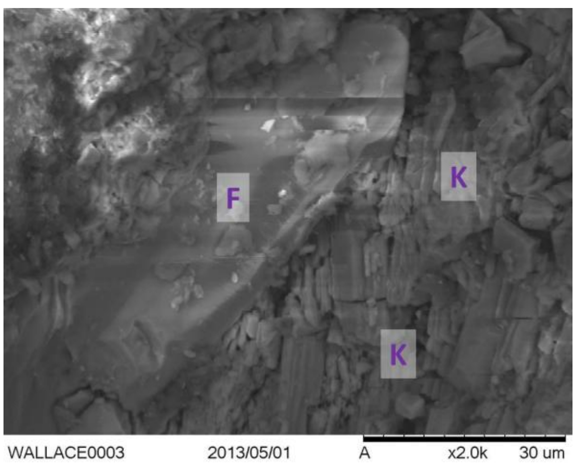

Figure 3.23: Wallace (2,000X) showing plagioclase feldspar and kaolinite

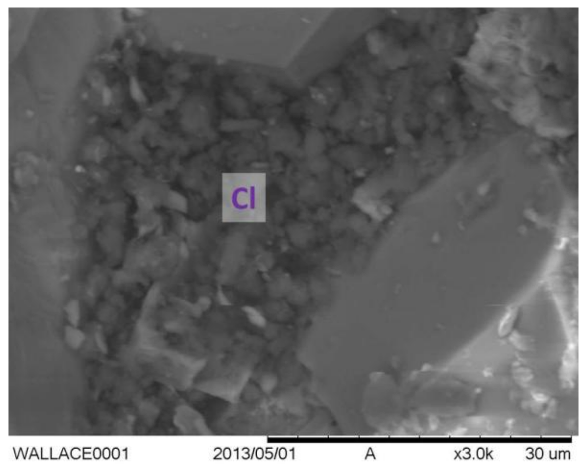

Figure 3.24: Wallace (3,000X) showing chlorite minerals

Stacked sheet-like minerals (perhaps mica) are observed in the Winterdale Arch 3 sample (Figure 3.25). Elemental analysis of the region shows presence of Na, Mg, K, Fe, Al, Si and O. Fibrous illite minerals are also noticed in the same sample (Figure 3.26).

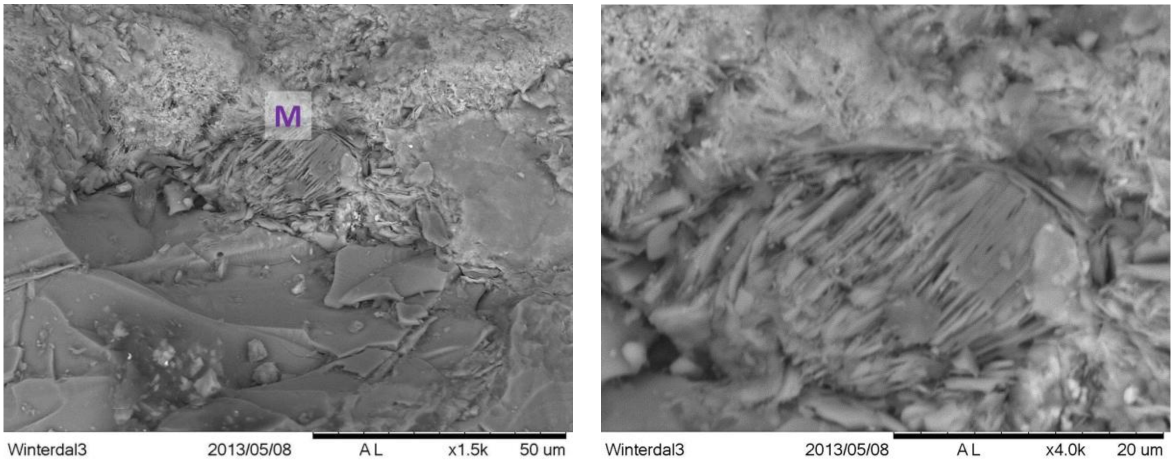

Figure 3.25: Winterdale Arch 3 (1,500X, left, and 4,000X, right) showing stacked sheet-like minerals (perhaps mica)

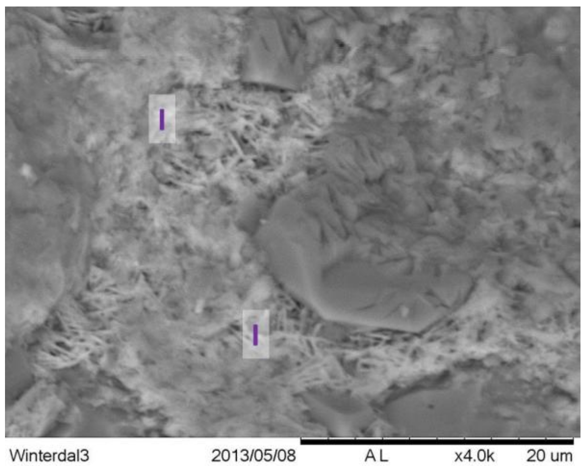

Figure 3.26: Winterdale Arch 3 (4,000X) showing fibrous illite

A weathered feldspar mineral is noticed in the Driprock Arch 1 sample (Figure 3.27). Elemental analysis of it indicates presence of K, Al, Si and O.

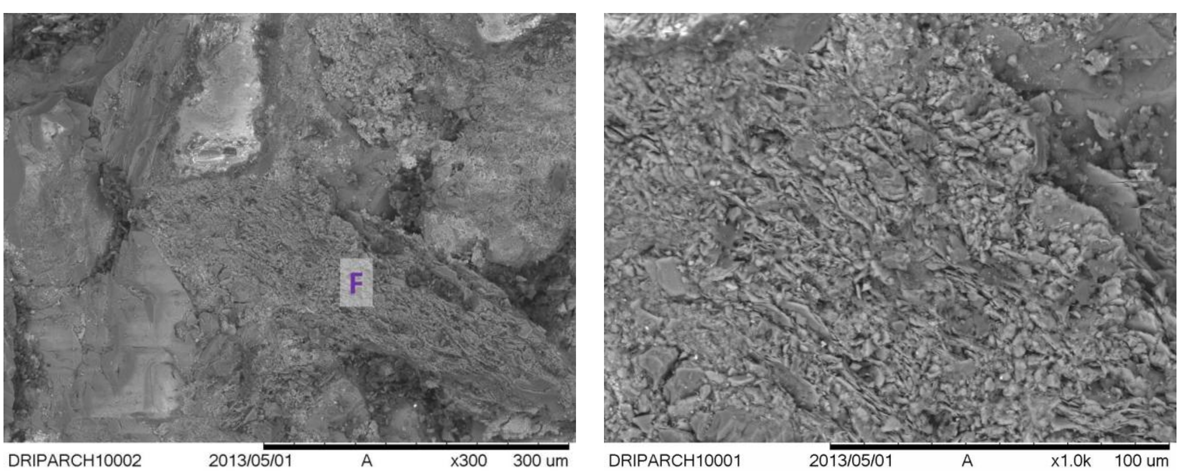

Figure 3.27: Driprock Arch 1 (300X, left, and 1,000X, right) showing weathered feldspar mineral

Both the Dorchester and the Bethesda Terrace 6 samples show weathering of a feldspar mineral (Figure 3.28 and 3.29). Elemental analysis of the weathered region in the Bethesda Terrace 6 sample shows presence of Na, Mg, K, Al, Fe, Si and O and its matrix shows strong peaks for K, Al, Si and O, and weak peaks for Na, Mg and Fe (Figure 3.30).

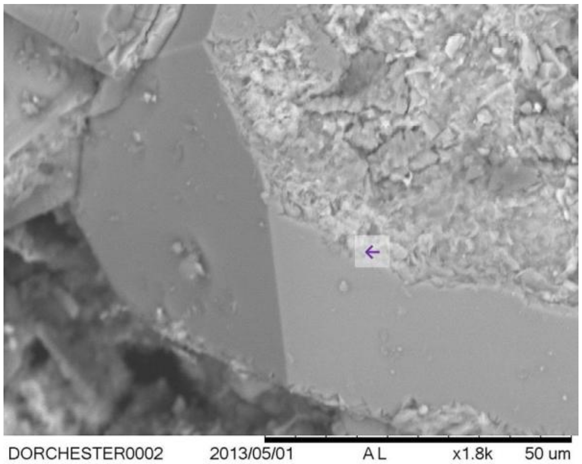

Figure 3.28: Dorchester (1,800X) showing weathering of a feldspar mineral

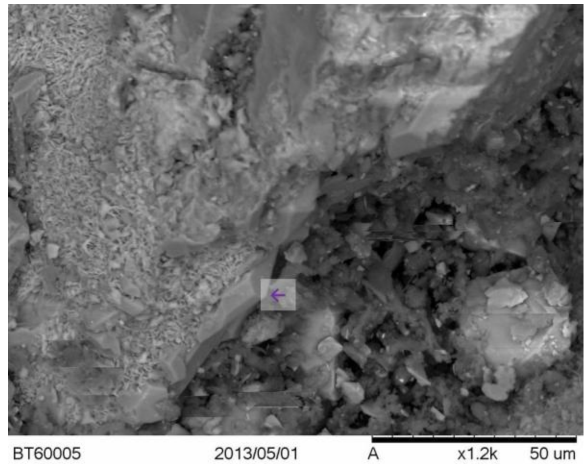

Figure 3.29: Bethesda Terrace 6 (1,200X) showing weathering of a feldspar mineral

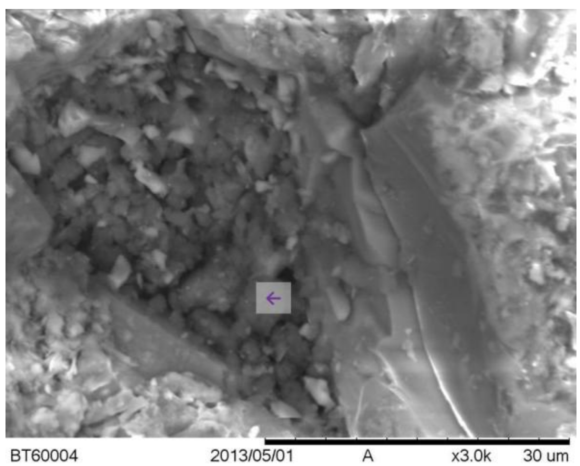

Figure 3.30: Bethesda Terrace 6 (3,000X), matrix

Under the microscope, twinning in plagioclase feldspar is noticed in the Denesmouth Arch 5 and the Winterdale Arch 3 samples (Figure 3.31 and 3.32).

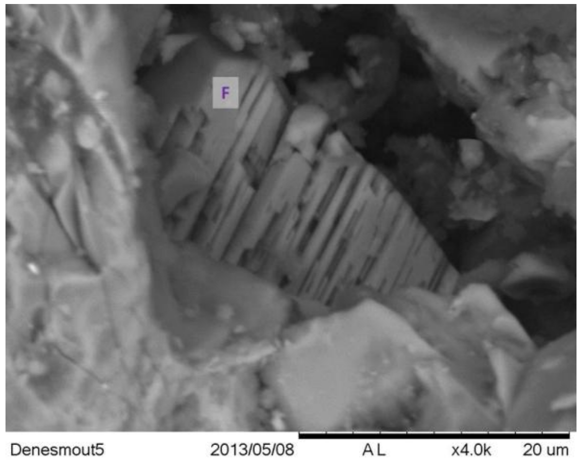

Figure 3.31: Denesmouth Arch 5 (4,000X) showing twinning in feldspar

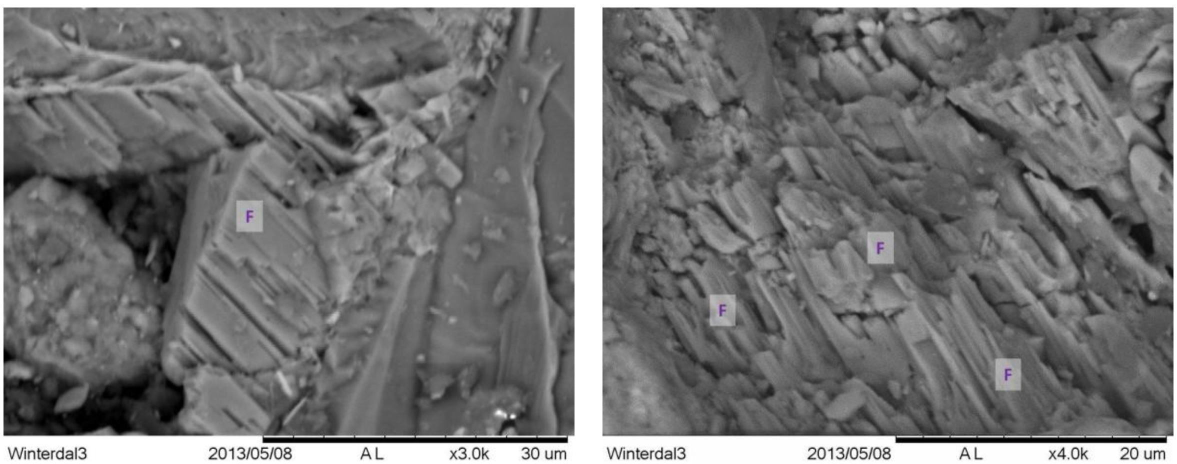

Figure 3.32: Winterdale Arch 3 (3,000X, left, and 4,000X, right) showing twinning in feldspar

Elemental analysis of the Denesmouth Arch 5 sample matrix shows presence of Na, Mg, K, Al, Fe, Si, O and Cl (Figure 3.33)

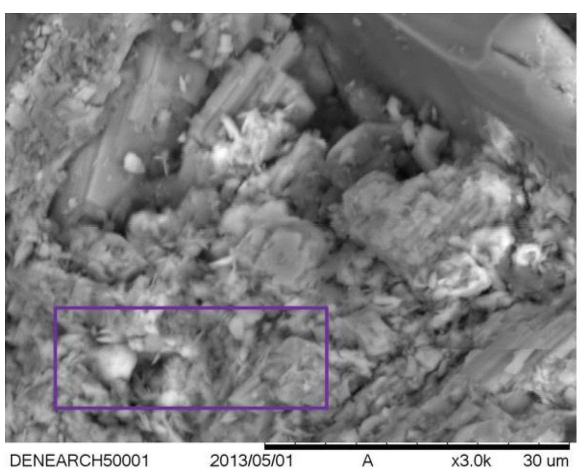

Figure 3.33: Denesmouth Arch 5 (3,000X), matrix

An overgrowth of quartz crystal is seen in the Denesmouth Arch 5 sample (Figure 3.34).

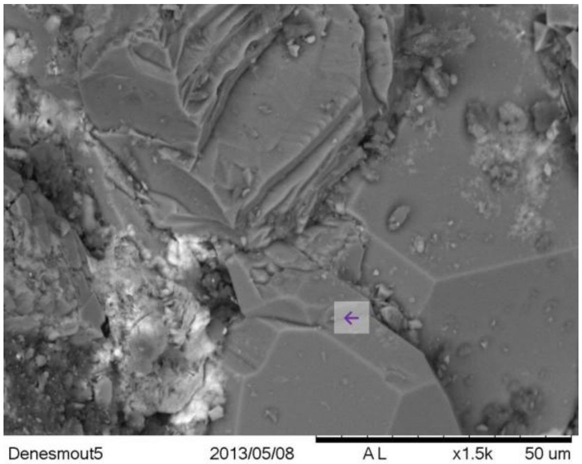

Figure 3.34: Denesmouth Arch 5 (1,500X) showing quartz overgrowth

3.3.4 METHYLENE BLUE INDEX (MBI) OF CLAY

The MBI of clay is useful in making qualitative comparison about the amount of clay minerals in the field samples taken from Central Park and two current quarry samples. After 24 hours, solutions in four flasks (Bethesda Terrace 10, Dorchester, Wallace and Winterdale Arch 3) were clear indicating a complete adsorption of methylene blue dye by clay particles in a sandstone sample as shown in Figure 3.35. The Balcony Bridge 1 flask had the most amount of the dye still in solution indicating lesser amount of clay in the stone compared to other tested samples. The test indicates both the current Dorchester and Wallace sandstones to be high in clay content and that the clay content varies among the Maritime Canadian sandstones used in Central Park.

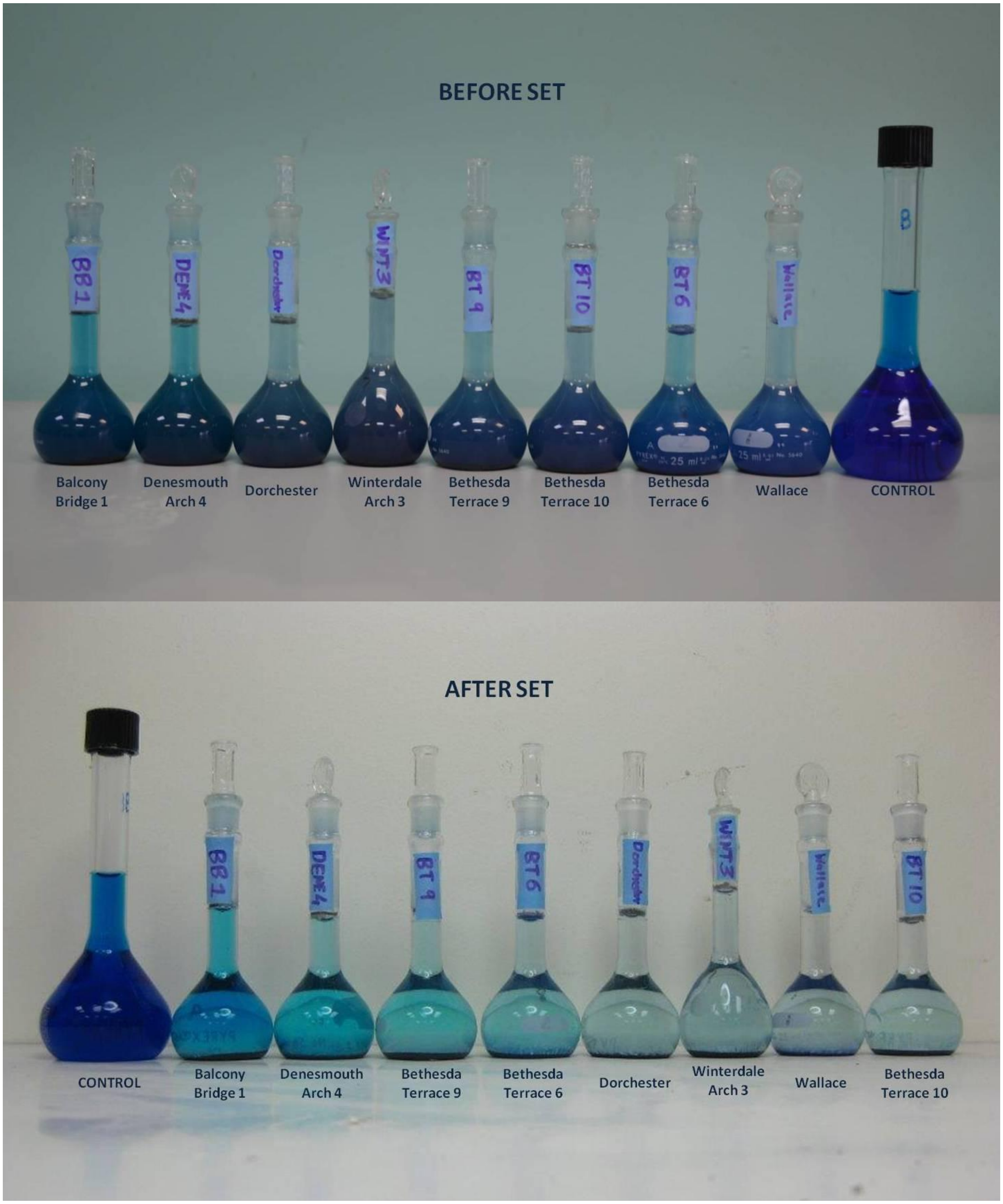

Figure 3.35: MBI of clay of the Dorchester, Wallace and field samples from Central Park

3.3.5 HYGRIC DILATION

Hygric swelling of 18 samples taken from Central Park and from the Dorchester and Wallace quarries was measured over 90 minutes period and water swelling strain of the sandstones is in Table 3.10 and 3.11. Swelling strain among the Maritime Canadian sandstones used in Central Park ranges from 0.04 mm/m to 0.28 mm/m. The highest value (Bethesda Terrace 6) is 7 times larger than the smallest value (Denesmouth Arch 4). Even hygric swelling of samples taken from the same structure is not about the same (Figure 3.36). Swelling strain of all the Bethesda Terrace samples is different and similarly, both Denesmouth Arch samples have different values.

The Dorchester sandstone has nearly double the amount of water swelling strain of the Wallace sandstone.

Table 3.10: Water swelling strain of the Maritime Canadian sandstones used in Central Park

Stone Sample	Avg. Swelling Strain (mm/m)	Max. Swelling Strain (mm/m)
Denesmouth Arch 4	0.04	0.06
Balcony Bridge 1	0.05	0.08
Dalehead Arch 4	0.06	0.07
Driprock Arch 1	0.06	0.07
Willowdell Arch 5	0.09	0.11
Bethesda Terrace 1	0.09	0.11
Denesmouth Arch 5	0.10	0.13
Greyshot Arch 2	0.10	0.12
Balcony Bridge 2	0.11	0.13
Bethesda Terrace 9	0.13	0.15
Green Gap Arch 2	0.21	0.23
Bethesda Terrace 10	0.23	0.25
Winterdale Arch 3	0.23	0.25
Glade Arch 5	0.23	0.25
Bethesda Terrace 6	0.28	0.33

Table 3.11: Water swelling strain of the current Dorchester and Wallace sandstones

Stone	Avg. Swelling Strain (mm/m)	Max. Swelling Strain (mm/m)
Wallace	0.13	0.14
Dorchester	0.29	0.30

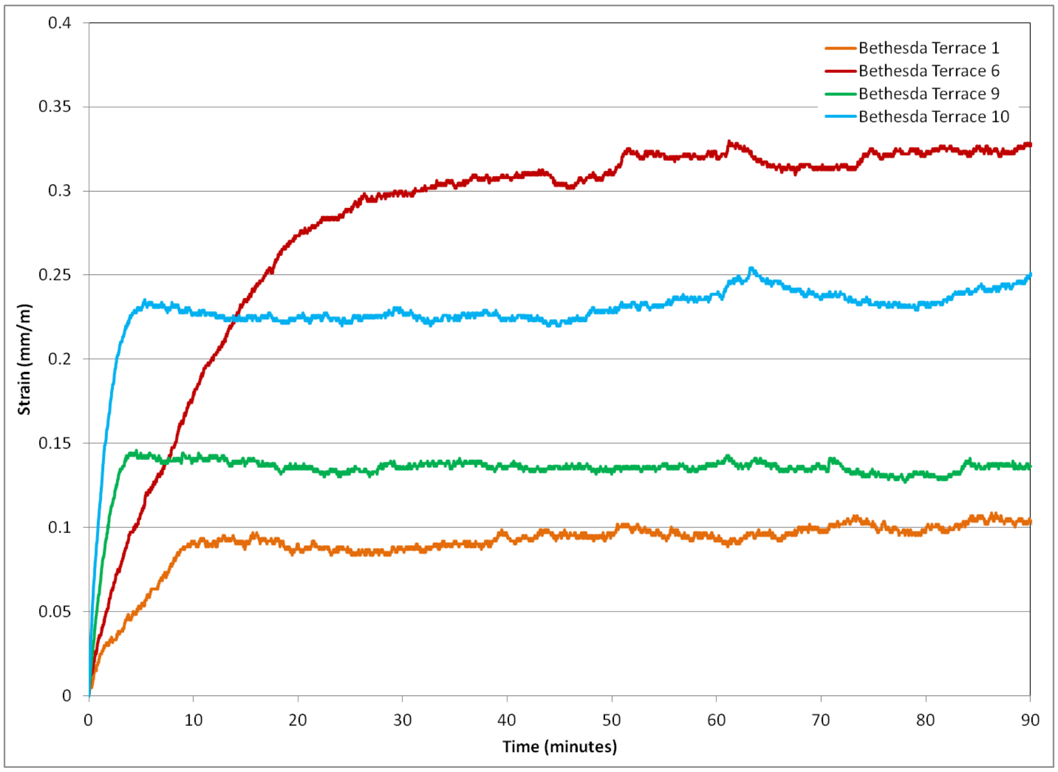

Figure 3.36: Water swelling strain of sandstone samples from Bethesda Terrace

From these results, it is not clear if undeteriorated samples swell more than the deteriorated samples or vice versa. The Dorchester sandstone from the quarry swelled the most compared to the sandstone samples from the same quarry that have been in use in Central Park for over 150 years now. In contrast, the Wallace sandstone from the quarry swelled nearly half the amount of the Bethesda Terrace 10 sample. The sample is one of the replacement sandstone blocks obtained from the Wallace quarries for the 1980s restoration.

Hygric swelling of the sandstones is also compared with swelling of the Portland brownstone, the Portage bluestone and the Aztec sandstone published by Timothy Wangler and

George W. Scherer in 2008 (Table 3.12).[80] Swelling strain of the Portland brownstone is 7 times larger than the amount of the Wallace sandstone and 3 times larger than the amount of the Dorchester sandstone. Both the Aztec sandstone and the Portage bluestone show 15 times larger the amount of hygric swelling of the Wallace sandstone and 7 times larger the amount of hygric swelling of the Dorchester sandstone.

Table 3.12: Comparison of water swelling strains of the Dorchester, Wallace and other sandstones

Stone	Swelling Strain (mm/m)
Wallace	0.13
Dorchester	0.29
Portland brownstone	1.0
Aztec sandstone	1.9
Portage bluestone	2.1

Swelling strain measured by Wangler and Scherer was perpendicular to the bedding planes, where they noted the strain to be maximal due to anisotropy of swelling. Both the Dorchester and Wallace sandstones do not have small, visible bedding planes like the Portland brownstone so anisotropy may not make a significant difference for the Maritime Canadian sandstones tested here but it requires further investigation. Swelling strain of the Wallace sandstone was measured both perpendicular and parallel to the bedding planes and there is not a significant difference in their values (Figure 3.37). Maximum swelling strain in both directions is the same, 0.14 mm/m; and average swelling strain in one direction is 0.13 mm/m and in another direction is 0.11 mm/m. For majority of the samples taken from Central Park, bedding planes are not visible and where they are visible, swelling strain was measured perpendicular to the bedding planes. (Hygric dilation graphs for all the samples are in Appendix F.)

[80] Timothy Wangler and George W. Scherer, "Swelling Mechanism in Clay-Bearing Sandstones," *Environmental Geology* 56, no. 3-4 (2008): 531.

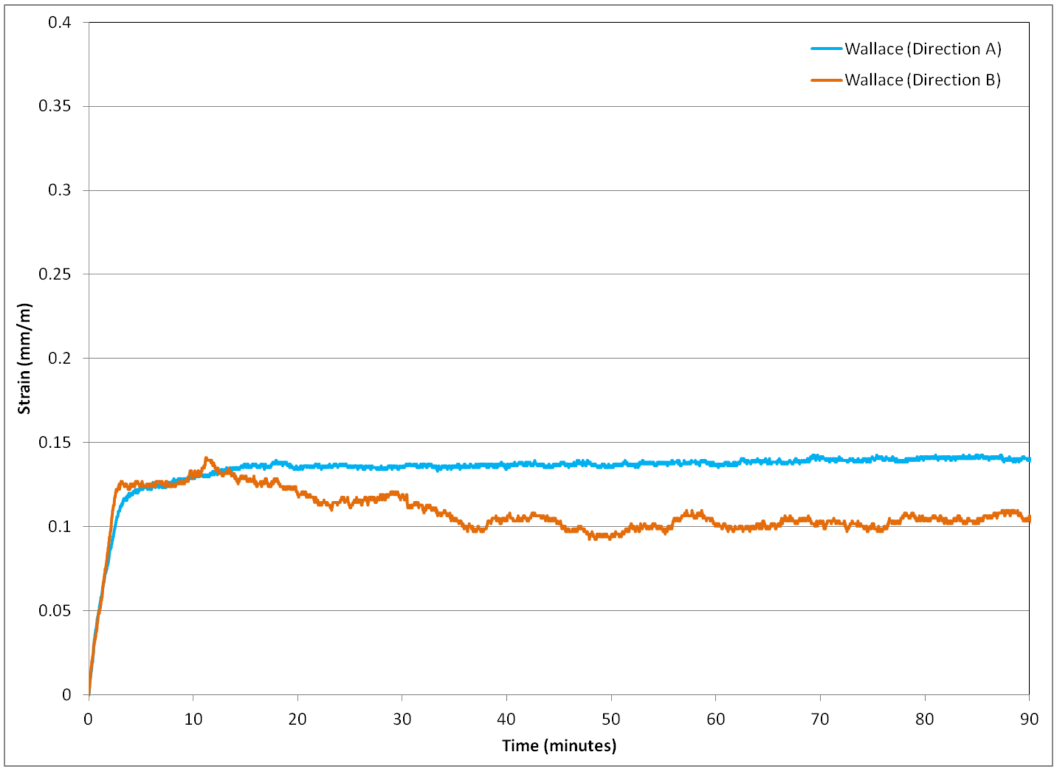

Figure 3.37: Water swelling strains of the Wallace sandstone

4. DISCUSSION

The Maritime Canadian sandstones used in Central Park are similar in their mineralogical composition but vary in texture with the original stones from the quarries in New Brunswick being coarser in grain size than the restoration sandstone from the Wallace quarries in Nova Scotia. The variation in the field samples taken from Central Park suggests that the original sandstones are not from the same quarry but are from multiple quarries in Shepody Bay area in New Brunswick and confirms the historic documentation. It is challenging, however, to identify a specific quarry source for all the samples that are studied due to overlap in textural and general descriptions of the rocks from different quarries and unavailability of fresh samples from the quarries that are closed now. On the other hand, the 1980s restoration stone from the Wallace quarries is easily distinguished from the original stones from New Brunswick quarries because the restoration stone either is of different color geologically or has not weathered to the same color as the original stones. In contrast, the Dorchester sandstone used for the restoration of some of the ornamental arches and bridges in the late 1980s is not easily distinguished from the original sandstones based on color. Therefore, it is more likely that the Wallace sandstone is of different color.

Figure 4.1: Restored quatrefoil panel at Bethesda Terrace

X-ray diffraction, polarized light microscopy, scanning electron microscopy, methylene blue index of clay and hygric dilation studies are useful in studying the Maritime Canadian sandstones used in Central Park for mineralogical and textural characterization and for tendency to well with water uptake. In order to measure the impact of intrinsic properties of the sandstone on deterioration, results from the above mentioned tests, observed deterioration mode(s) and information about stone's orientation in the wall are mapped together (Table 4.1). The following observations are made about deterioration mechanisms.

- Granular disintegration, delamination and exfoliation occur on sandstone of all varied texture and regardless of whether a stone block is exposed to the sun or is facing north, south, east or west.
- Granular disintegration is normally observed on stone blocks for which face-bedding orientation in the wall is not visible.
- Differential erosion often occurs in conjunction with granular disintegration.
- One stone block is found to deteriorate through both granular disintegration and delamination.
- Face-bedding orientation is noted for sandstone that deteriorated through exfoliation and delamination.

The observed deterioration is not directly related to one factor such as texture, porosity, mineralogy, location, orientation in the wall or exposure to the sun but rather appears to have been triggered by combined actions of both intrinsic and extrinsic factors, some of which are not studied here.

The effects of porosity and clay content on water swelling strain are evaluated by analyzing all three together (Table 4.2). It is noted that swelling strain is generally greater for samples with low to medium porosity and higher clay content; and swelling strain is generally lower for samples with medium to high porosity and lower clay content.

Table 4.1: Relationship between deterioration, texture, porosity, mineralogy, location and orientation in the wall

Stone sample	Deterioration mechanism	Texture	Porosity	Mineralogy (general)	Location	Orient. in the wall	Side facing	Expo.to the sun
Balcony Bridge 1	Granular disintegration	Medium to coarse, sub-rounded to angular grains; moderately compacted	Medium to high, evenly distributed	Quartz, plagioclase feldspar, very little mica, chlorite, iron oxides	Balustrade	Not visible	East	Yes
Bethesda Terrace 6	Granular disintegration	Fine to coarse, sub-rounded to angular grains; mostly coarse grains; well compacted	Low to medium, unevenly distributed	Quartz, K-feldspar (microcline), mica (illite and muscovite), gneiss, chlorite, iron oxides, microcrystalline rock mass	Diaper panel on the exterior	Not visible	East	Yes
Denesmouth Arch 4	Granular disintegration, differential erosion	Coarse, rounded to angular grains; few medium grains; compaction varies	Medium to high, evenly distributed	Quartz, plagioclase feldspar, little mica, schist, gneiss, chlorite, lots of iron oxides	Archway	Not clear	East	No
Denesmouth Arch 5	Granular disintegration, alveolization, differential erosion	Medium to coarse, sub-angular to angular grains; moderately compacted; less uniform distribution of grains	Medium, evenly distributed	Quartz, plagioclase feldspar, fairly good amount of k-feldspar (microcline), very little mica, volcanic rock, chlorite, lots of iron oxides	Archway	Not clear	West	No
Driprock Arch 1	Granular disintegration, differential erosion	Medium to coarse; rounded to angular grains; poorly compacted	High, evenly distributed	Quartz, plagioclase feldspar, volcanic rock, schist, chlorite, iron oxides	Archway	Not visible	South	No
Glade Arch 5	Blistering, coving, granular disintegration	Fine to medium, sub-rounded to angular grains; few coarse grains; moderately compacted	Low to medium, evenly distributed porosity	Quartz, plagioclase feldspar, k-feldspar (microcline), mica (muscovite), volcanic rock, chlorite, iron oxides, microcrystalline rock mass	Arch entrance	Face-bedding	South	No
Green Gap Arch 2	Granular disintegration	Medium to coarse, sub-angular to angular grains; moderately compacted	Medium to very high, unevenly distributed	Quartz, plagioclase feldspar, mica (illite and muscovite), chlorite, iron oxides, microcrystalline rock mass	Underneath balustrade base rail	Not visible	East	No
Greyshot Arch 1	Granular disintegration, flaking	Fine to coarse, sub-rounded to angular grains; mostly coarse grains; non-uniform dist. of grain sizes, well compacted	Low, evenly distributed porosity	Quartz, plagioclase feldspar, mica, chlorite, iron oxides, microcrystalline rock mass	Arch buttress	Not clear	South	Not sure

Stone sample	Deterioration mechanism	Texture	Porosity	Mineralogy (general)	Location	Orient. in the wall	Side facing	Expo.to the sun
Willowdell Arch 4	Granular disintegration, differential erosion	Medium, angular grains; poorly compacted	Very high, unevenly distributed	Quartz, plagioclase feldspar, mica (muscovite and biotite), chlorite, iron oxides	Arch entrance	Not visible	East	Yes
Winterdale Arch 2	Granular disintegration, differential erosion	Medium, rounded to sub-angular grains; few coarse grains; uniform distribution of grain sizes; poorly compacted	Medium to high, evenly distributed	Quartz, plagioclase feldspar, mica (illite and biotite), chlorite, iron oxides	Arch entrance	Not visible	West	Yes
Winterdale Arch 3	Granular disintegration	Fine to coarse, sub-rounded to angular grains; mostly medium grains; poorly to well compacted	Medium, unevenly distributed	Quartz, plagioclase feldspar, mica (illite), schist, chlorite, iron oxides	Arch entrance	Not visible	East	Yes
Bethesda Terrace 9	Exfoliation	Medium, rounded to sub-angular grains; few coarse grains; overall well compacted	Medium, evenly distributed; few areas have large pores	Quartz, plagioclase feldspar, very little mica (illite), volcanic rock, chlorite, some iron oxides	Pier panel	Face-bedding	West	Yes
Glade Arch 4	Exfoliation	Coarse, sub-rounded to sub-angular grains; poorly compacted	Very high, evenly distributed	Quartz, fairly good amount of feldspar, plagioclase feldspar, k-feldspar (microcline), very little mica, schist, gneiss, chlorite, iron oxides, very little microcrystalline rock mass	Balustrade pier base	Face-bedding	South	Yes
Greyshot Arch 2	Exfoliation	Medium to coarse, rounded to angular grains; moderately compacted	High, unevenly distributed porosity	Quartz, plagioclase feldspar, k-feldspar (microcline), mica, schist, chlorite, iron oxides	Arch entrance	Face-bedding	West	Yes
Dalehead Arch 5	Delamination	Medium, angular grains; few coarse grains; poorly compacted; uniform distribution of grains	Medium to high, evenly distributed; small pores overall	Quartz, plagioclase feldspar, fairly good amount of mica (illite and muscovite), volcanic rock, chlorite, iron oxides	Balustrade base rail	Face-bedding	East	Yes

Stone sample	Deterioration mechanism	Texture	Porosity	Mineralogy (general)	Location	Orient. in the wall	Side facing	Expo.to the sun
Driprock Arch 2	Granular disintegration, contour exfoliation	Medium to coarse, sub-rounded to sub-angular grains; non-uniform distribution of grain sizes; compaction varies	Low to medium, evenly distributed	Quartz, plagioclase feldspar, mica (illite and biotite), gneiss, chlorite, iron oxides	Archway	Face-bedding	South	No
Green Gap Arch 3	Blistering	Medium to coarse, sub-rounded to angular grains; mostly coarse grains; compaction varies	Low to medium, unevenly distributed	Quartz, plagioclase feldspar, k-feldspar (microcline), Mica (muscovite), schist, gneiss, chlorite, iron oxides, microcrystalline rock mass	Balustrade end	Face-bedding	West	Yes
Bethesda Terrace 1	Undeteriorated	Medium to coarse, sub-angular grains; few fine grains; compaction varies	Medium porosity, almost evenly distributed	Quartz, plagioclase feldspar, k-feldspar (microcline), little mica (illite), schist, chlorite, iron oxides	Pier panel	Not clear	North	Yes
Bethesda Terrace 10	Undeteriorated	Fine to coarse, sub-rounded to angular grains; well compacted	Low, evenly distributed	Quartz, plagioclase feldspar, fairly good amount of mica (biotite), schist, chlorite, some iron oxides	Balustrade	Not visible	West	Yes
Dalehead Arch 4	Undeteriorated	Fine to coarse, rounded to sub-angular grains; mostly coarse; non-uniform distribution of different size grains; poorly compacted	Medium to very high, unevenly distributed	Quartz, plagioclase feldspar, k-feldspar (microcline), mica (biotite), schist, gneiss, chlorite, iron oxides, microcrystalline rock mass	Archway	Not visible	North	No
Willowdell Arch 5	Undeteriorated	Medium to coarse, rounded to sub-angular grains; well compacted	Medium to high, unevenly distributed	Quartz, plagioclase feldspar, K-feldspar (microcline), mica (muscovite), volcanic rock, schist, chlorite, iron oxides, microcrystalline rock mass	Balustrade base rail	Not clear	East	Yes
Balcony Bridge 2	Other	Medium to coarse, sub-rounded to angular grains; moderately compacted	Medium, unevenly distributed	Quartz, plagioclase feldspar, very little mica (illite), schist, gneiss, chlorite, iron oxides	Balustrade top rail	Not visible	West	Yes
Bethesda Terrace 2	Other	Fine to coarse, sub-angular to angular grains; mostly medium grains; well compacted	Low to medium, unevenly distributed	Quartz, plagioclase feldspar, k-feldspar (microcline), Mica (illite), schist, chlorite, Microcrystalline rock mass	Balustrade pier capstone	Not visible	East	Yes

Table 4.2: Relationship between water swelling strain, porosity and clay content

Stone sample	Water swelling strain (mm/m)	Porosity	Clay content (based on MBI)
Denesmouth Arch 4	0.04	Medium to high, evenly distributed	Low
Balcony Bridge 1	0.05	Medium to high, evenly distributed	Very low
Dalehead Arch 4	0.06	Medium to very high, unevenly distributed	Not analyzed
Driprock Arch 1	0.06	High, evenly distributed	Not analyzed
Willowdell Arch 5	0.09	Medium to high, unevenly distributed	Not analyzed
Bethesda Terrace 1	0.09	Medium porosity, almost evenly distributed	Not analyzed
Denesmouth Arch 5	0.10	Medium, evenly distributed	Not analyzed
Greyshot Arch 2	0.10	High, unevenly distributed porosity	Not analyzed
Balcony Bridge 2	0.11	Medium, unevenly distributed	Not analyzed
Wallace	0.13	Low to medium porosity, unevenly distributed	Very high
Bethesda Terrace 9	0.13	Medium, evenly distributed; few areas have large pores	Medium
Green Gap Arch 2	0.21	Medium to very high, unevenly distributed	Not analyzed
Bethesda Terrace 10	0.23	Low, evenly distributed	Very High
Winterdale Arch 3	0.23	Medium, unevenly distributed	Very High
Glade Arch 5	0.23	Low to medium, evenly distributed porosity	Not analyzed
Bethesda Terrace 6	0.28	Low to medium, unevenly distributed	High
Dorchester	0.29	Very low to low porosity, overall evenly distributed	Very high

5. CONCLUSION

Regarding sandstone deterioration it is noted that "threshold decay phenomena such as granular disintegration, scaling and flaking…are triggered by the crossing of intrinsic and/or extrinsic stress/strength thresholds".[81] In order to prevent further deterioration and identify conservation treatment, it is critical to understand "factors that can trigger the development of such features, and the conditions that promote continuation of deterioration and failure".[82]

Through mineralogical and textural characterization of the Maritime Canadian sandstones used in Central Park, the stones are found to vary in mineralogy, texture and cementing material in various degrees. However, when evaluating their impact on deterioration alone without understanding contribution of extrinsic factors, concrete conclusions cannot be made about performance of the stone when used as a building material.

Due to a short amount of time a limited number of samples were studied for few intrinsic factors. Additionally, samples collected from the ornamental arches and bridges in Central Park posed many challenges as each sample had been in use for over 150 years now and had been subjected to natural and manmade impacts in various amounts. (Some of the extrinsic factors are described in Chapter 3.)

For further research, extrinsic factors such as moisture and salt availability and intrinsic properties such as moisture absorption and susceptibility, and water retention need to be studied. Understanding ways in which these different factors affect sandstone can better explain deterioration mechanisms such as alveolization and delamination. It is also recommended that testing in the future should be conducted on quarry samples and not field samples. When it is

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[81] Stavros K. Kourkoulis, ed., *Fracture and Failure of Natural Building Stones: Applications in the Restoration of Ancient Monuments* (Dordrecht: Springer, 2006), 323.
[82] Ibid., 324

not possible to take a large number of samples from a single stone block in a historic structure and when samples are taken from multiple similar areas, there are too many unknown variables associated with testing samples and samples cannot be compared evenly.

Hygric swelling study should be expanded to better understand damaging stresses generated during wetting/drying cycles. Through x-ray diffraction, polarized light microscopy and scanning electron microscopy, the presence of chlorite, illite and kaolinite clay mineral groups is confirmed. The effects of both swelling and non-swelling clays in the Maritime Canadian sandstones need to be further investigated by understanding differences in swelling strain parallel and perpendicular to the bedding, calculating swelling strain of the sandstone pretreated with various cations, and observing swelling strain in different solvents. Swelling of the sandstone treated with different consolidants should also be evaluated.

The deterioration mechanisms of delamination, granular disintegration and flaking are complex phenomena that are not fully understood by scientists yet and need to be actively studied. A stronger understanding of them is critical in preserving historic ornamental arches and bridges that are vital to the landscape of Central Park.

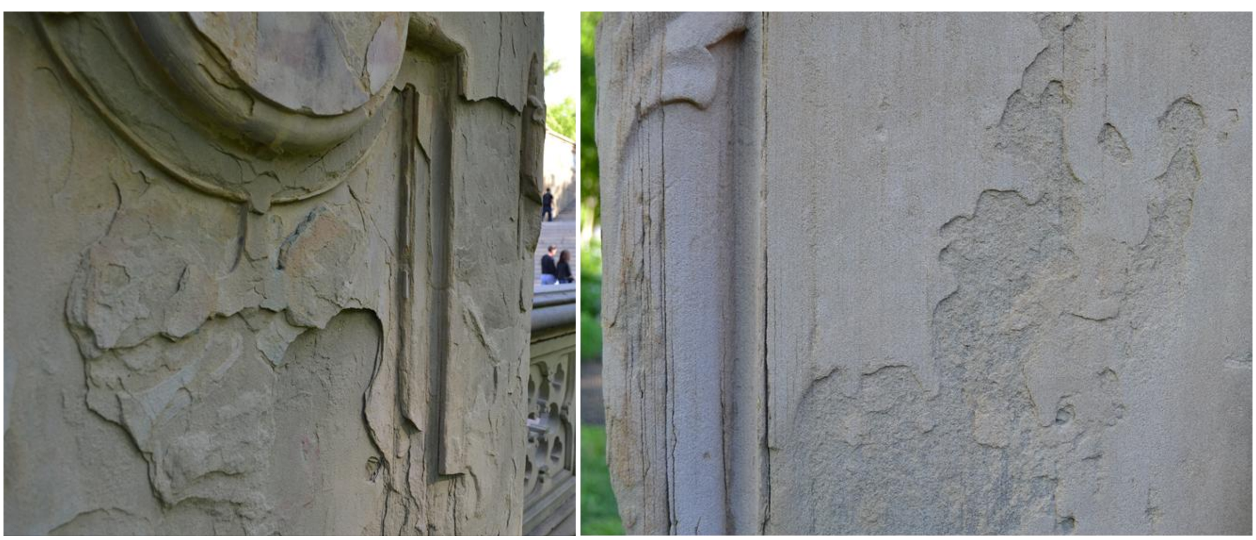

Figure 5.1: Bethesda Terrace pier deteriorating through exfoliation on one side and flaking on the other side

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APPENDIX A: FIELD SAMPLE IDENTIFICATION

A map of Central Park showing field sampling sites

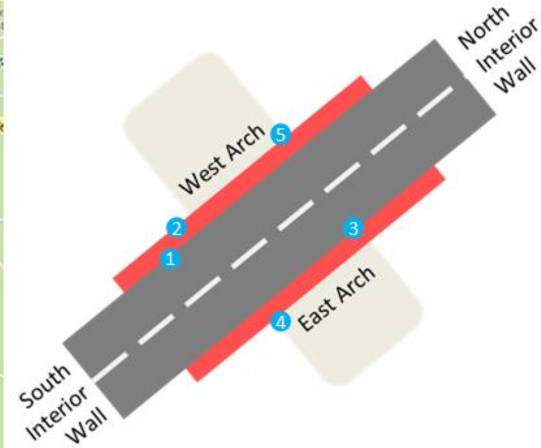
Image source: Google Maps, 2012

Balcony Bridge

Location	West side at 77th Street and West Drive
Date of completion[83]	1859
Original bridge no.	4
Areas of use	New Brunswick sandstone trimmings and balustrades
Description	Balcony Bridge was named for its two small balconies with stone benches. The bridge provides the scenic views of Central Park and the New York City skyline over the Lake. The archway and facings are of Manhattan schist excavated in the Park with the Maritime Canadian sandstone used for the trimmings, balustrade and balcony buttresses. The balustrade is decorated with quatrefoil cutouts.
Sample	Location
1	West balustrade (side facing east)
2	West balustrade (side facing west)
3	East balustrade (side facing west)
4	East arch balcony buttress
5	West arch voussoir

[83] Date of completion, original bridge no. and original areas of use for each bridge are recorded in the *Fifth Annual Report of the Board of Commissioners of the Central Park* for the Year 1861. The date for bridges that were still in construction when the report was produced is taken from *Bridges of Central Park* by Henry Hope Reed, Robert M. McGee and Esther Mipaas.


W 77th St
W 77th St
West Dr
79th Street Transve
Swedish Cottage
Marionette Theat
Bank
Rock Bay
Central Park West
Ladies'
Pavilion
N


North
Interior
Wall
West Arch
East Arch
South
Interior
Wall
1
2
3
4
5


1


2


3


4


5

Balcony Bridge (looking south)

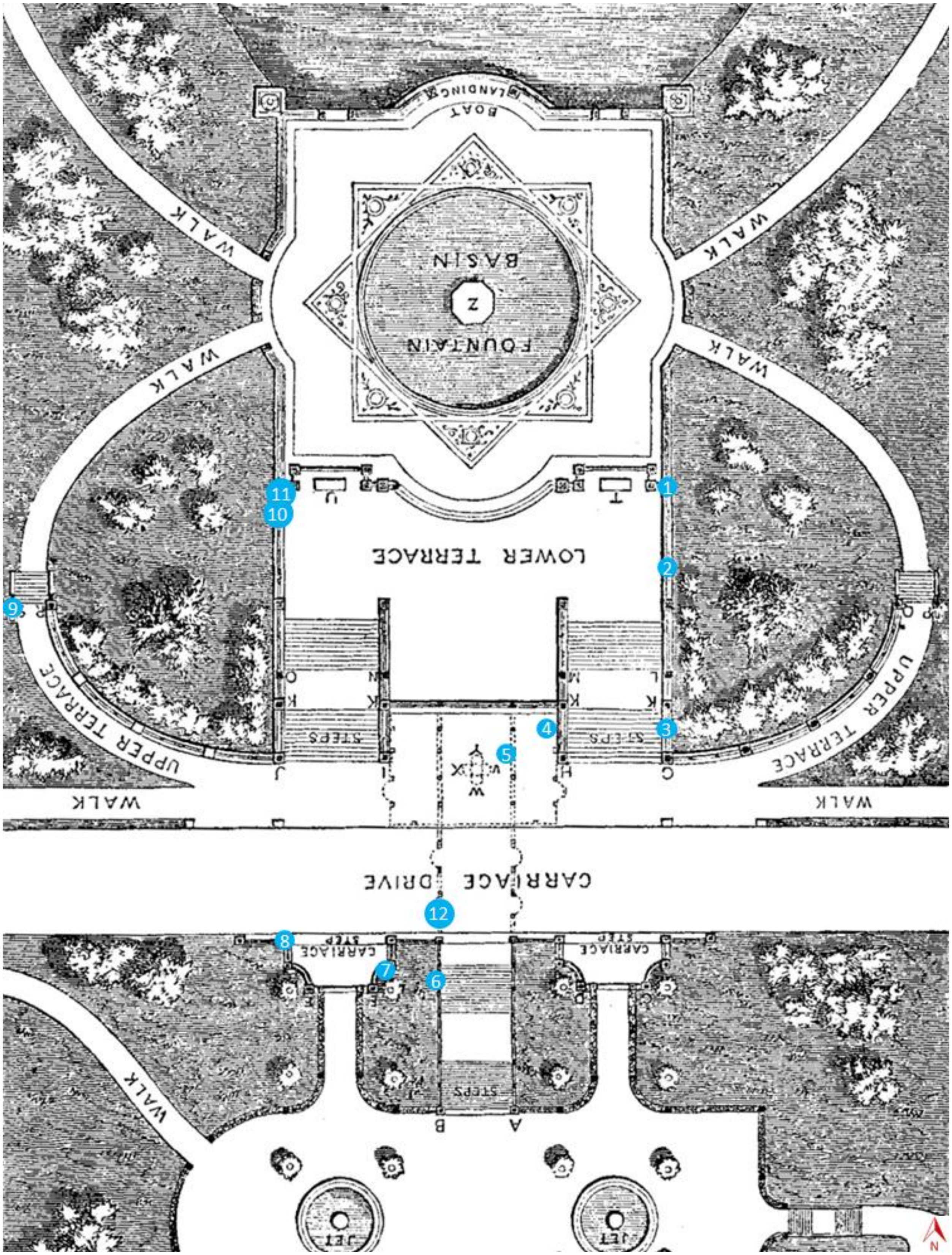
Balcony Bridge (east elevation)

Balcony Bridge (west elevation and east balustrade)
Image source: Herbert Mitchell Collection at the Metropolitan Museum of Art

Bethesda Terrace

Location	Mid-Park at 72nd Street
Date of completion	1863
Original bridge no.	1
Areas of use	New Brunswick sandstone face-work, trimmings and balustrades
Description	Bethesda Terrace, the heart of Central Park, links the formal, linear Mall with the informal, mazelike Ramble. It consists of an upper and a lower terrace, which are connected by two grand staircases on sides and a smaller staircase in the center leading to the arcade of Romanesque arches and columns. The terrace is a superb example of stone structure where sandstone carvings of flowers, fruits, birds, insects, animals and human tasks related to seasons and times of a day are woven into a tapestry of abstract fantasy. This complex serves as an underpass beneath the 72nd Street Drive, a gathering point for visitors at a termination of the Mall and a place to enjoy scenic views of the fountain, the Lake, the Belvedere Castle and the wooded Ramble. *1980s Restoration* • The arcade was cleaned by removing graffiti and the consequent cleaning of the stone. No other treatments were implemented or replacement or repair of the existing stone was carried out. • Diaper panels on the central staircase and selected piers and balustrade panels were consolidated. • Restoration included patching, profile rebuilding, pointing, grouting and dutchman repair.

	• Severely deteriorated or missing sandstone elements were replaced with the Wallace sandstone. • Deteriorated surfaces, with the exception of decorative sculpture, were retooled and honed to a sound finish to reduce surface area and porosity of the stone.
Sample	Location
1	Lower terrace pier
2	Lower terrace balustrade capstone
3	East staircase wall leading to lower terrace (side facing east)
4	Bethesda arcade column base
5	Bethesda arcade column base
6	Diaper panel on the west wall of the central staircase leading to the arcade
7	Upper terrace balustrade
8	Upper terrace pier
9	Upper terrace pier
10	Lower terrace balustrade panel
11	Lower terrace pier capstone
12	Bethesda arcade column arch



Bethesda Terrace floor plan showing sample locations

Image source: Fifth Annual Report of the Board of Commissioners of the Central Park


1


2


3


4


5


6

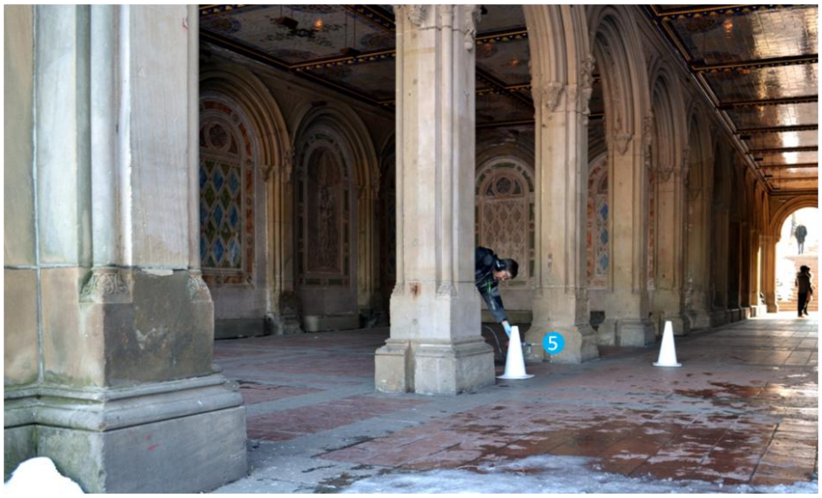

7


8

Bethesda Terrace pier and balustrade (lower terrace on east side)

Bethesda Terrace wall adjacent to east staircase

Bethesda Terrace arcade column base (east wall)



Bethesda Terrace arcade column base

Bethesda Terrace diaper panel (west wall)

Bethesda Terrace balustrade (upper terrace on west side)

Bethesda Terrace pier (upper terrace)

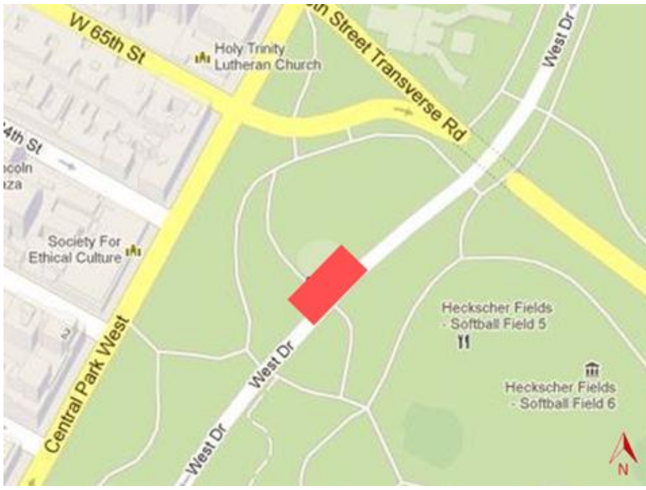
Bethesda Terrace pier (upper terrace)

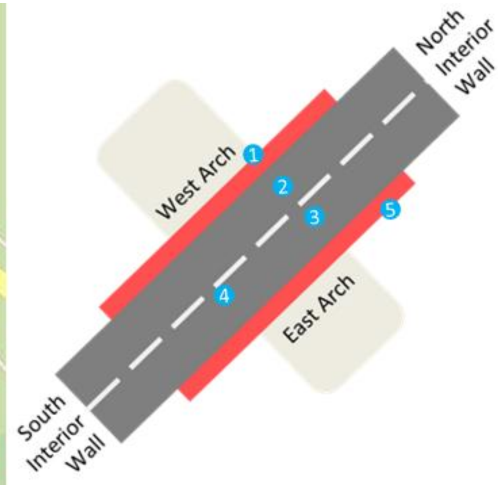
Bethesda Terrace pier cap and balustrade (lower terrace on west side)

Bethesda Terrace arcade arch near the central staircase

Dalehead Arch

Location	West side at 64th Street and West Drive
Date of completion	1860
Original bridge no.	6
Areas of use	New Brunswick sandstone facings of ends and fronts of the bridge, trimmings and balustrades
Description	Dalehead Arch carries the West Drive over the bridle path near Central Park West at 64th Street. Its elevations are built of sandstone blocks of random size and the elliptical arch is hemmed with a sandstone ring molding. The sandstone balustrade is carved in quatrefoil cutouts.
Sample	Location
1	West arch voussoir
2	North interior wall voussoir (2nd row of intrados from west)
3	North interior wall voussoir (4th row of intrados from east)
4	South interior wall horizontal trimming
5	East balustrade (side facing east)


W 65th St
Holy Trinity Lutheran Church
West Dr
Society For Ethical Culture
Central Park West
West Dr
West Dr
Heckscher Fields - Softball Field 5
Heckscher Fields - Softball Field 6
N


North Interior Wall
West Arch
East Arch
South Interior Wall
1
2
3
4
5


1


2


3


4


5

Dalehead Arch (looking east)

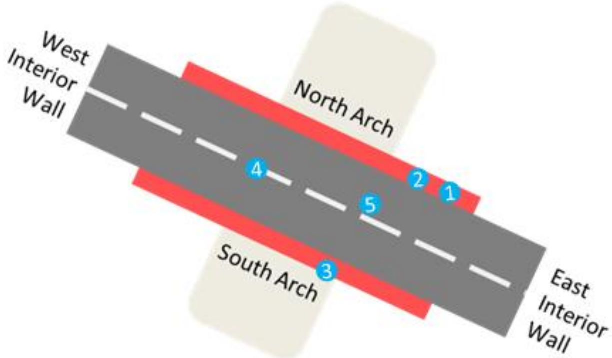
Dalehead Arch (looking east)

Dalehead Arch balustrade (east elevation)

Denesmouth Arch

Location	East side north of the Central Park Wildlife Conservation Center at 65th Street and Fifth Avenue
Date of completion	1860
Original bridge no.	7
Areas of use	New Brunswick sandstone facings throughout, balustrades and trimmings
Description	Denesmouth Arch is the only bridge made entirely of New Brunswick sandstone. The arch is built above a former stream bed that originated from the Mall and passed through the Central Park Zoo toward Inscope Arch. It carries cross-town traffic along 65th Street Transverse Road and permits pedestrian traffic to pass through the archway.
Sample	Location
1	North balustrade (side facing south)
2	North balustrade (side facing south)
3	South balustrade pier
4	West interior wall voussoir
5	East interior wall voussoir

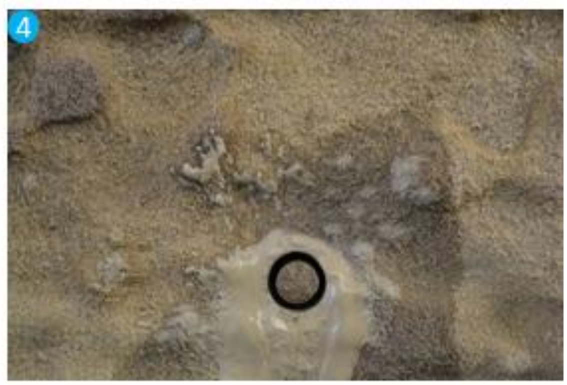

107th Infantry Memorial
Fifth Ave
Fifth Ave
E 65th St
Central Park Zoo
834 Fifth Avenue


West Interior Wall
North Arch
South Arch
East Interior Wall
1
2
3
4
5


1


2


3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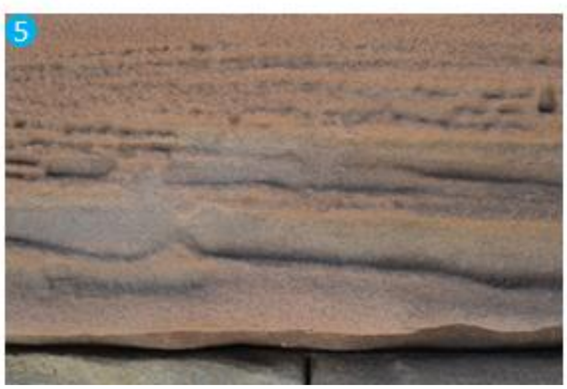

5

Denesmouth Arch north balustrade (side facing south)

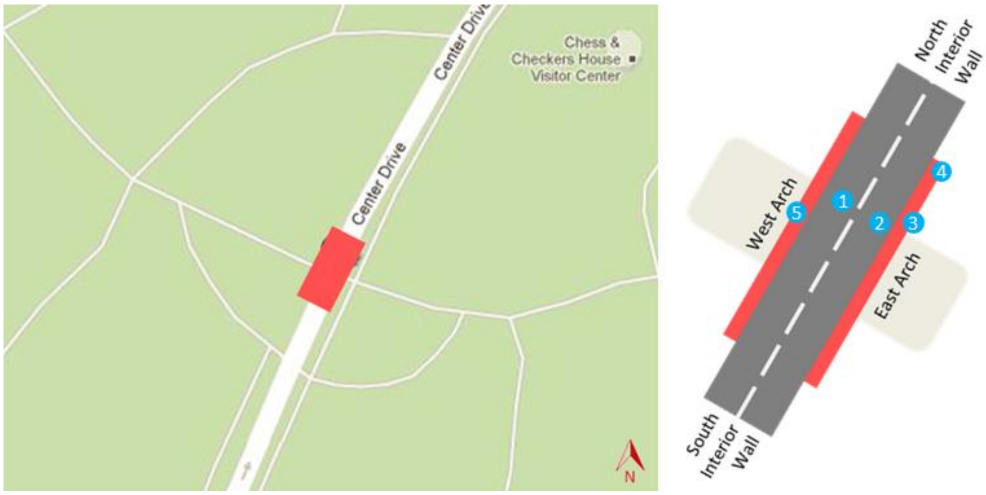
Denesmouth Arch south balustrade (side facing north)
Image source: Google Maps

Denesmouth Arch (looking north)

Driprock Arch

Location	Mid-Park at 63rd Street
Date of completion	1859
Original bridge no.	2
Areas of use	New Brunswick sandstone trimmings and balustrades
Description	The Driprock archway originally provided a passage for the bridle path, which was eliminated with expansion of the Heckscher Playground in the 1930s. Today it allows pedestrians to pass underneath one of the busiest stretches of a carriage drive. It is one of the few archways in the Park where red brick is used for facings. *1990s Restoration* • Return end panels were replaced. • Pierced balustrade panels and coping were restored.

Sample	Location
1	North interior wall base
2	North interior wall horizontal trimming
3	East arch buttress
4	East balustrade (side facing east)
5	West balustrade (side facing east)


Center Drive
Center Drive
Chess &
Checkers House
Visitor Center
N
North
Interior
Wall
West Arch
East Arch
South
Interior
Wall
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3
4
5


1


2


3


4


5

Driprock Arch (looking east)

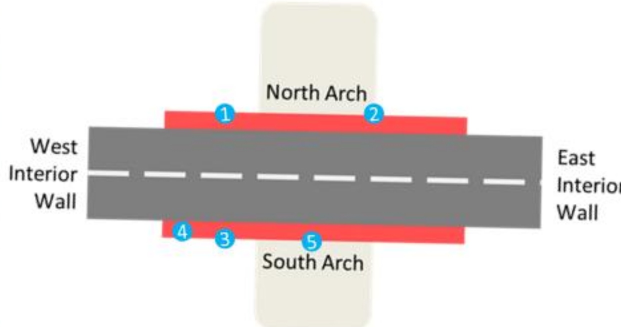
Driprock Arch (east elevation)

Driprock Arch west balustrade (side facing east)
Image source: Google Maps

Glade Arch

Location	East side between 77th and 78th Streets east of Cedar Hill
Date of completion	1860
Original bridge no.	8
Areas of use	New Brunswick sandstone facings throughout and balustrades
Description	Glade Arch originally supported carriage traffic to Fifth Avenue, but today it provides a walkway for visitors. It is among the first of Calvert Vaux's designs with a low elliptical span. Constructed of light-colored New Brunswick sandstone, the arch has suffered much damage over the years. Its balustrade was severely damaged by a snowplow in 1980. *1980s Restoration* • Restoration included washing of the stone, resetting the coping, replacement of the missing parts of the balustrade, removal of graffiti and repair of original stone posts and bases. • Thirty new replica balusters of cast stone were used.
Sample	**Location**
1	North arch spandrel wall
2	North arch voussoir
3	South arch spandrel wall
4	South balustrade (side facing south)
5	South arch keystone


East
Cedar Hill
College
Advisement
Associates
Ukrainian
Institute of
America
Still Hunt
5th Ave
970
980
N


North Arch
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2
West
Interior
Wall
East
Interior
Wall
4
3
5
South Arch


1

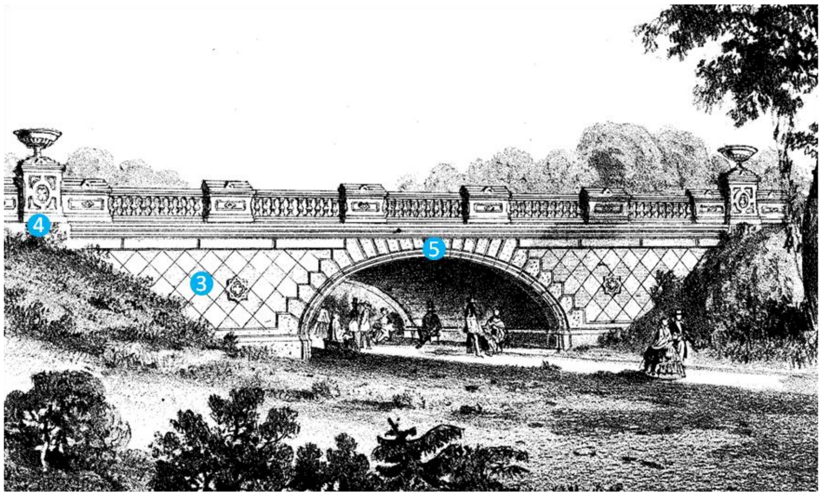

2


3


4


5

Glade Arch (north elevation)

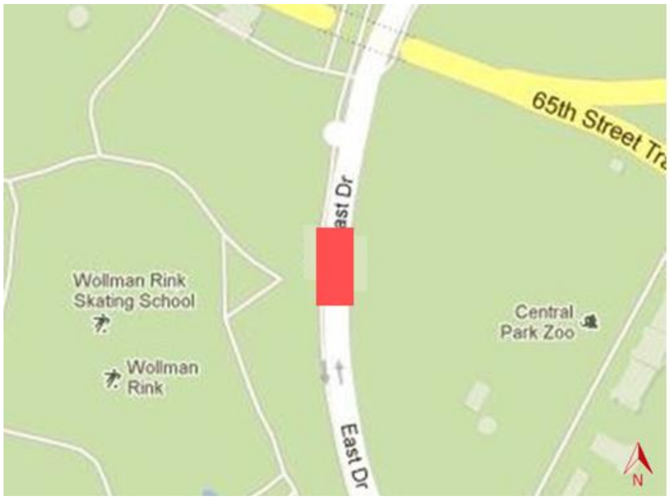


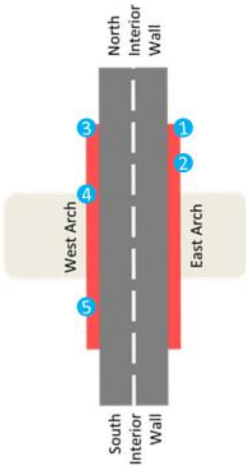
Glade Arch (south elevation)

Image Source: Third Annual Report of the Board of Commissioners of the Central Park

Green Gap Arch

Location	East side at 63rd Street and East Drive
Date of completion	1860
Original bridge no.	11
Areas of use	New Brunswick sandstone facings throughout and balustrades
Description	Green Gap Arch was designed to carry a large volume of pedestrians and horse-drawn carriages from Scholar's Gate at 60th Street. The walkway underneath was closed in 1988 during Central Park Zoo renovations and is now being used as a storage. The facings of the arch are of sandstone from Albert quarries in New Brunswick. The arch was repaired in 1988 when the bridge was made part of the zoo. *1990s Restoration* • Balustrades were restored by replacing panels, balusters and copings
Sample	Location
1	East balustrade (side facing east)
2	East arch spandrel wall
3	West balustrade (side facing west)
4	West arch buttress
5	West arch spandrel wall


65th Street Tr
East Dr
East Dr
Wollman Rink
Skating School
Wollman
Rink
Central
Park Zoo
N


North
Interior
Wall
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2
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5
West Arch
East Arch
South
Interior
Wall

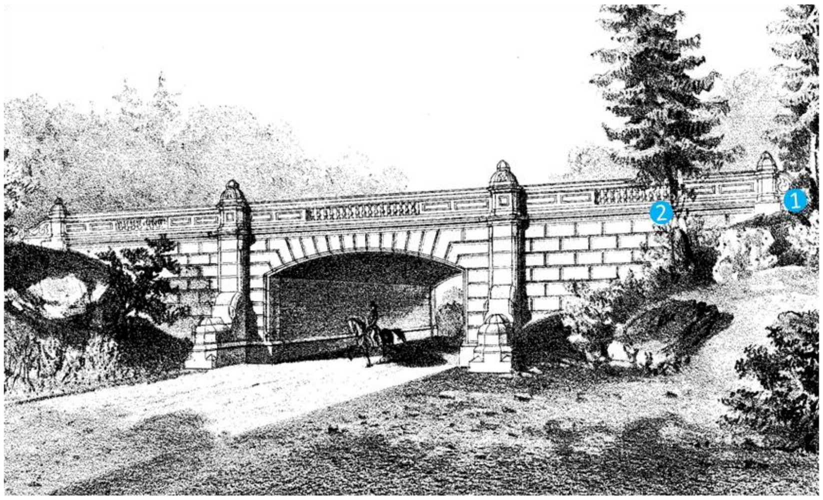

1


2


3


4


5



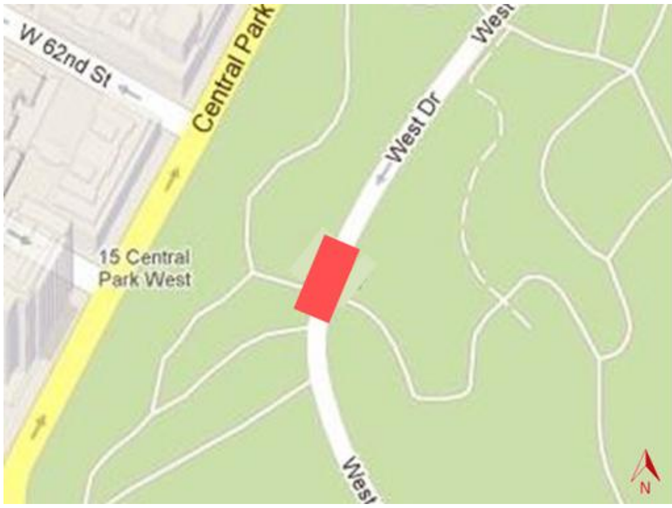
Green Gap Arch (east elevation)

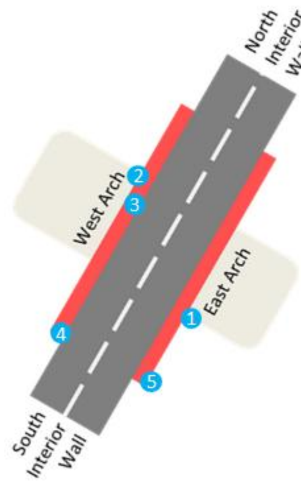
Image Source: Third Annual Report of the Board of Commissioners of the Central Park

Green Gap Arch (west elevation)

Greyshot Arch

Location	West side between 61st and 62nd Streets
Date of completion	1860
Original bridge no.	13
Areas of use	New Brunswick sandstone trimmings and balustrades
Description	Located a short distance from Columbus Circle, Greyshot arch is faced with ornamental Westchester County variegated gneiss with New Brunswick sandstone moldings of the elliptical arch and balustrades. The balustrade is carved with delicate, repetitive fleur-de-lis pattern. The vaulted archway is lined with Philadelphia red brick.
Sample	Location
1	East arch buttress
2	West arch voussoir
3	West balustrade (side facing east)
4	West balustrade (side facing east)
5	East balustrade (side facing east)


W 62nd St
Central Park
West Dr
15 Central
Park West
N


North
Interior
Wall
West Arch
East Arch
South
Interior
Wall
1
2
3
4
5


1


2


3


4


5

Greyshot Arch (east elevation)

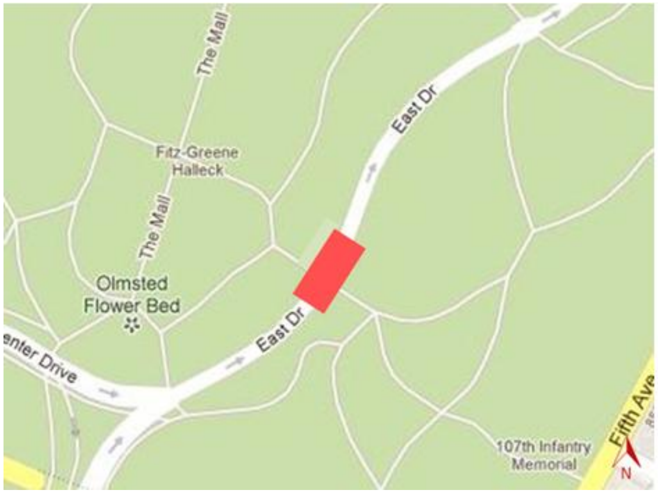
Greyshot Arch (west elevation)

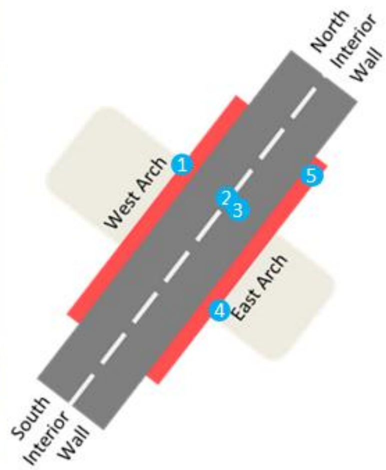
Image source: Herbert Mitchell Collection at the Metropolitan Museum of Art

Greyshot Arch west balustrade (side facing east)

Willowdell Arch

Location	East side at 67th Street
Date of completion	1860
Original bridge no.	3
Areas of use	New Brunswick sandstone trimmings and balustrades
Description	Willowdell Arch located between the Mall and Fifth Avenue leads visitors to the bronze statue of Balto from the Mall. It features rusticated voussoirs and a bench seating in the walls of the underpass originally meant to give mothers a place to sit and rest with their children. A center niche once contained a fountain. Red brick facings and sandstone trimmings of the arch give it a resemblance to Driprock Arch. The original cast-iron railings were replaced with wooden guardrails.
Sample	Location
1	West arch voussoir
2	North interior wall trimming (4th niche from west)
3	North interior wall (4th niche from west)
4	East arch voussoir
5	East balustrade (side facing east)


The Mall
Fitz-Greene
Halleck
The Mall
East Dr
Olmsted
Flower Bed
East Dr
Center Drive
107th Infantry
Memorial
Fifth Ave
N


North
Interior
Wall
West Arch
1
2
3
5
East Arch
4
South
Interior
Wall


1


2


3


4


5

Willowdell Arch (west elevation)

Willowdell Arch (north interior wall)

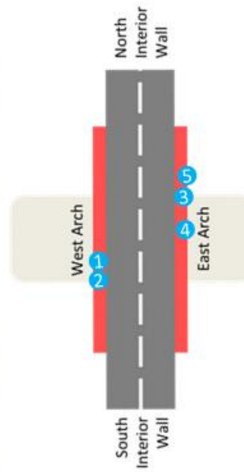
Willowdell Arch (east elevation)

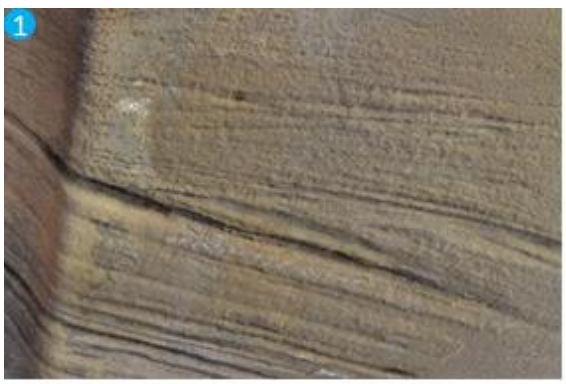
Willowdell Arch (east elevation)

Winterdale Arch

Location	West side at 82nd Street
Date of completion	1861
Original bridge no.	17
Areas of use	New Brunswick sandstone trimmings
Description	Winterdale Arch is among the masonry bridges with a largest span in Central Park. It carries the West Drive and a pedestrian walkway over the bridle path. The arch was originally set in a winter landscape with evergreens planted on its both sides and hence it was named 'Winterdale Arch'. Its facings are of Maine granite and moldings are of New Brunswick sandstone. The ornamental cast-iron railings are not original and were reconstructed in 1994. They were previously destroyed by repeated automobile accidents.
Sample	Location
1	West arch voussoir
2	West arch voussoir
3	East arch voussoir
4	East arch voussoir
5	East arch buttress


Summit Rock
Diana Ross Playground
West Dr
225
201
N


North Interior Wall
West Arch
East Arch
South Interior Wall
1
2
3
4
5


1

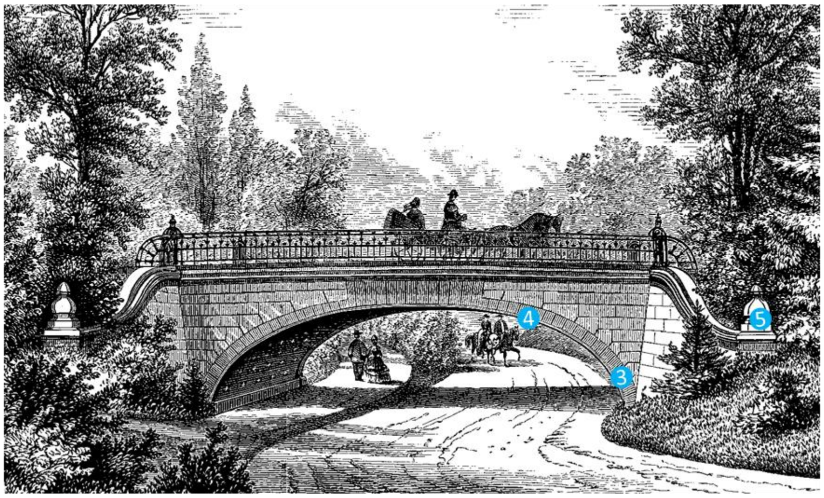

2


3


4


5

Winterdale Arch (west elevation)



Winterdale Arch (east elevation)

Image Source: Seventh Annual Report of the Board of Commissioners of the Central Park

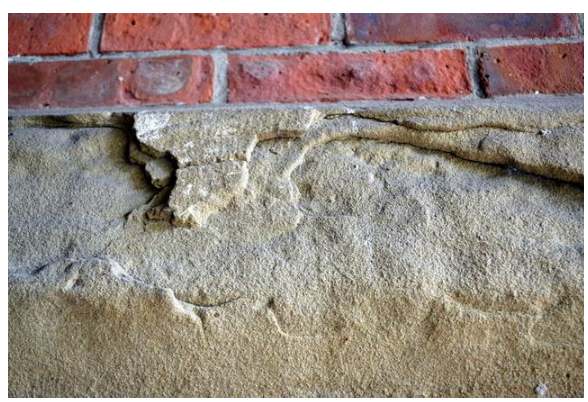
APPENDIX B: ILLUSTRATED GLOSSARY OF STONE DETERIORATION

The following illustrated glossary describes the conditions surveyed between September 2012 and May 2013. The list is limited to conditions that refer to any chemical or physical modification of the intrinsic stone properties that result in worsening or lowering of quality, value or character. The definitions in the glossary are adopted from *ICOMOS-ISCS: Illustrated glossary on stone deterioration patterns* and *A Glossary of Historic Masonry Deterioration Problems and Preservation Treatments* by Anne E. Grimmer.

Alveolization – The formation of cavities, or *alveoles*, on the stone surface due to inhomogeneities in physical or chemical properties of the stone, is known as Alveolization. The cavities may be interconnected and have variable shapes and sizes. It may occur with granular disintegration and/or scaling.
Image: Denesmouth Arch
Also see Coving.

Blistering – It is a type of swelling that causes detachment of a thin uniform skin both across and parallel to the bedding planes of the stone.
Image: Bethesda Terrace

Contour Exfoliation – It refers to loss of the surface along the sectional contours of a profiled stone. A stone may lose between 1 to 20 mm of its surface in a single exfoliation.
Image: Driprock Arch
Also see Delamination and Exfoliation.

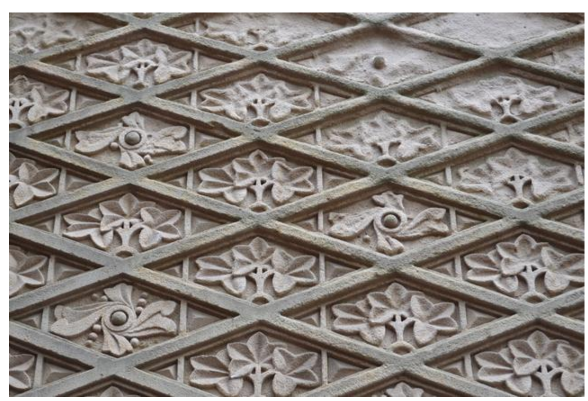


Contour Scaling – A sub-type of scaling in which the interface with the sound part of the stone is parallel to the stone surface. The detachment of stone elements occurs as a scale or a stack of scales.
Image: Bethesda Terrace
Also see Scaling and Flaking.

Coving – It is a sub-type of alveolization that refers to erosion consisting in a single alveole developing from the edge of the stone block.
Image: Denesmouth Arch
Also see Alveolization.

Delamination – It refers to splitting of the laminated stone into laminae or thin layers along the natural bedding planes when the stone is laid vertically on the wall.
Image: Bethesda Terrace
Also see Contour Exfoliation and Exfoliation.

Differential Erosion – It refers to erosion that does not proceed at the same rate from one area of the stone to other. It is common for heterogeneous stones with harder and/or less porous zones.
Image: Bethesda Terrace
Also see Erosion and Rounding.



Erosion – It refers to loss of the original crispness of the stone resulting in smoothed surface, edges, corners or carved details due to the natural action of wind, windblown particles or water.
Image: Glade Arch
Also see Differential Erosion and Rounding.

Exfoliation – It is a type of delamination that causes peeling, scaling or flaking of the surface of the stone into thin layers along its natural bedding planes. The layers may bend or twist in a way as book pages.
Image: Bethesda Terrace
Also see Contour Exfoliation and Delamination.

Flaking – A sub-type of scaling, it refers to detachment of the outer layer of the stone in small, thin flat or curved pieces.
Image: Bethesda Terrace
Also see Contour Scaling and Scaling.

Granular Disintegration – In sedimentary rocks, it refers to the breakdown of the intergranular clays or other minerals that bind together the grains of silica.
Image: Bethesda Terrace

Rounding – Preferential erosion of originally angular stone edges to a distinctly rounded profile is referred to as rounding. It is observed on stones that tend to deteriorate through granular disintegration.
Image: Dalehead Arch
Also see Differential Erosion and Erosion.

Scaling – It refers to detachment of the surface of the stone as a scale or a stack of scales. The detachment does not follow any stone structure like in delamination and detaches like fish scales or parallel to the stone surface.
Image: Denesmouth Arch
Also see Flaking and Contour Scaling.

Splitting – It refers to the fracturing of a stone along planes of weakness such as microcracks or clay/slit layers.
Image: Bethesda Terrace

APPENDIX C: GLOSSARY OF ARCHITECTURAL TERMS AND STONE TYPES

Balcony – a platform that projects from a wall of a building or a bridge and is enclosed by a parapet or railing

Balustrade – a row of repeating balusters, small posts that support the upper rail of a railing

Bedding plane – the direction of layers or strata in sedimentary and stratified rocks

Building stone – a type of stone used to construct buildings and other structures that can be used in a structural capacity or for decorative purposes

Buttress – a projecting support of stone or brick on the exterior to strengthen a wall

Dimension stone – a rock that has undergone some shaping or finishing

Elliptical arch – an arch with the shape of half an ellipse

Face-bedding – when the bedding planes of the stone are set parallel to the plane of the wall

Freestone – a fine-grained or uniform textured stone that can be worked equally in any direction

Grindstone – a revolving stone shaped like a disk used for grinding, sharpening or polishing metal objects

Keystone – a central stone at the summit of an arch

Natural bed – the setting of the stone in the wall on the same plane as it was formed in a quarry

Pier – a vertical masonry support for an arch, bridge or wall

Quarry bed – the direction in which the bedding planes naturally lie in a quarry

Quatrefoil – a pattern of four lobes and four cusps set in a circle

Spandrel – a space between two arches, or between an arch and a rectangular enclosure

Spandrel wall – a wall on the outer surface of an arch

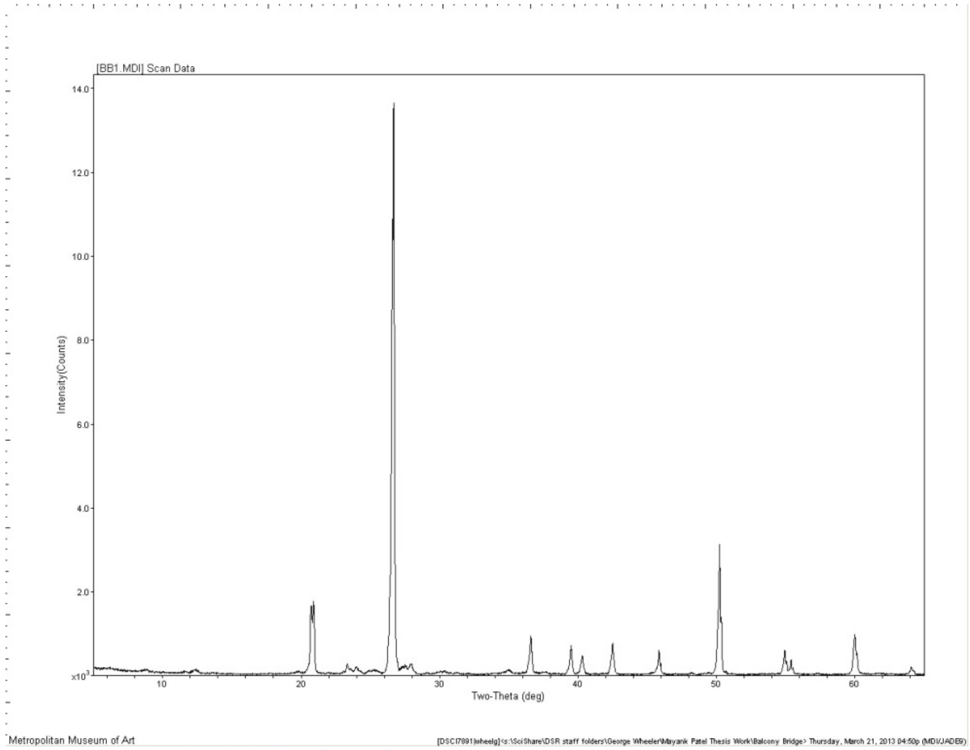
Traditional stone setting – where the stone is set on its natural bed so the bedding planes are perpendicular to the plane of the wall

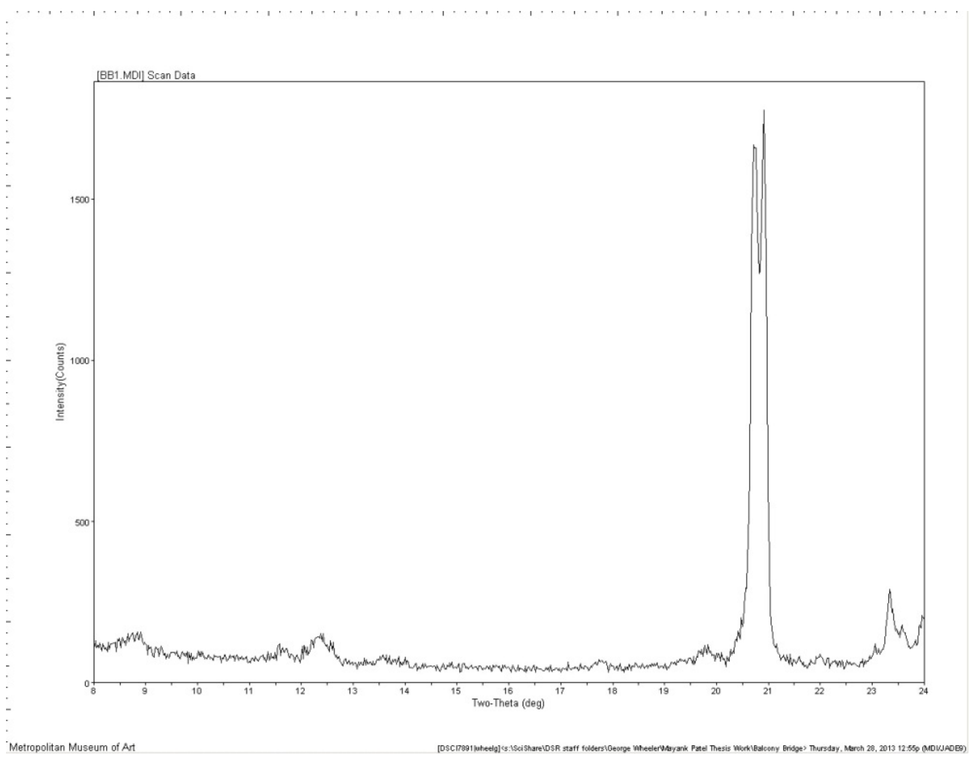
Voussoir – a wedge-shaped element, typically a stone, used to build an arch or vault

APPENDIX D: X-RAY DIFFRACTOGRAMS

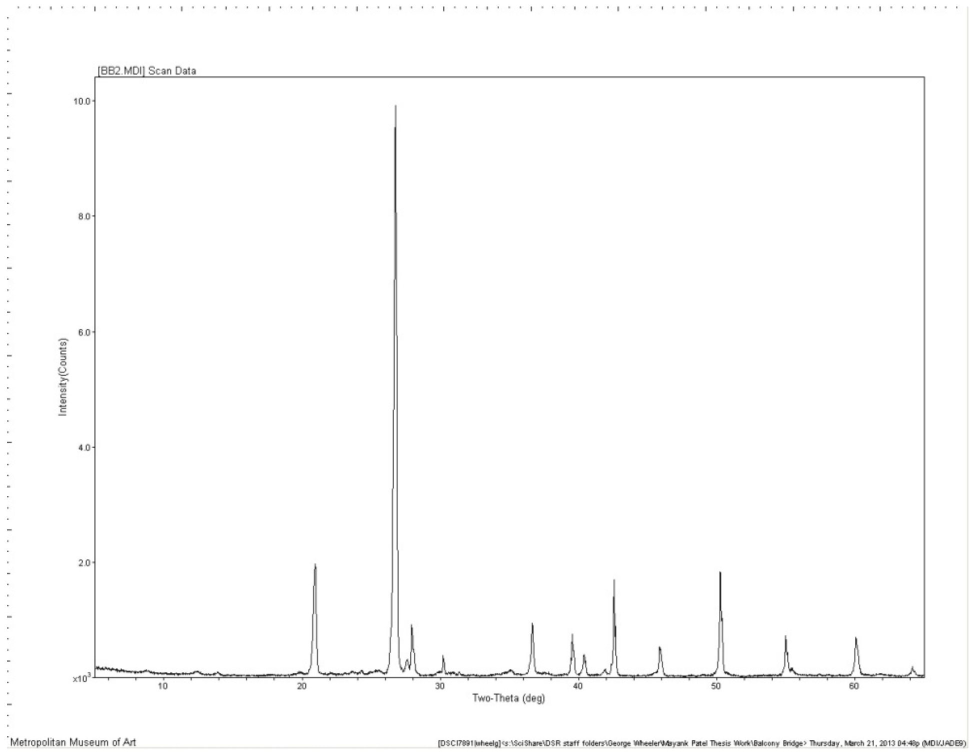
Mineral Name	Chemical Formula
Akaganeite	Iron (III) oxide hydroxide, $Fe^{+3}O(OH,Cl)$
Albite	Sodium aluminum silicate, $NaAlSi_3O_8$
Anorthoclase	Sodium-potassium aluminum silicate, $(Na,K)AlSi_3O8$
Clinochlore	Magnesium aluminum silicate hydroxide, $(Mg,Fe^{+2})_5Al(AlSi_3O_{10})(OH)_8$
Gypsum	Calcium sulfate hydrate, $CaSO_4{\cdot}2H_20$
Illite	Potassium aluminum silicate hydroxide, $(K, H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$
Kaolinite	$Al_2Si_2O_5(OH)_4$
Microcline	Potassium aluminum silicate, $KAlSi_3O_8$
Muscovite	Potassium aluminum silicate hydroxide, $KAl_2(AlSi_3O_{10})(F,OH)_2$
Orthoclase	Potassium aluminum silicate, $KAlSi_3O_8$
Quartz	Silicone oxide, SiO_2

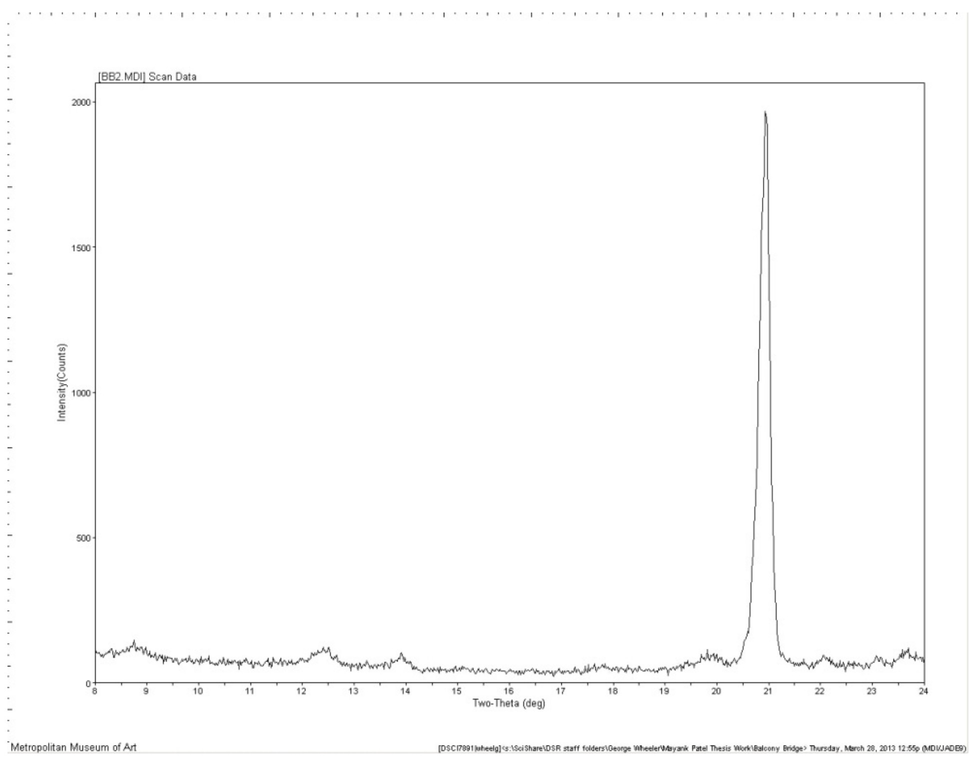
Balcony Bridge 1



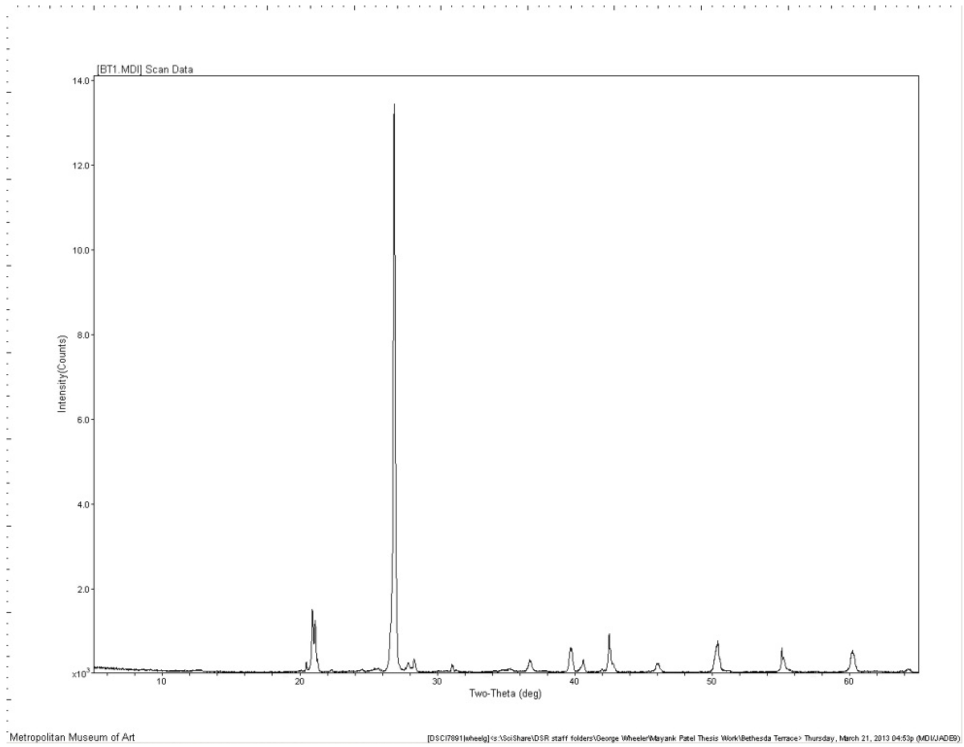


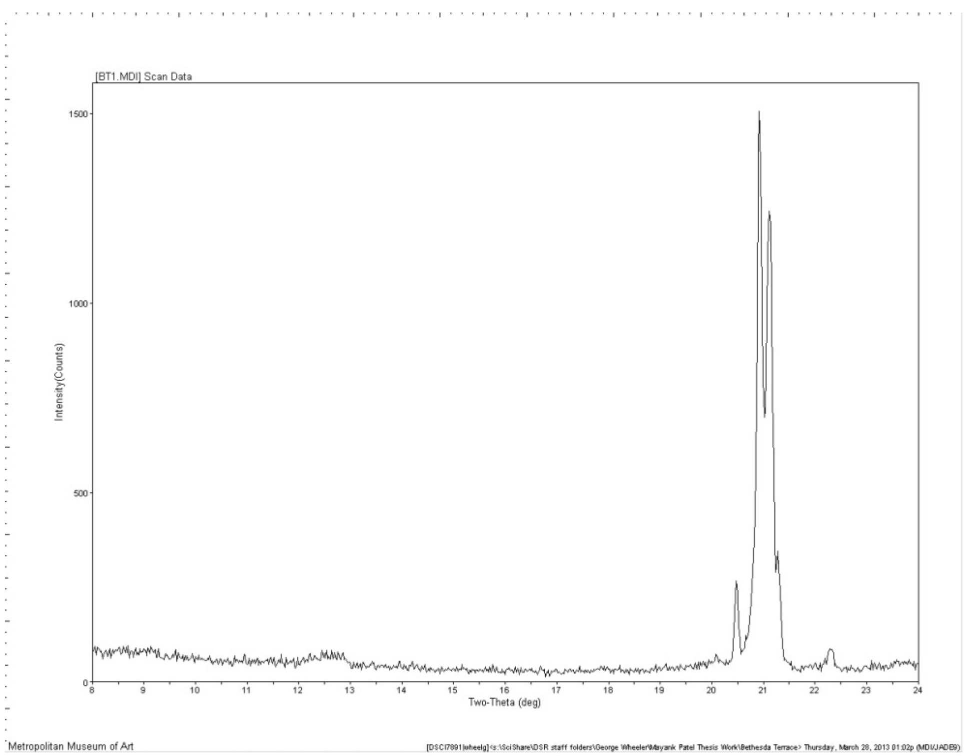
Balcony Bridge 2



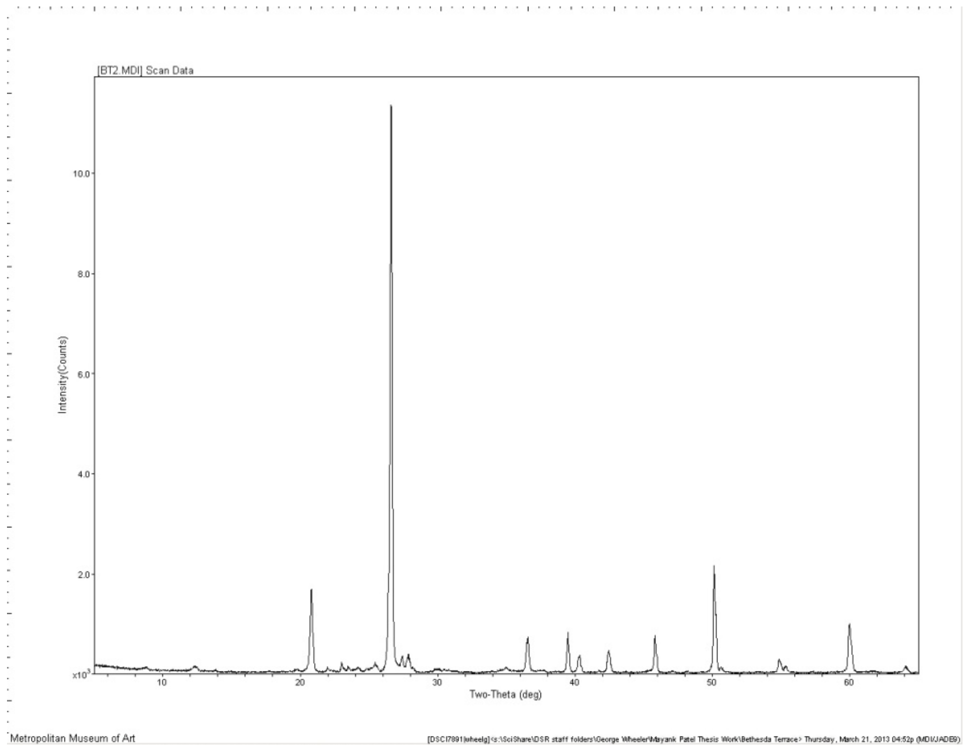


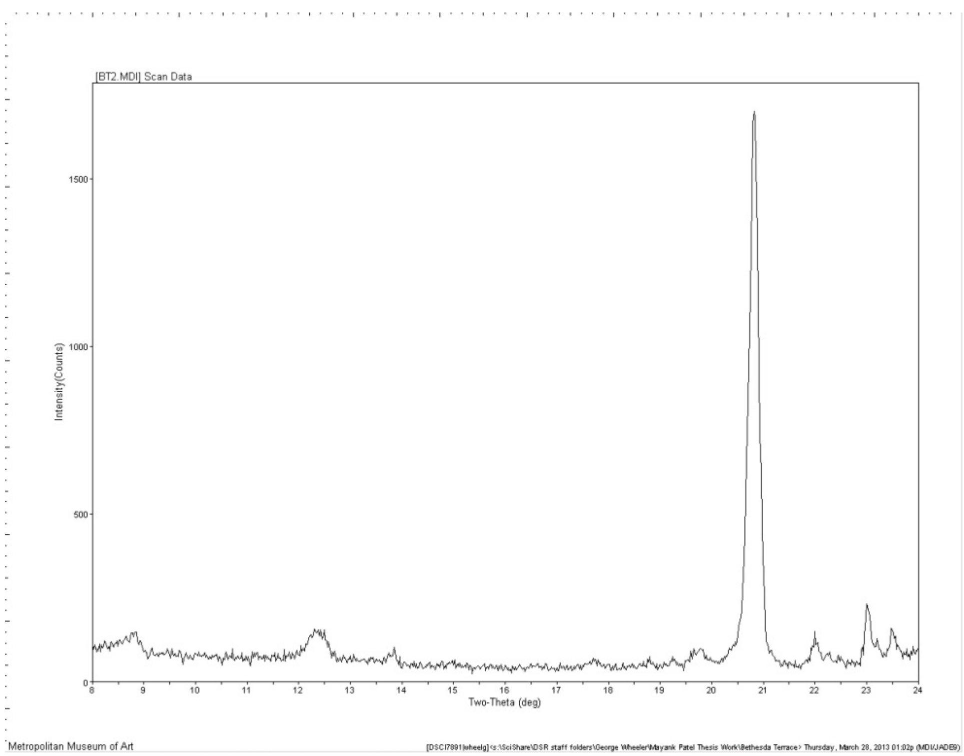
Bethesda Terrace 1



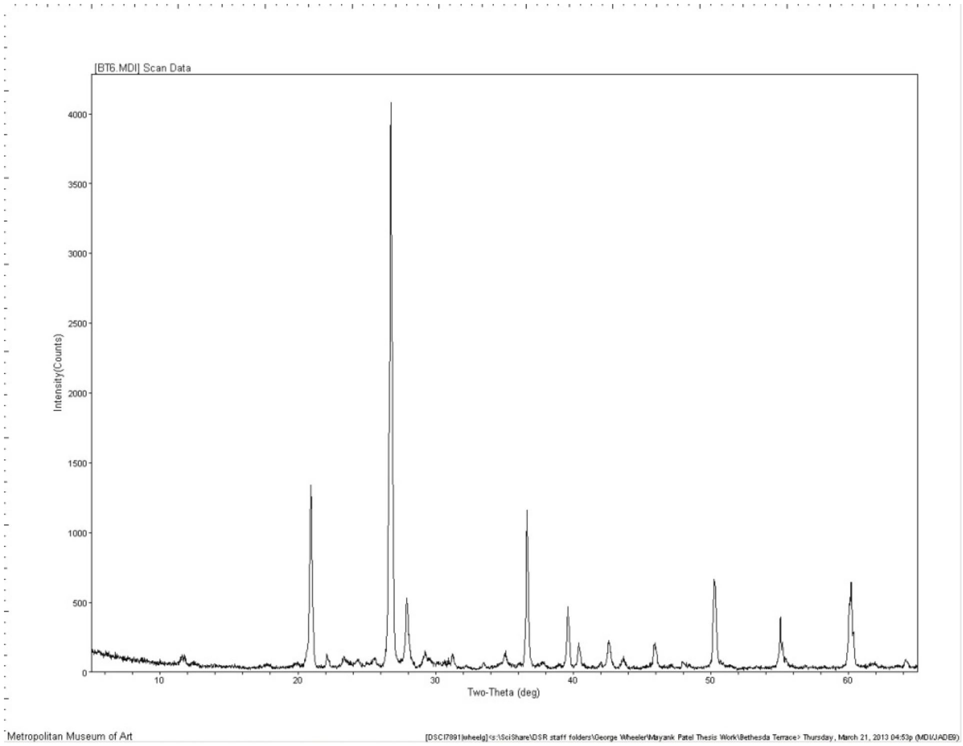


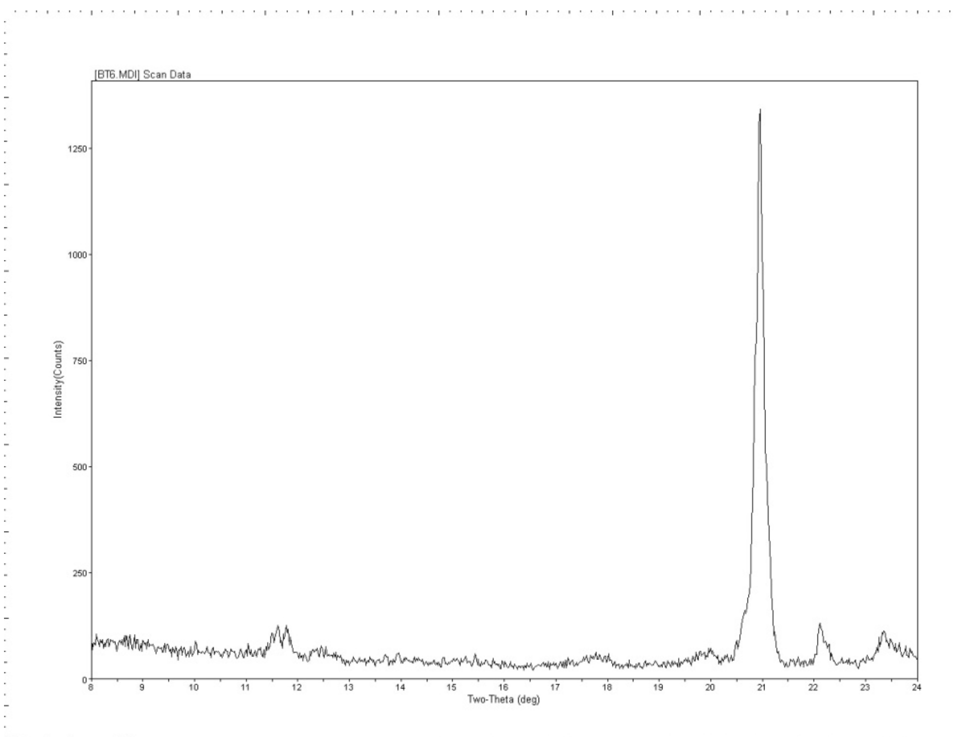
Bethesda Terrace 2



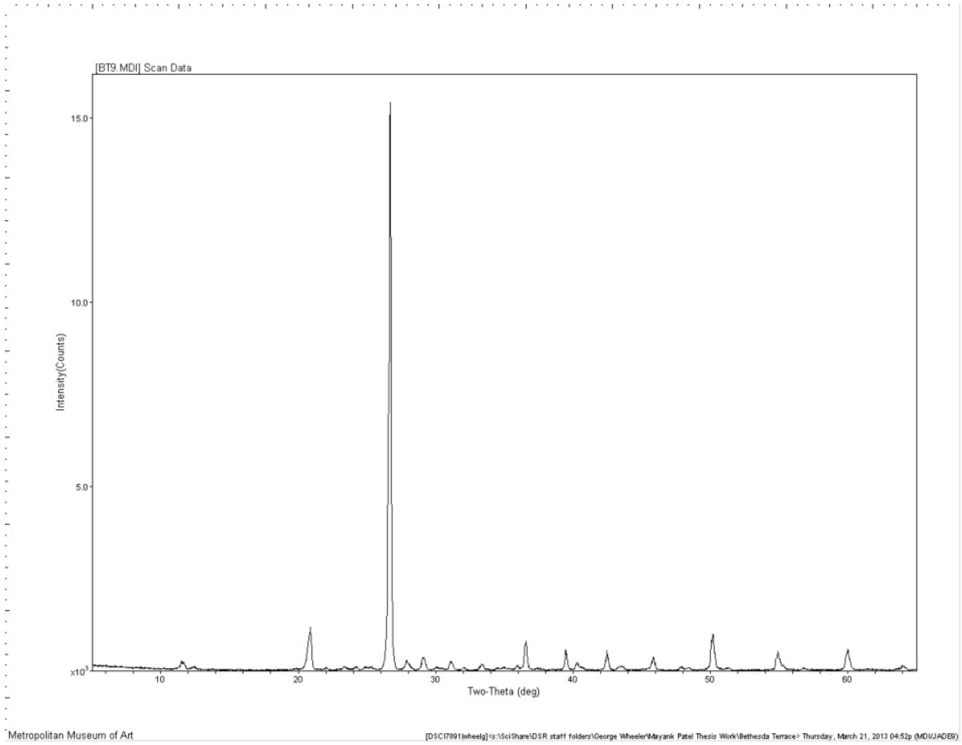


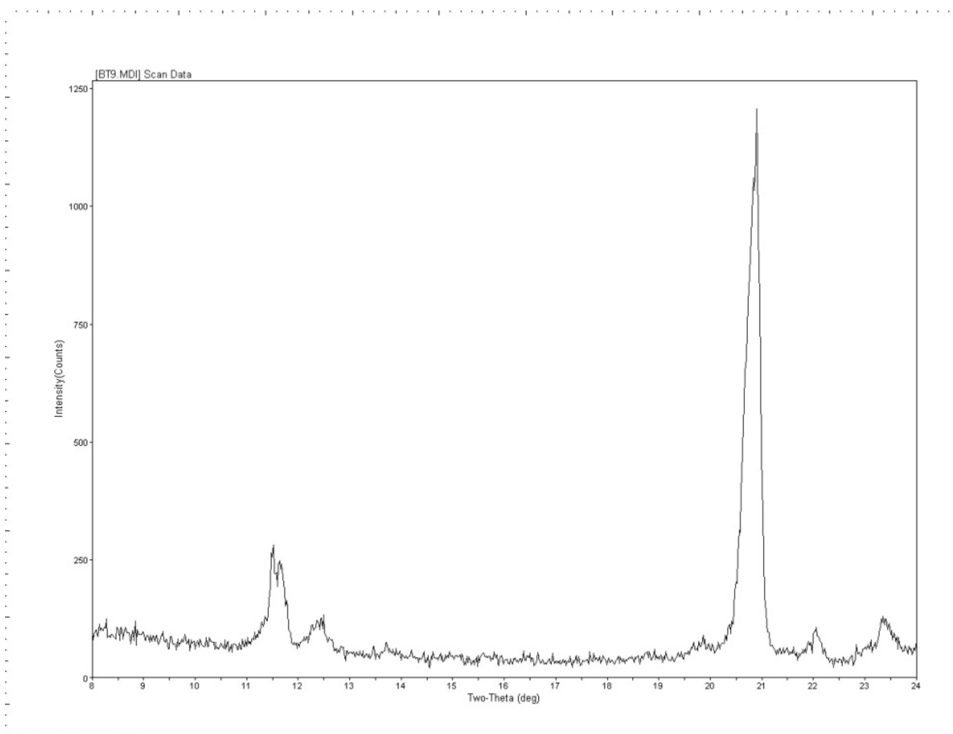
Bethesda Terrace 6



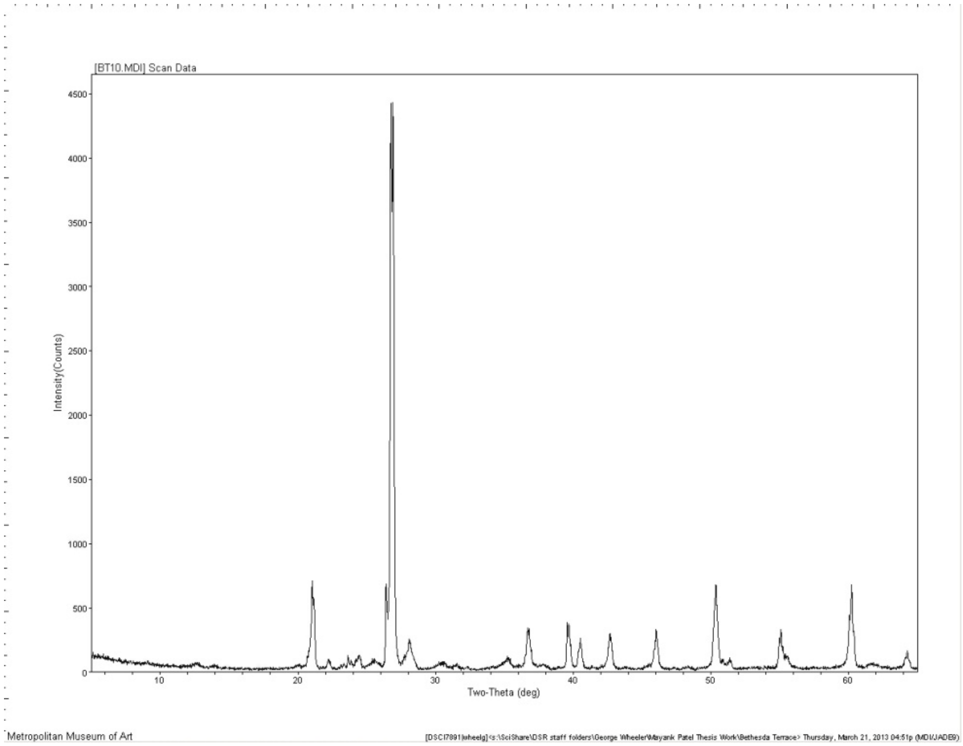


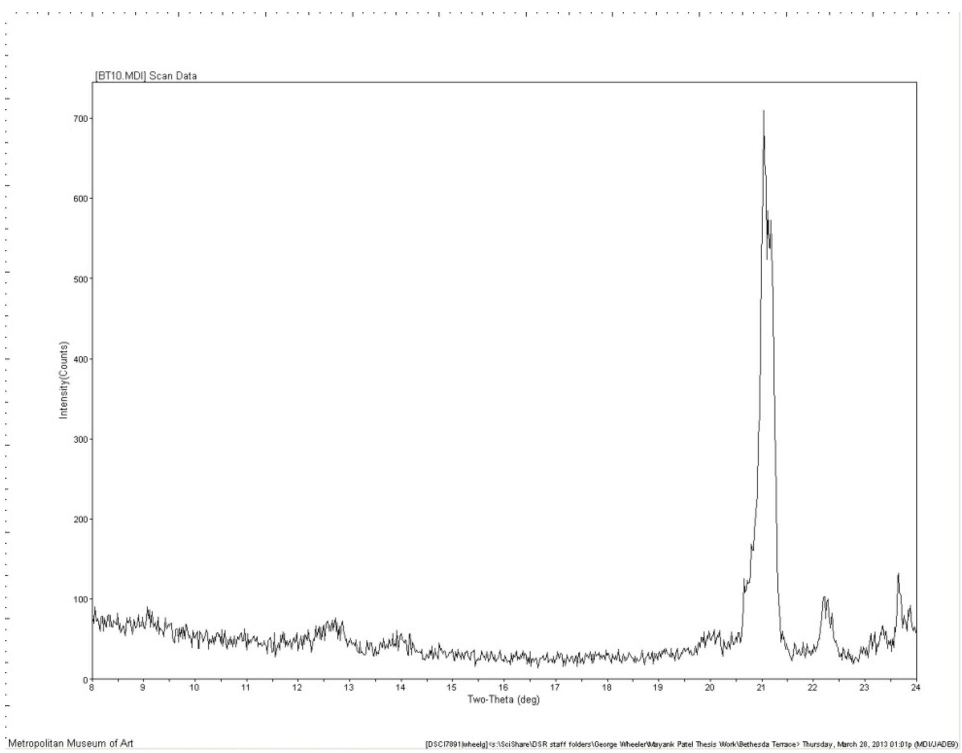
Bethesda Terrace 9



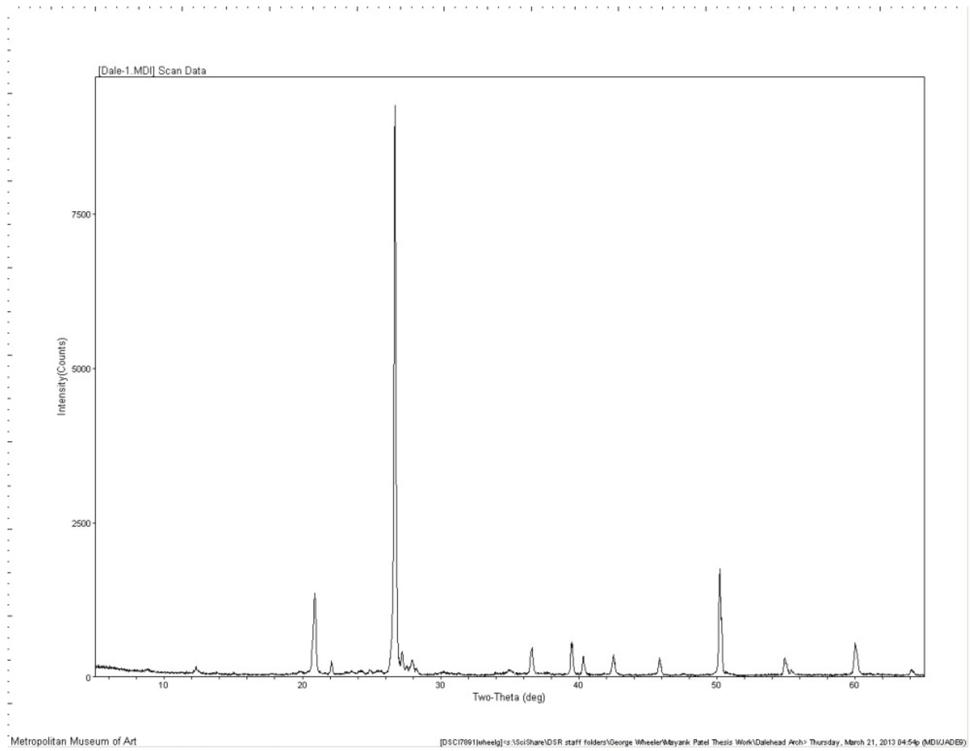


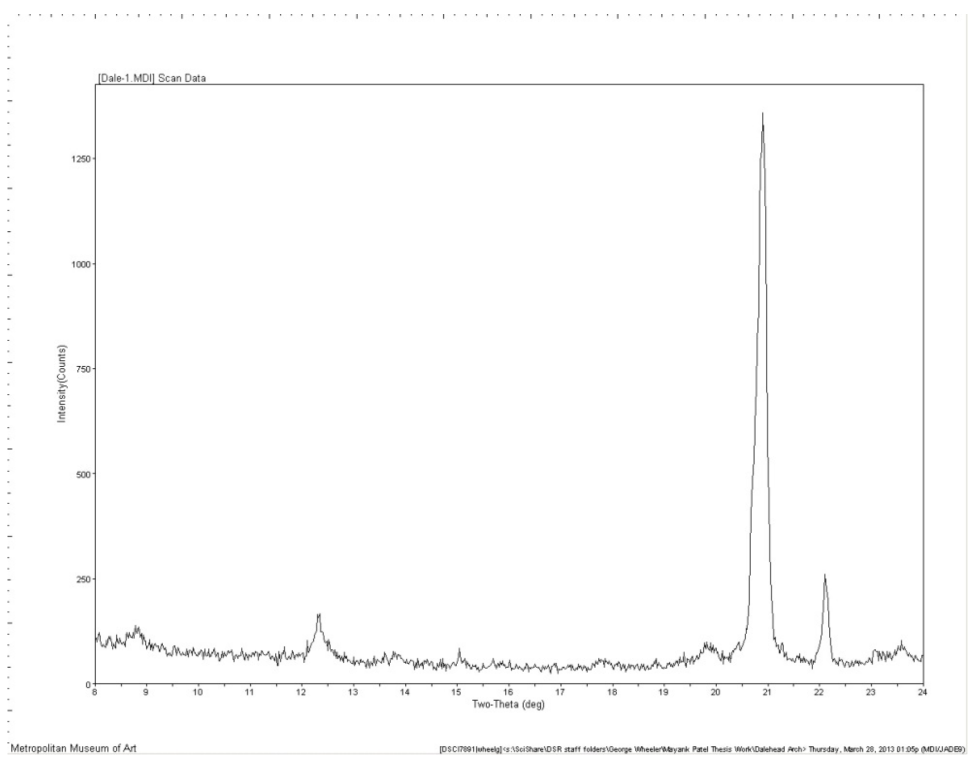
Bethesda Terrace 10





Dalehead Arch 1





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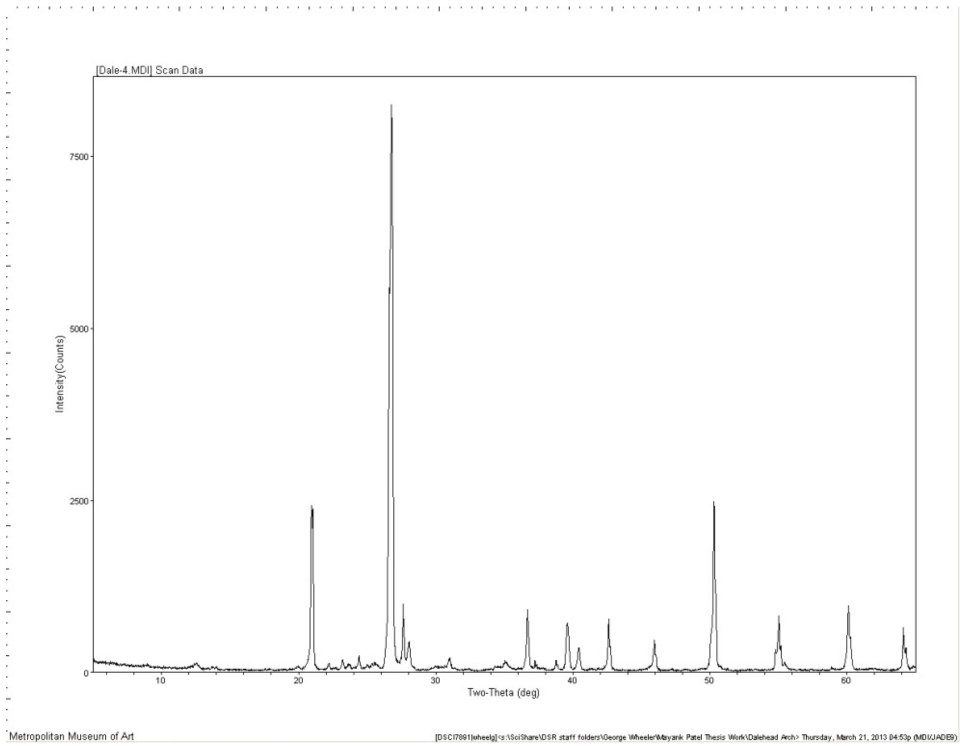

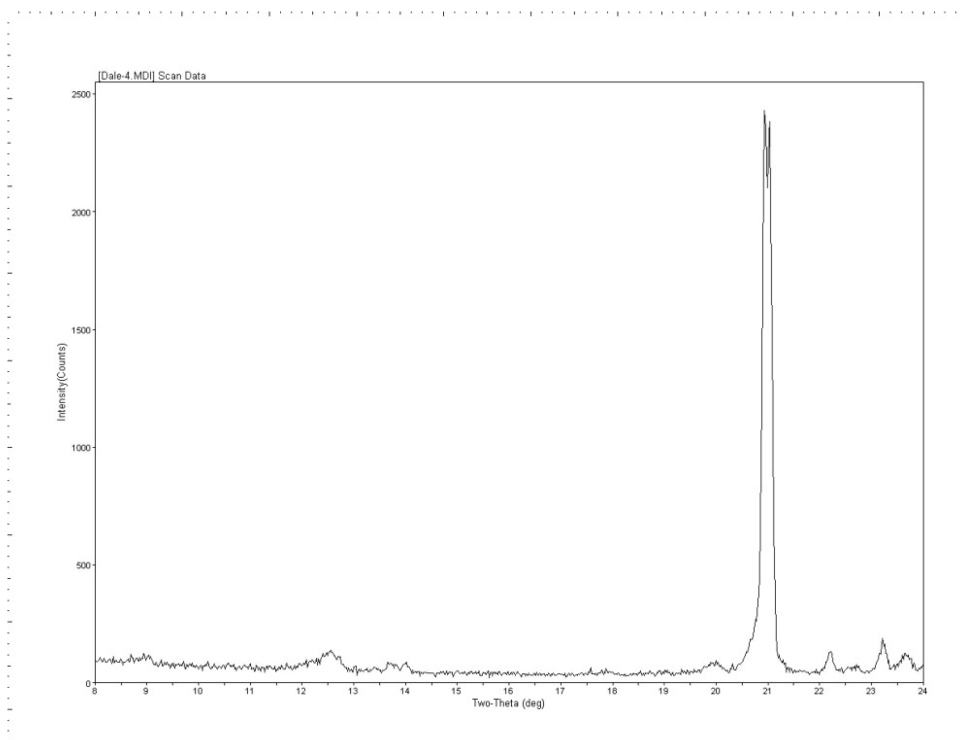

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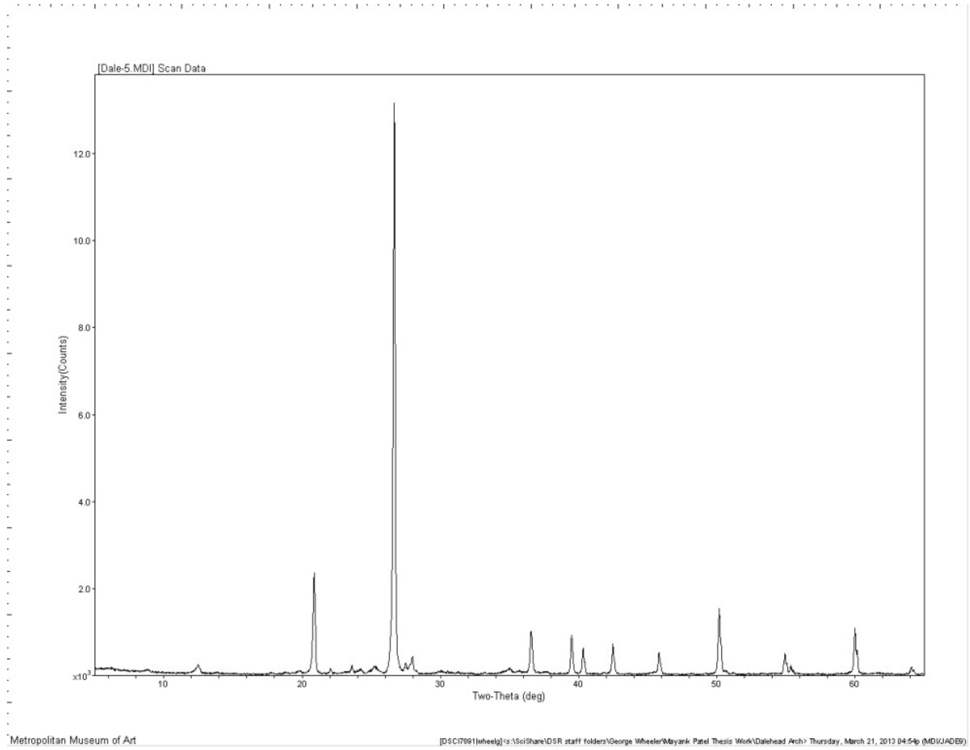
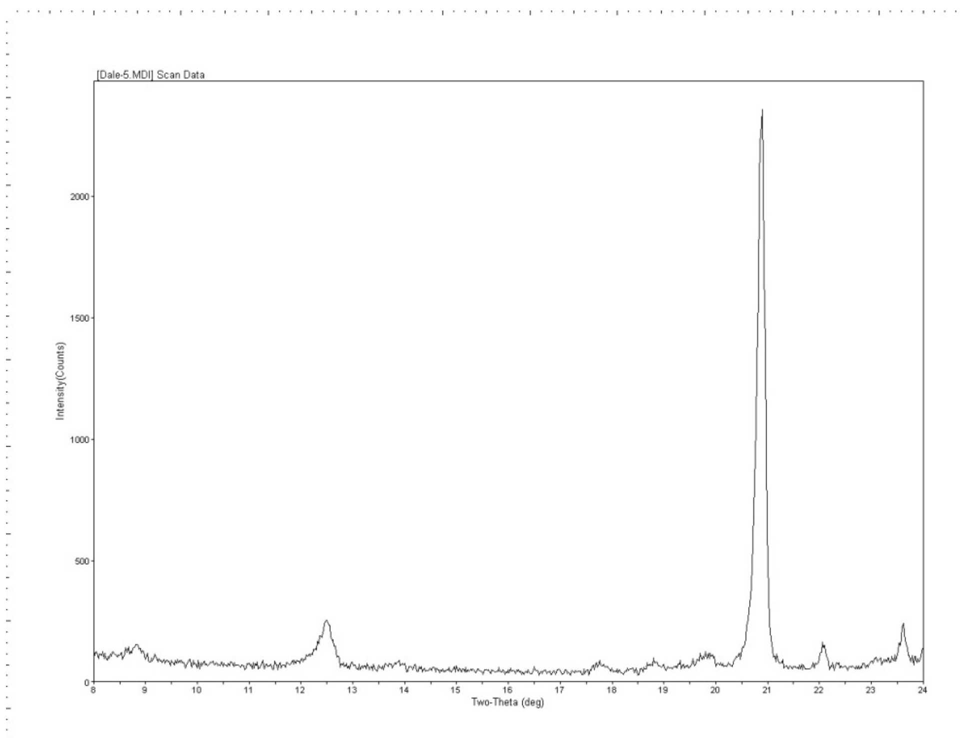
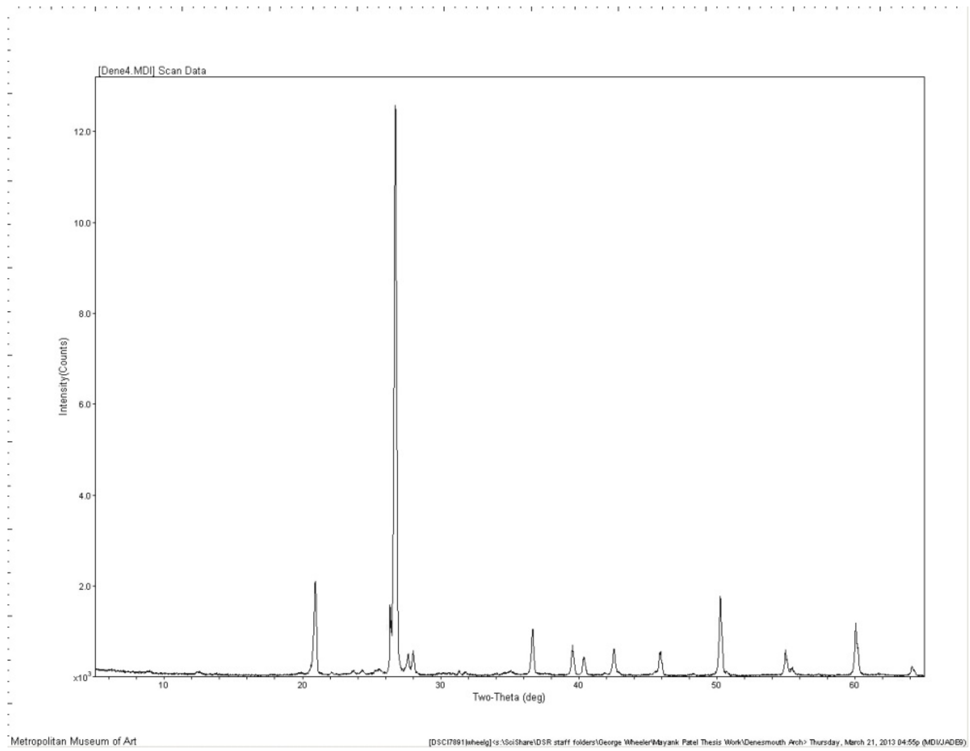
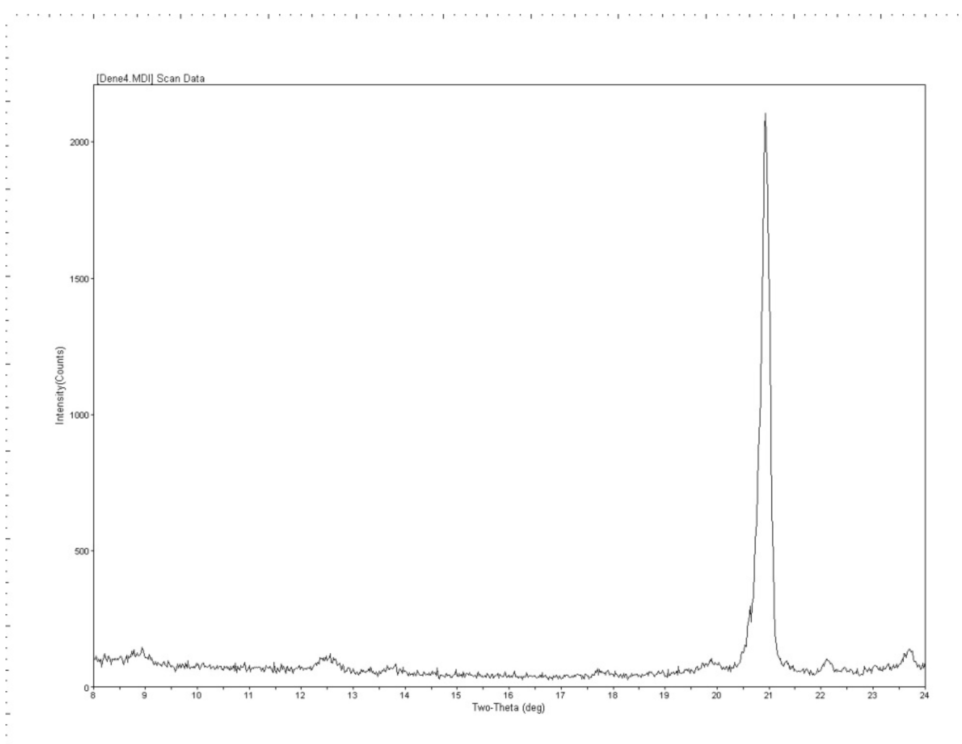


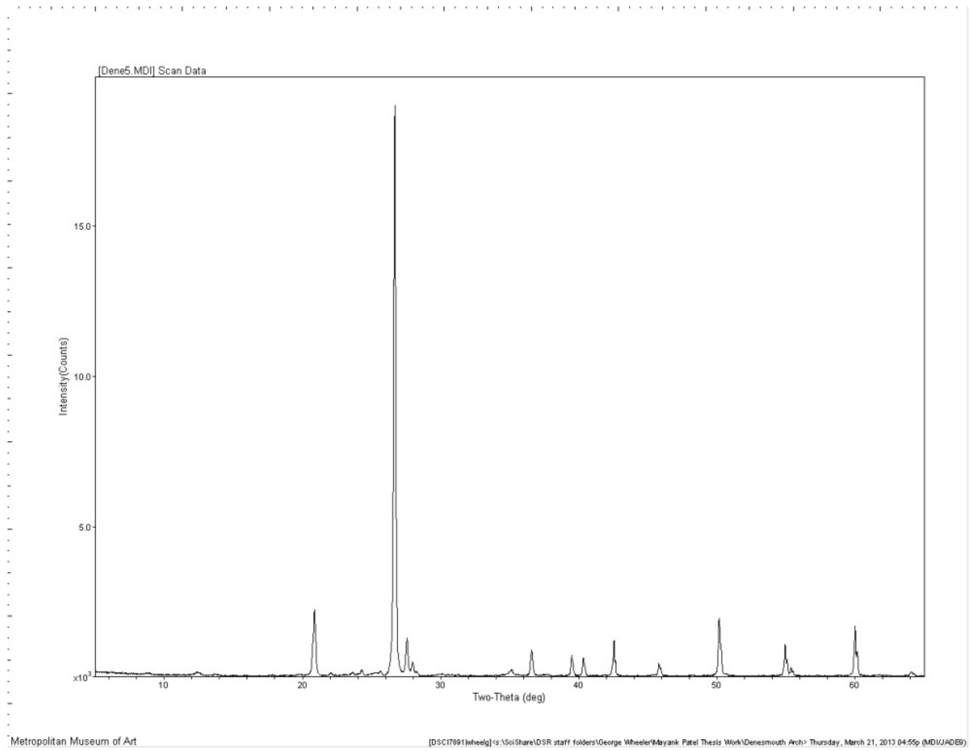


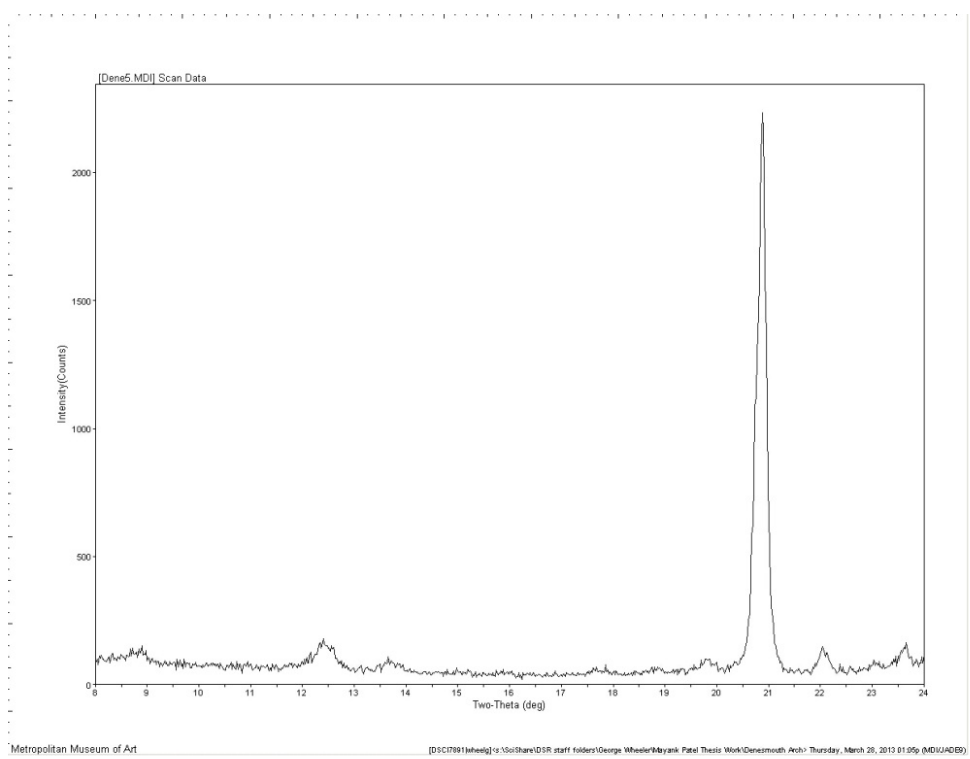
Denesmouth Arch 4





Denesmouth Arch 5





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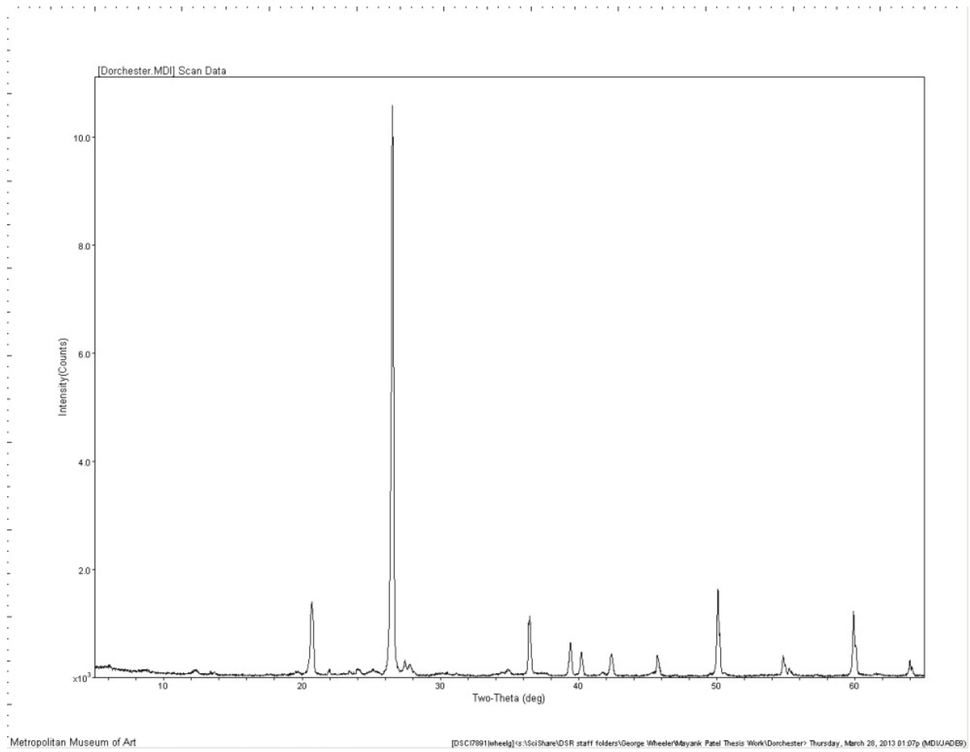
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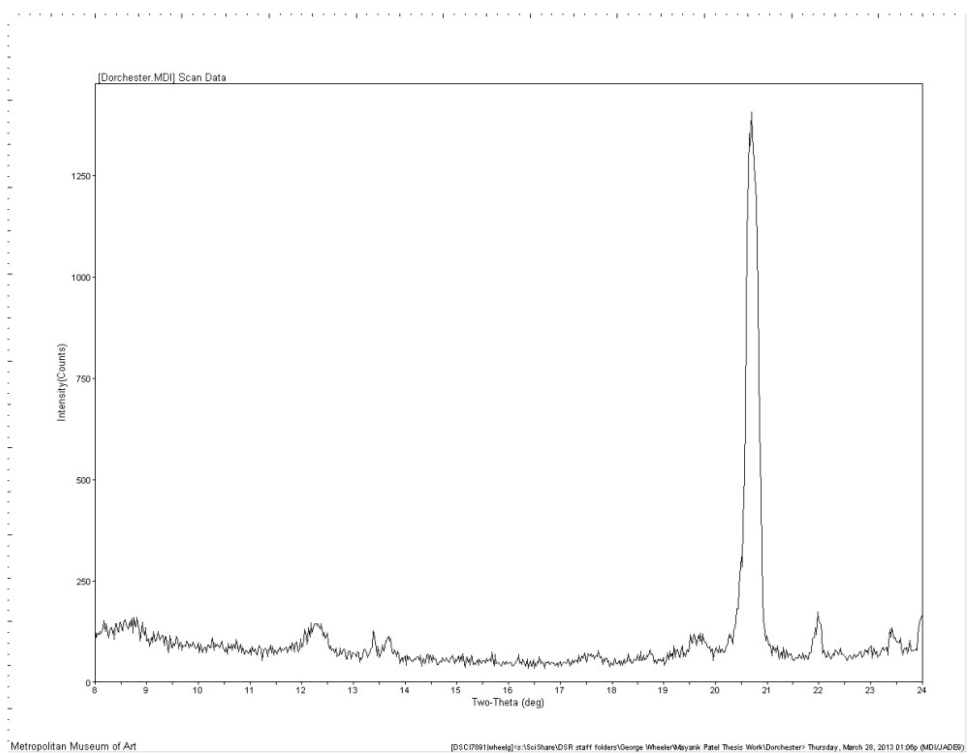
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Metropolitan Museum of Art
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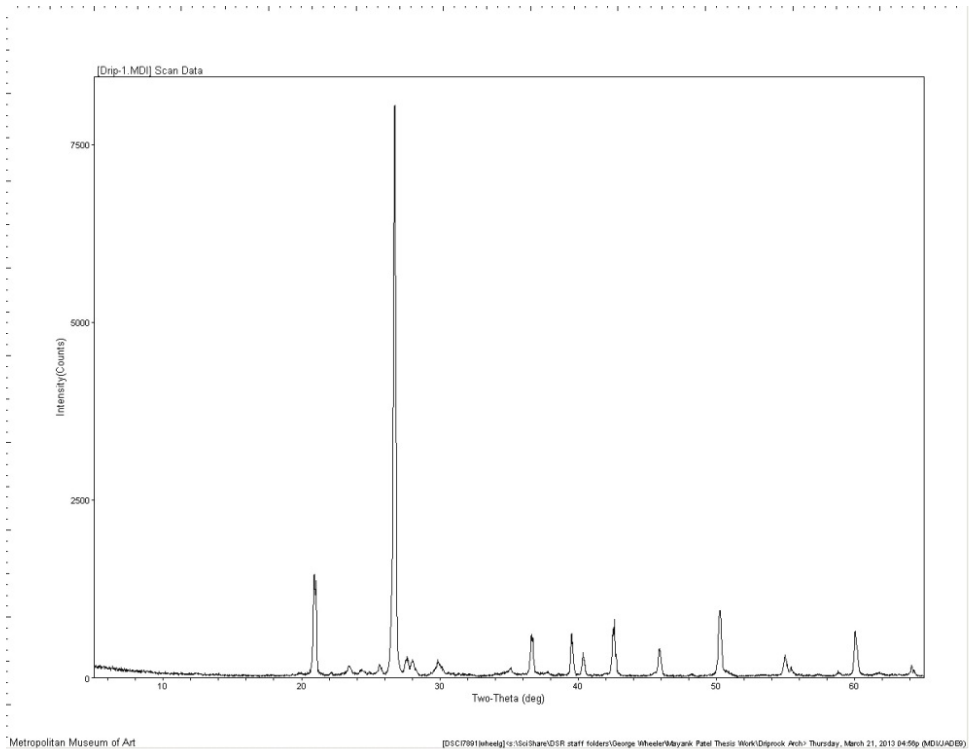
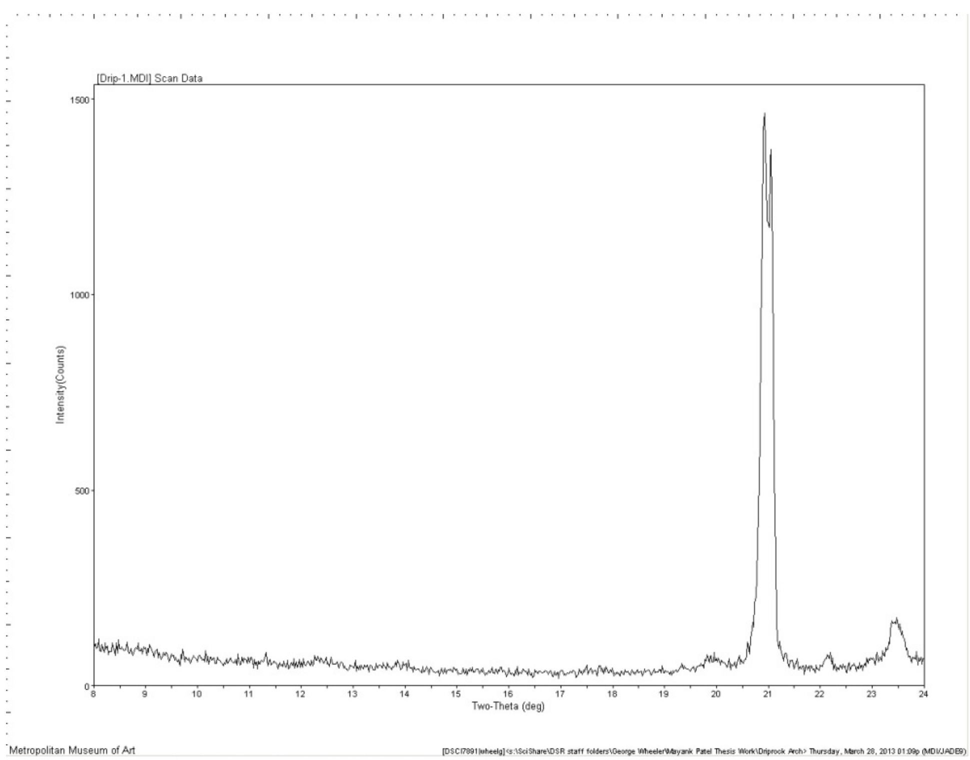
Driprock Arch 1





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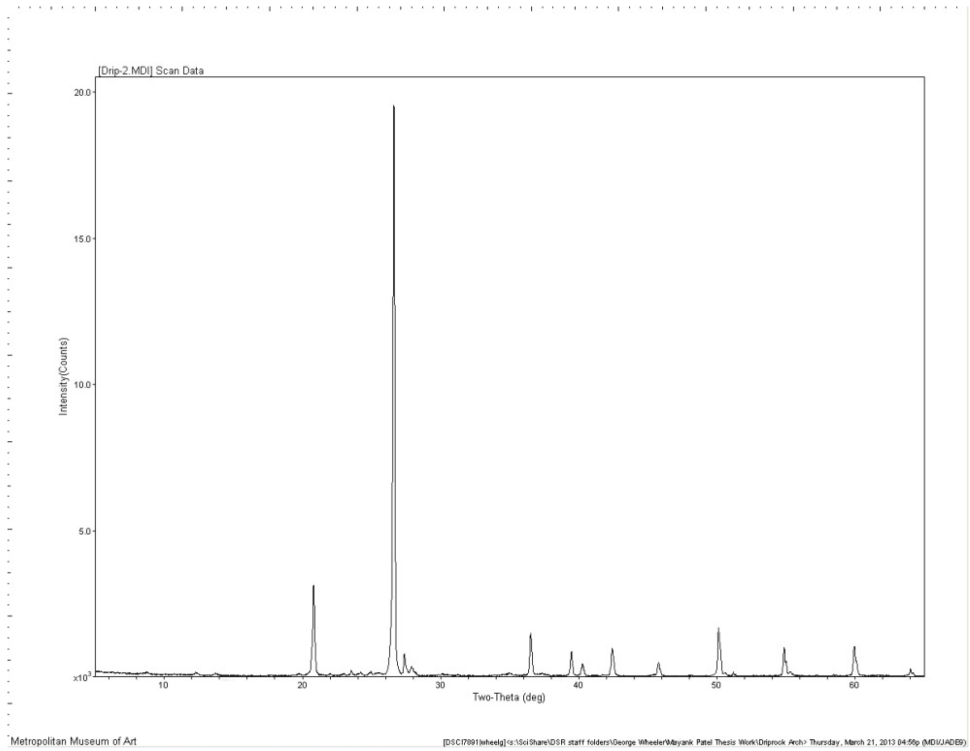
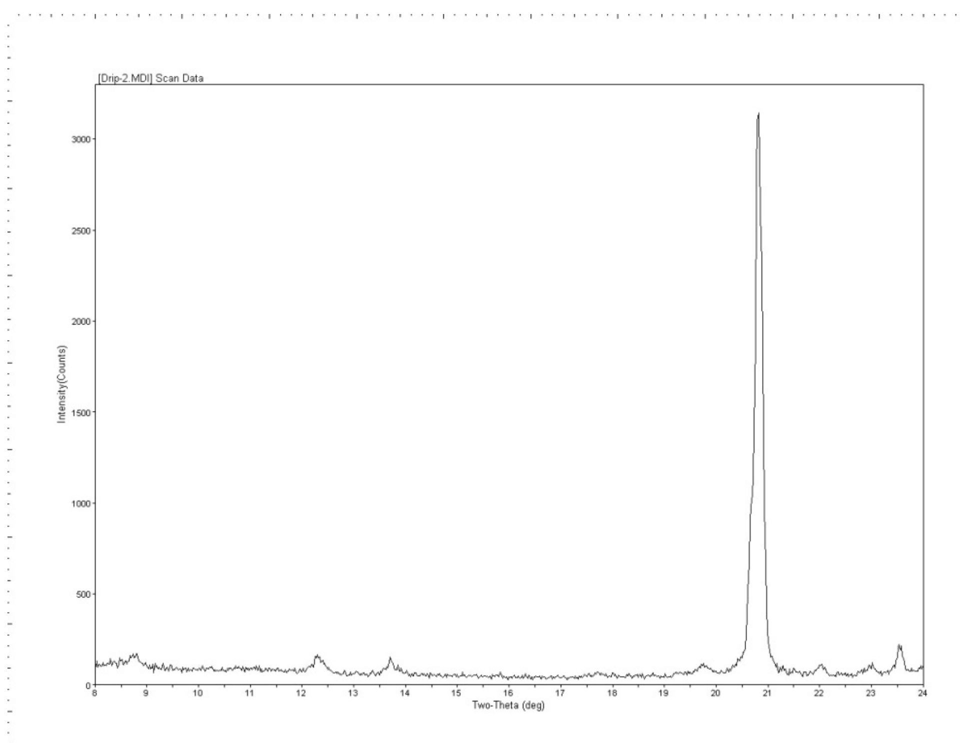
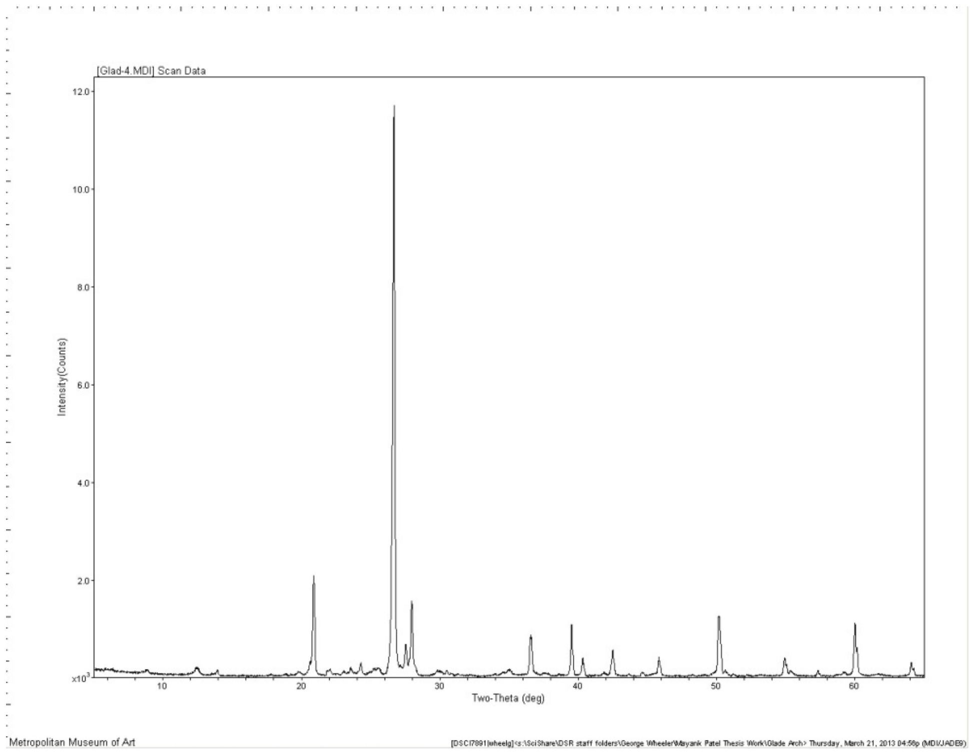




Glade Arch 4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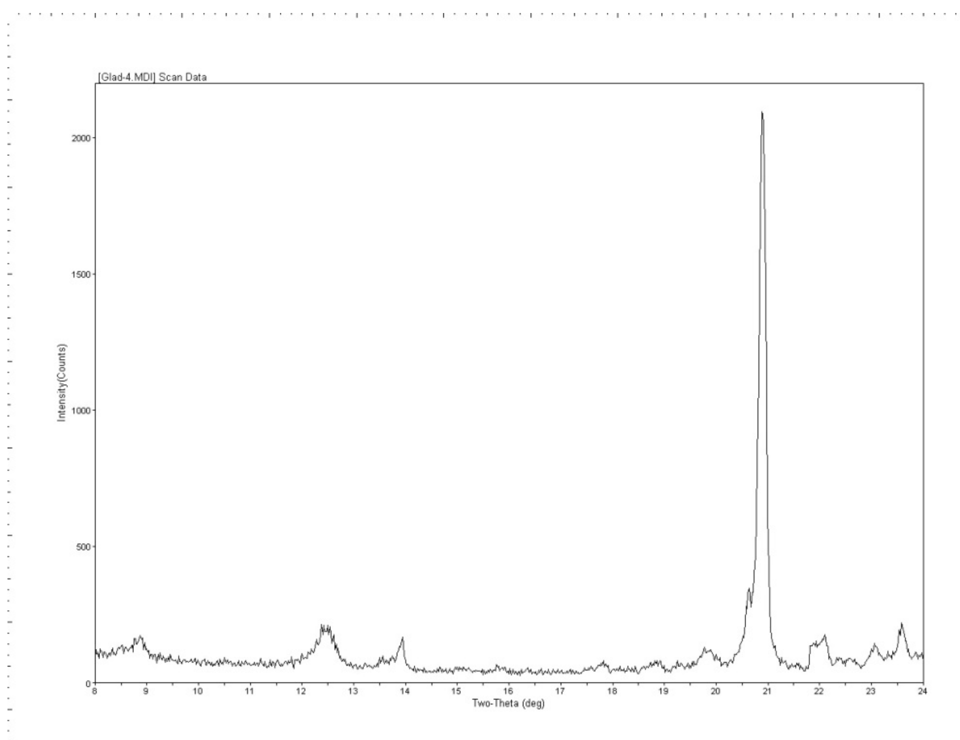
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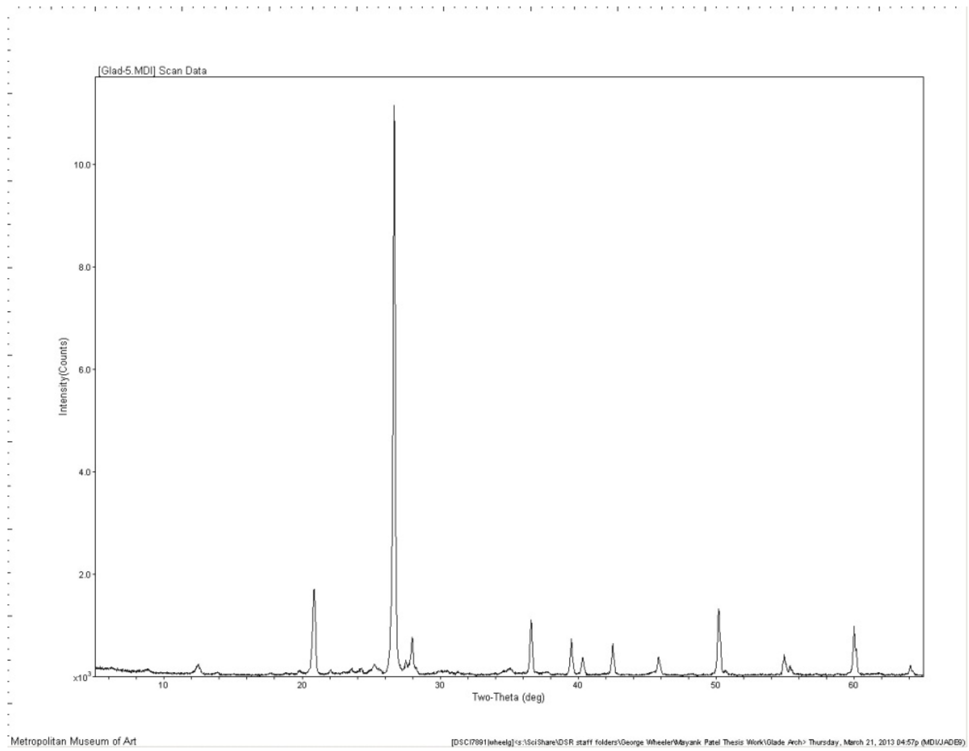
Metropolitan Museum of Art

Glade Arch 5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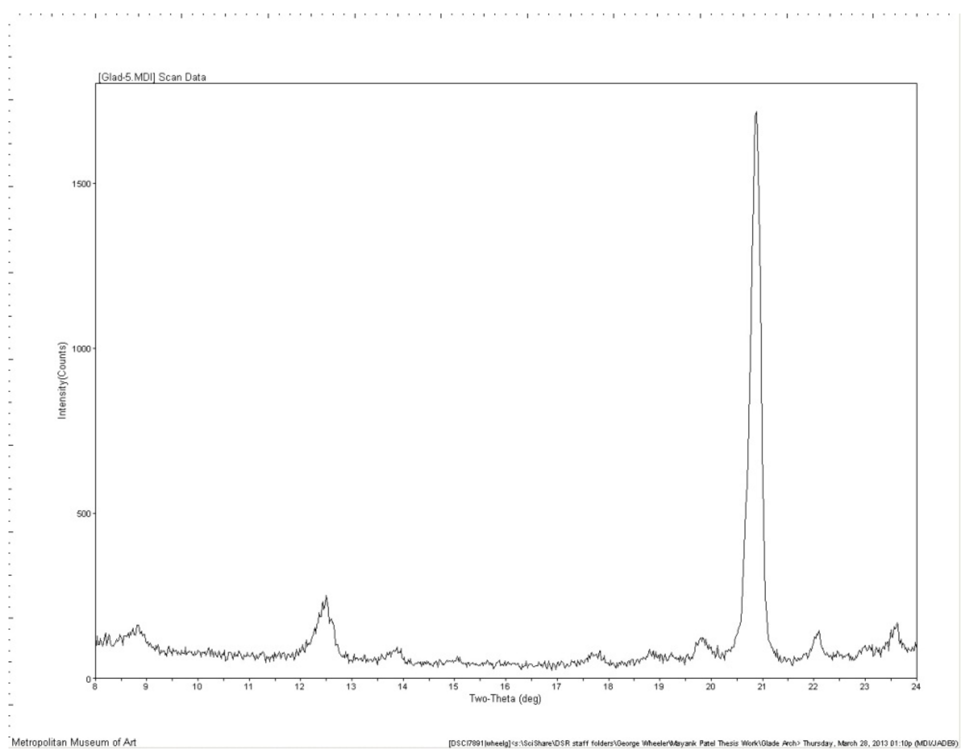
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22
23
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Two-Theta (deg)
Metropolitan Museum of Art
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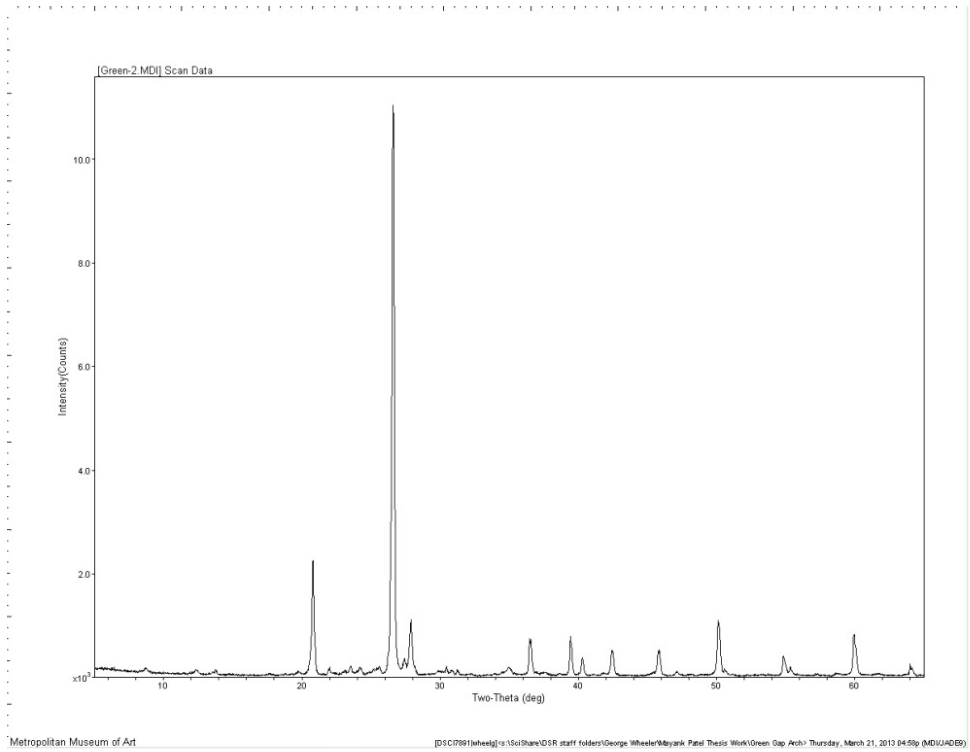
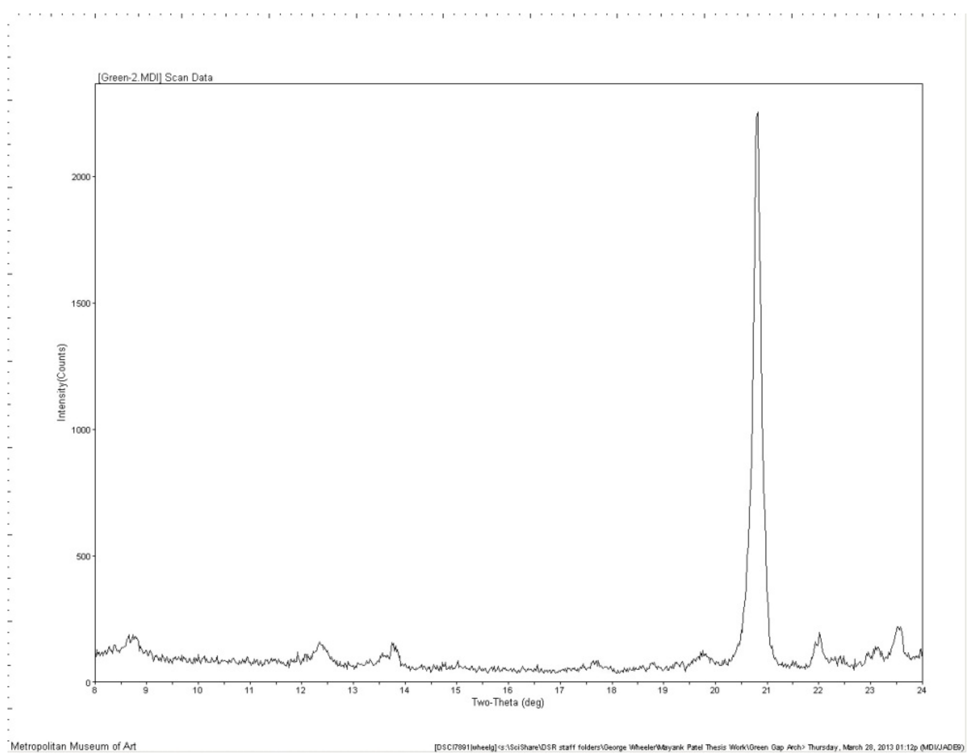
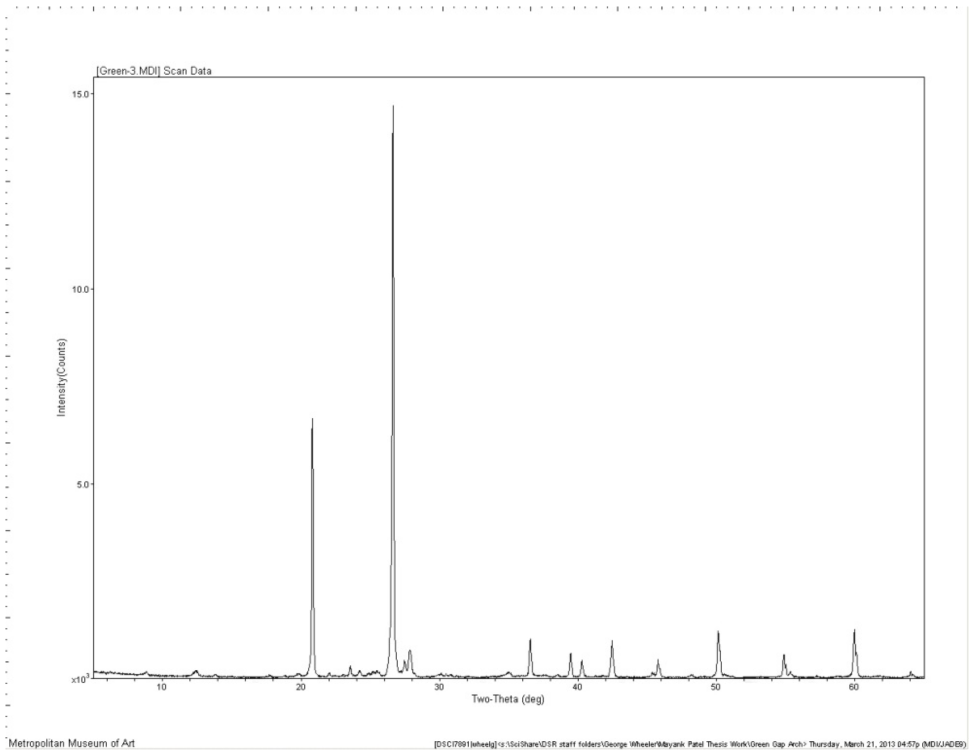
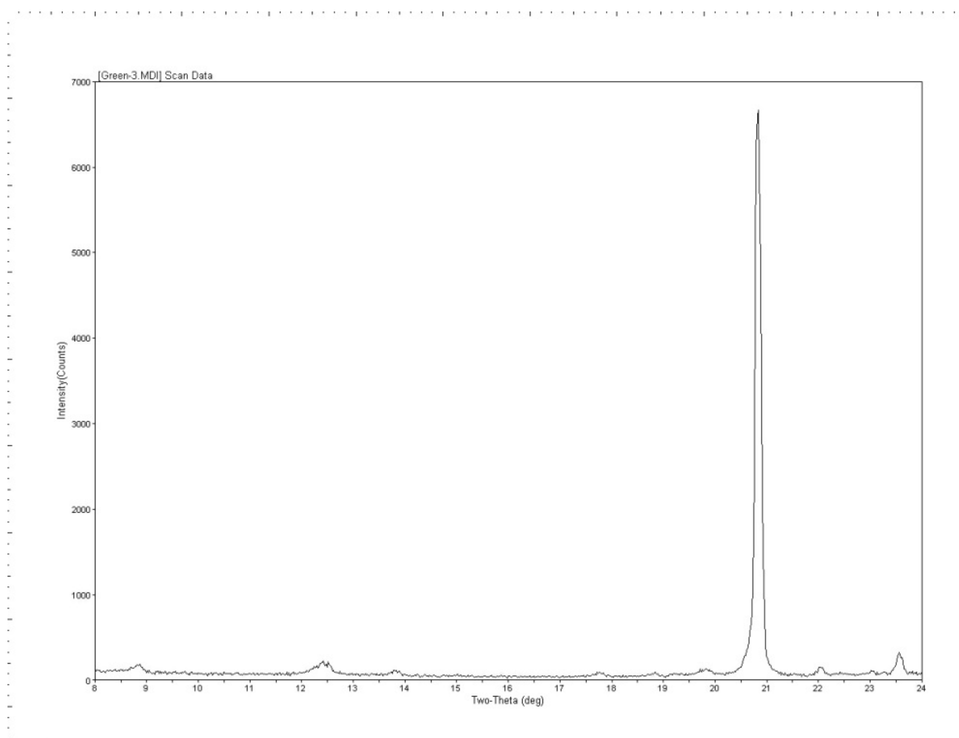
Green Gap Arch 2



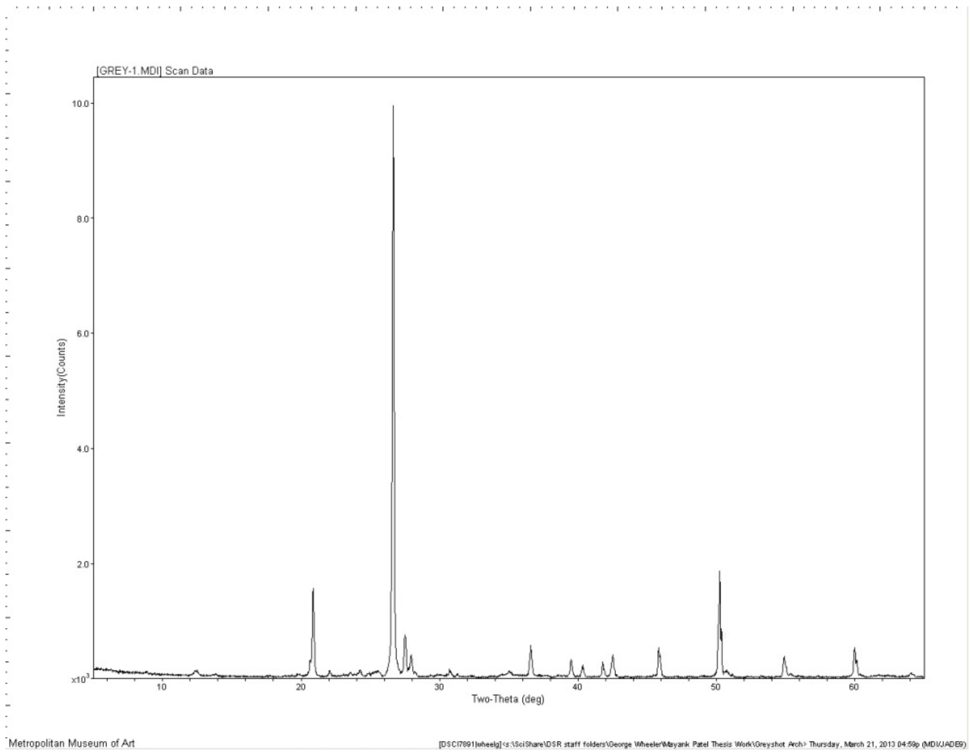


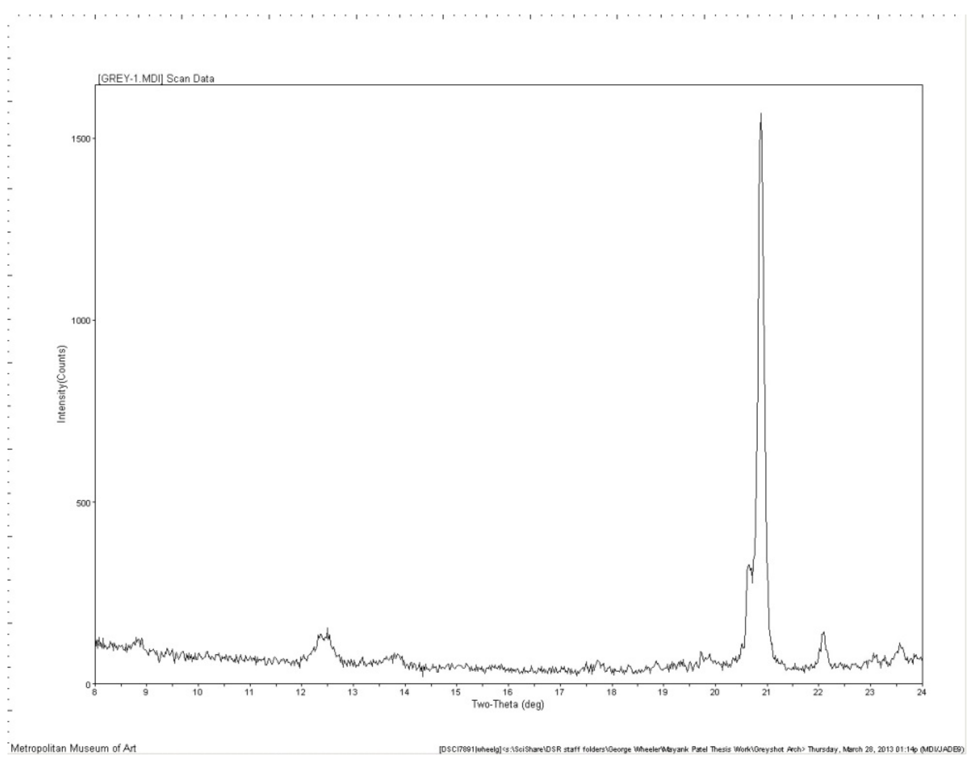
Green Gap Arch 3



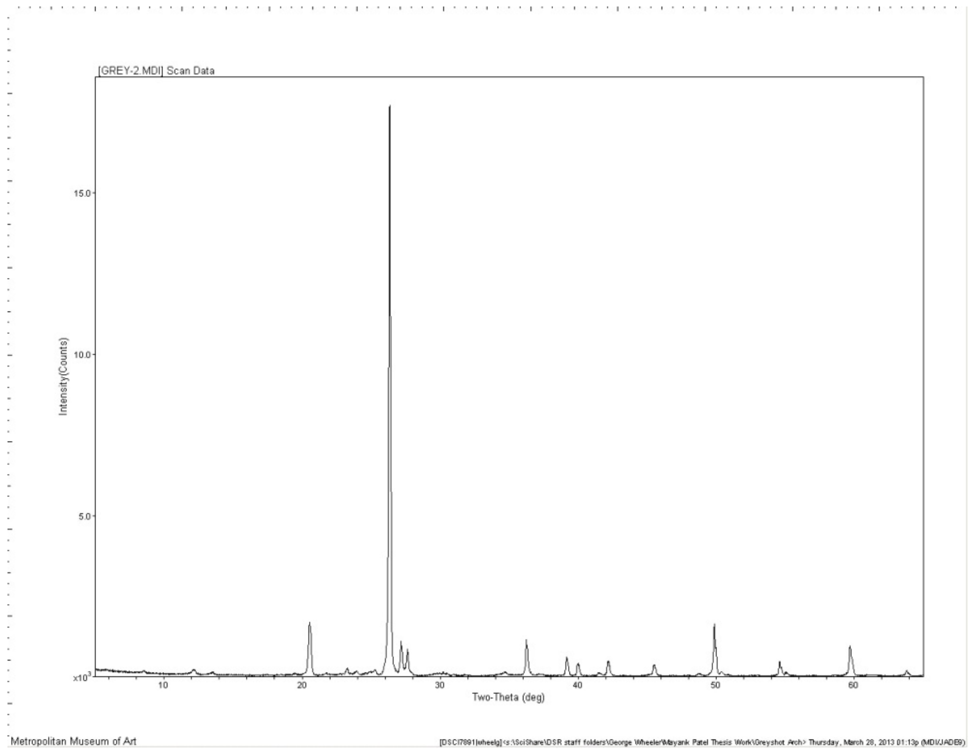


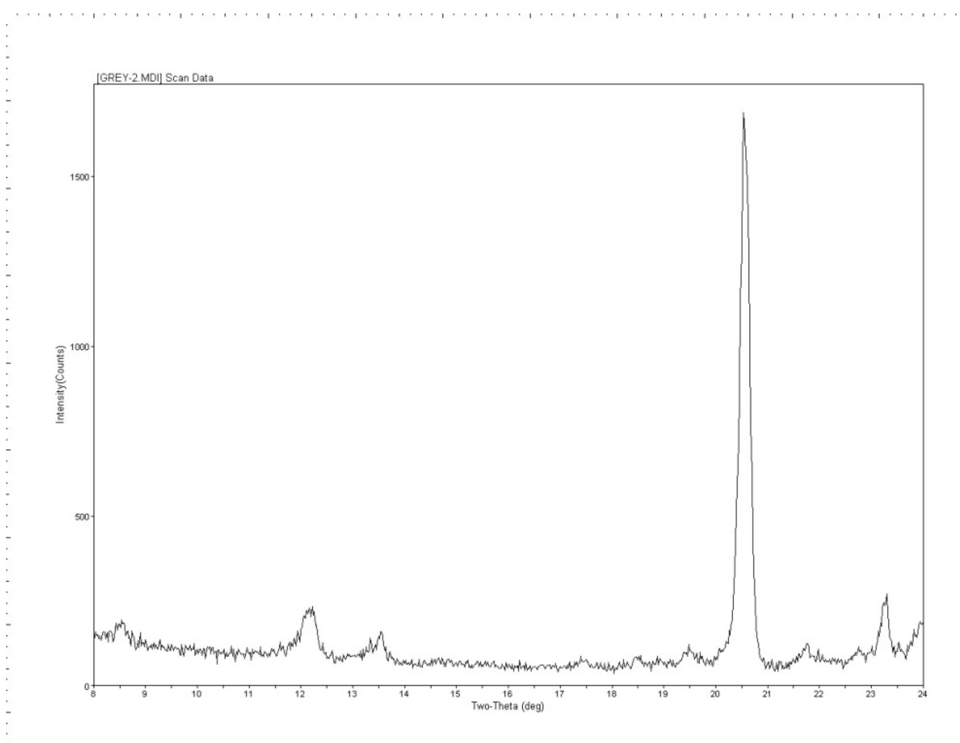
Greyshot Arch 1



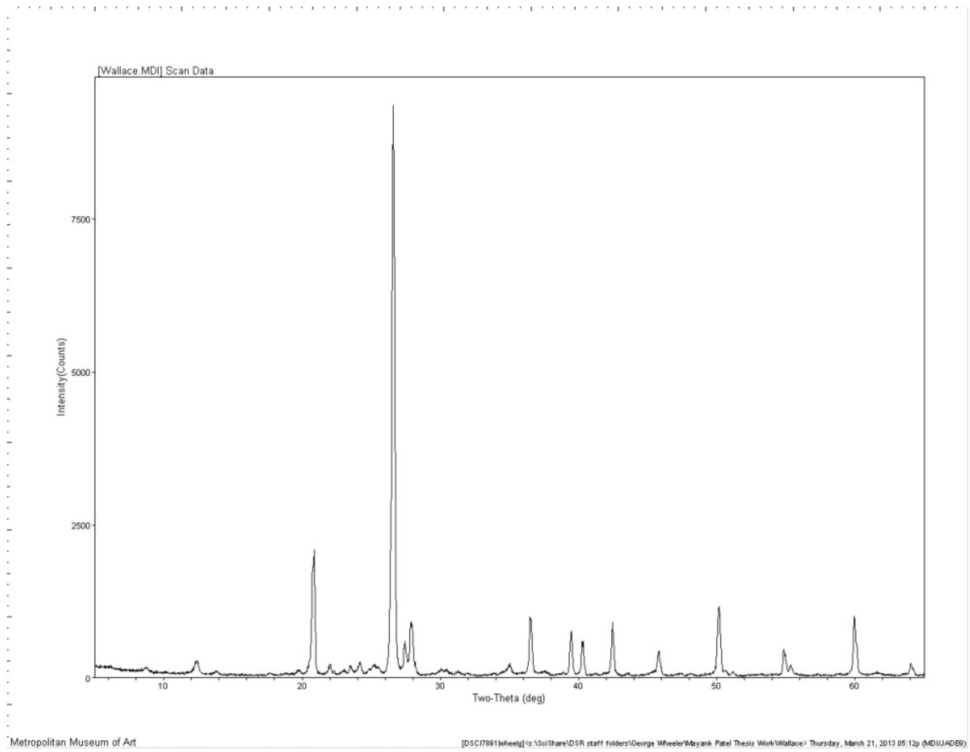


Greyshot Arch 2





Wallace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50
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Two-Theta (deg)
Metropolitan Museum of Art
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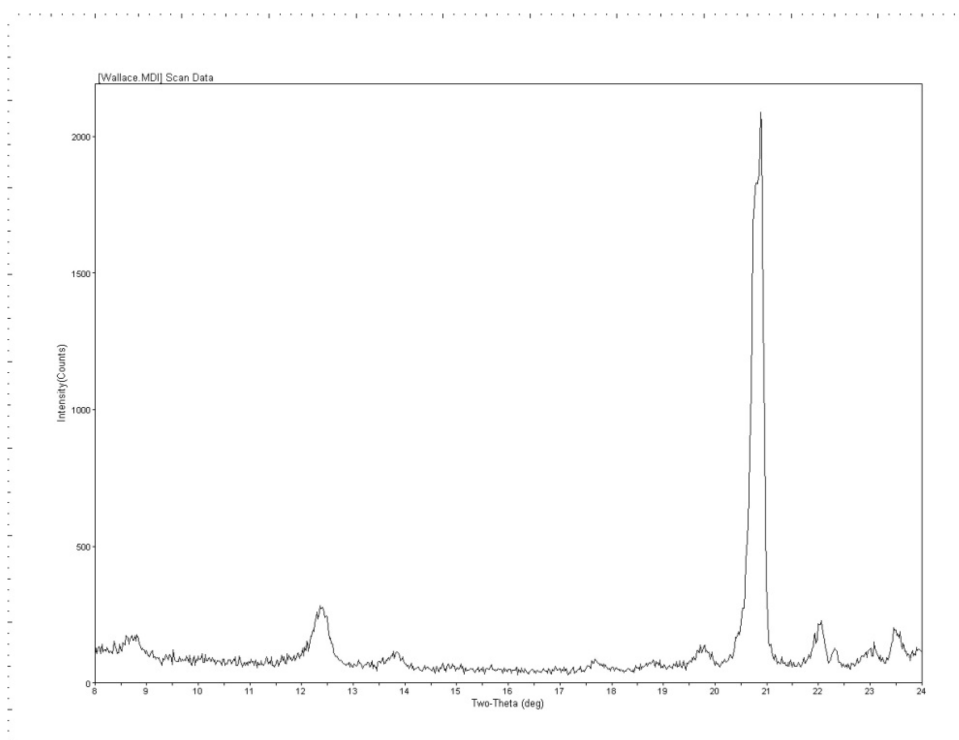
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21
22
23
24
Two-Theta (deg)
Metropolitan Museum of Art
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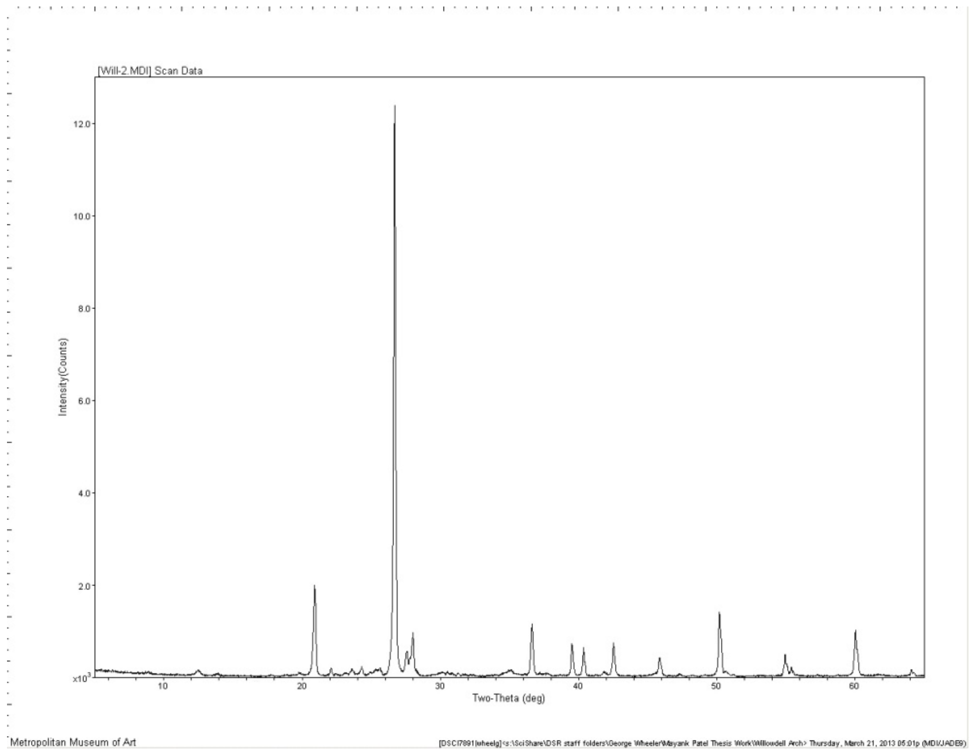
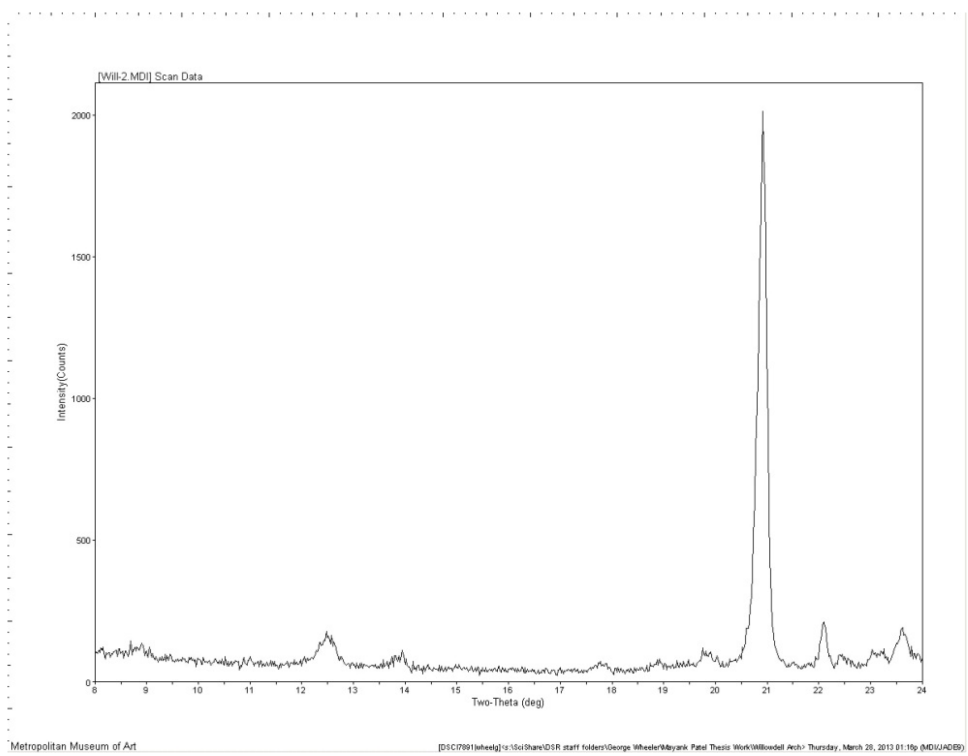
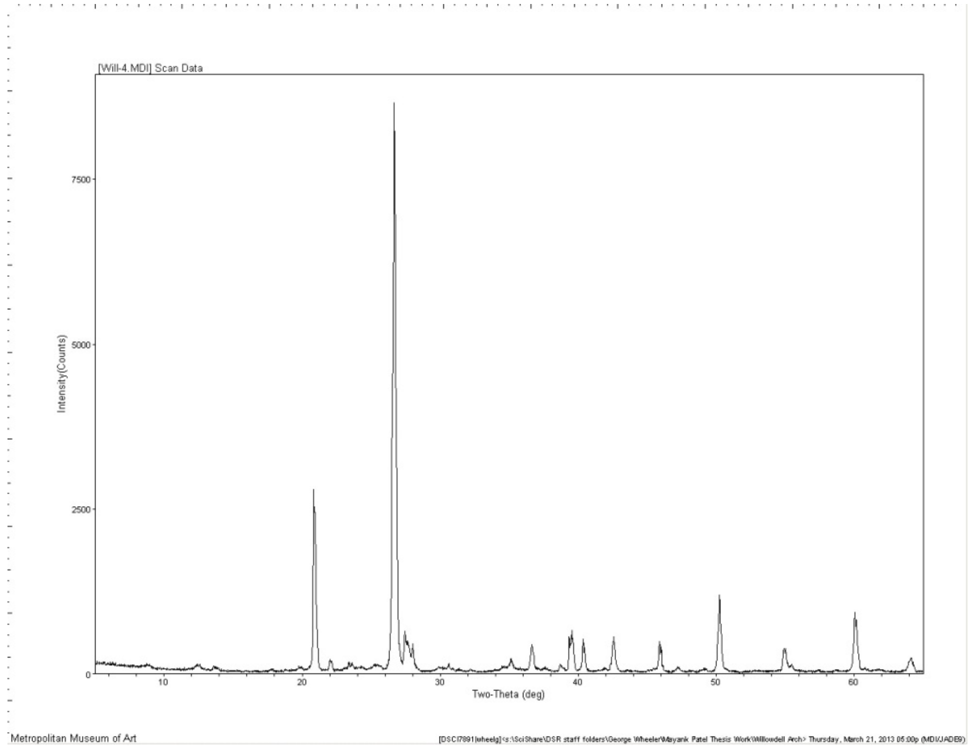
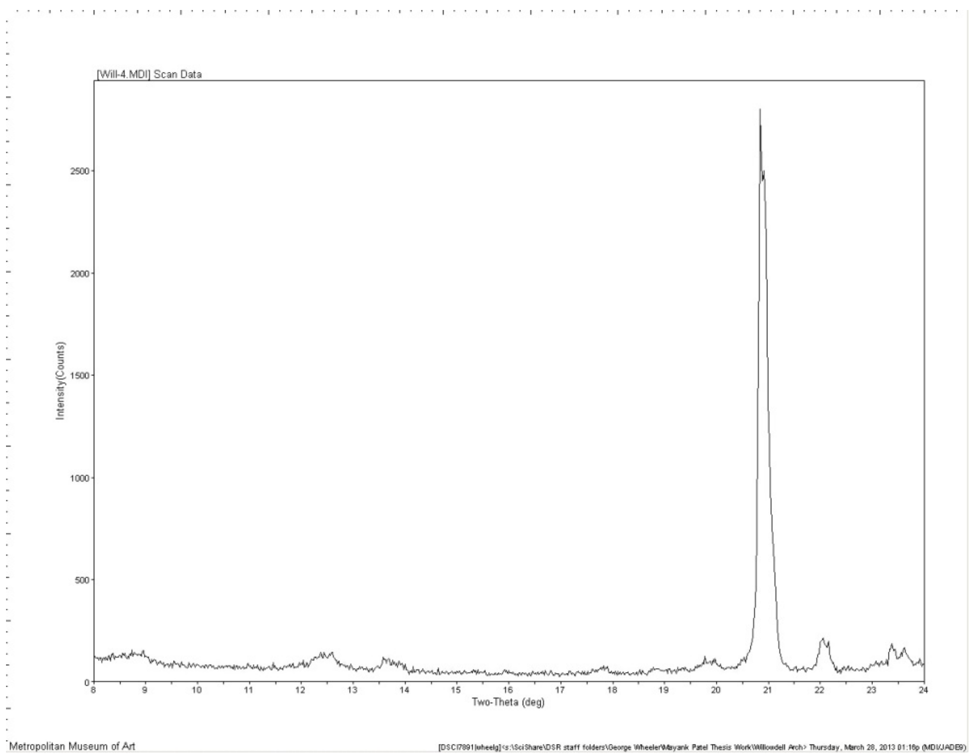
Willowdell Arch 2



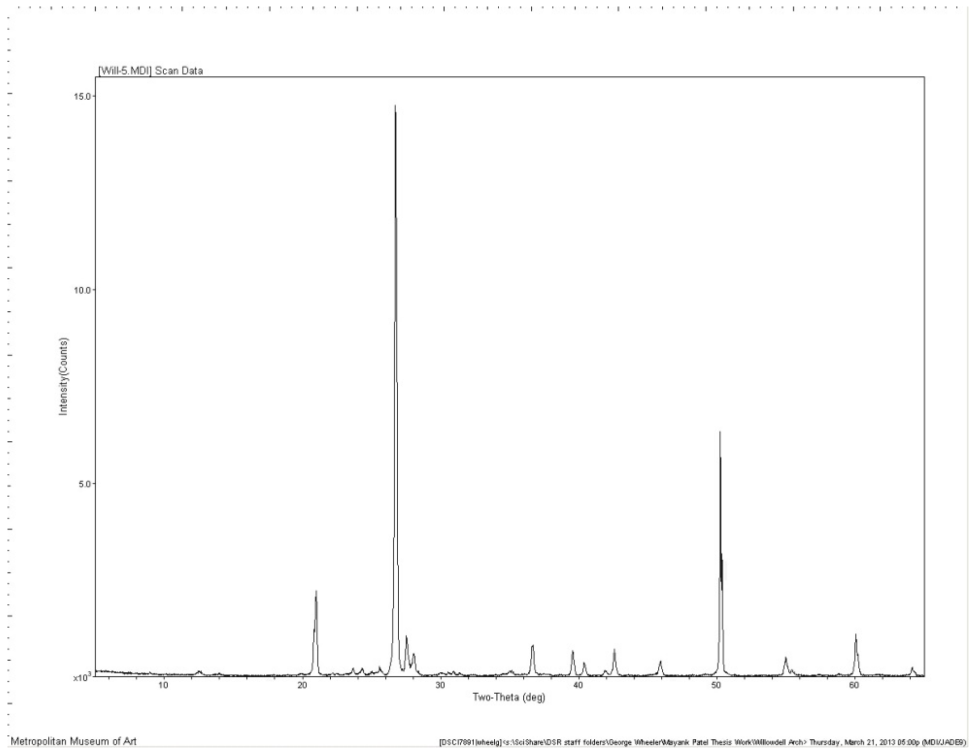


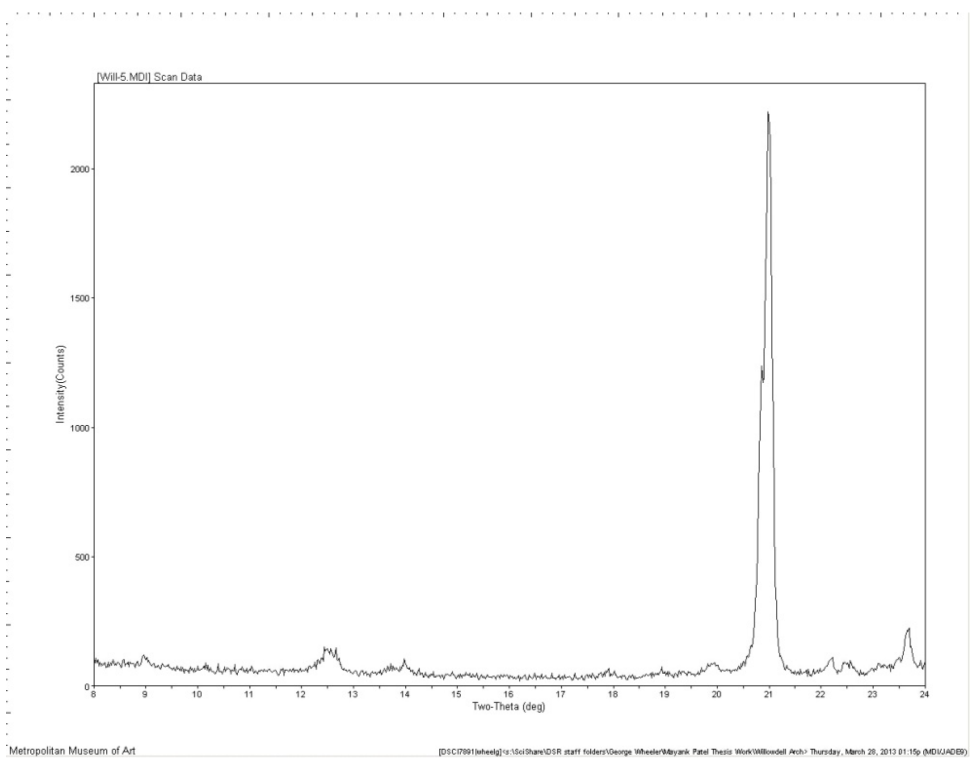
Willowdell Arch 4



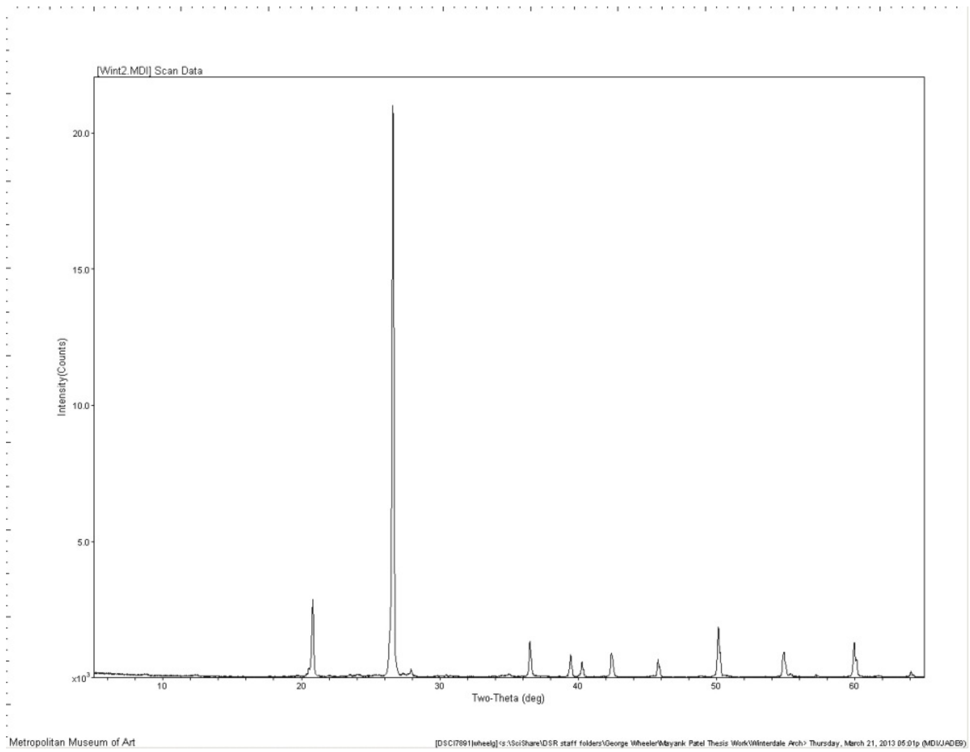


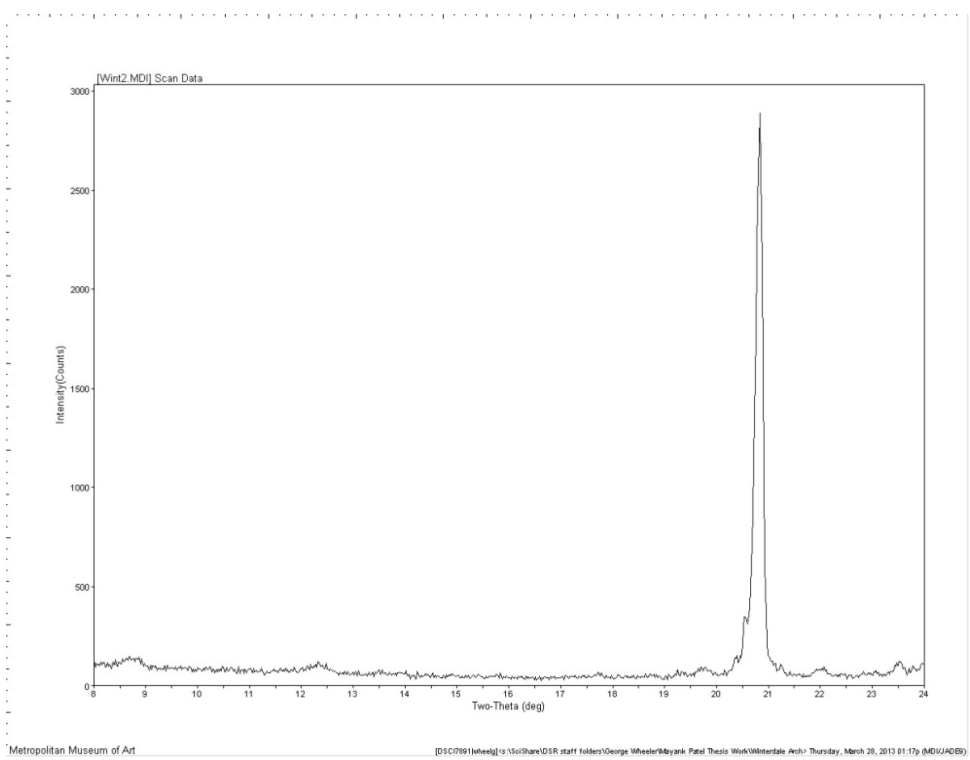
Willowdell Arch 5



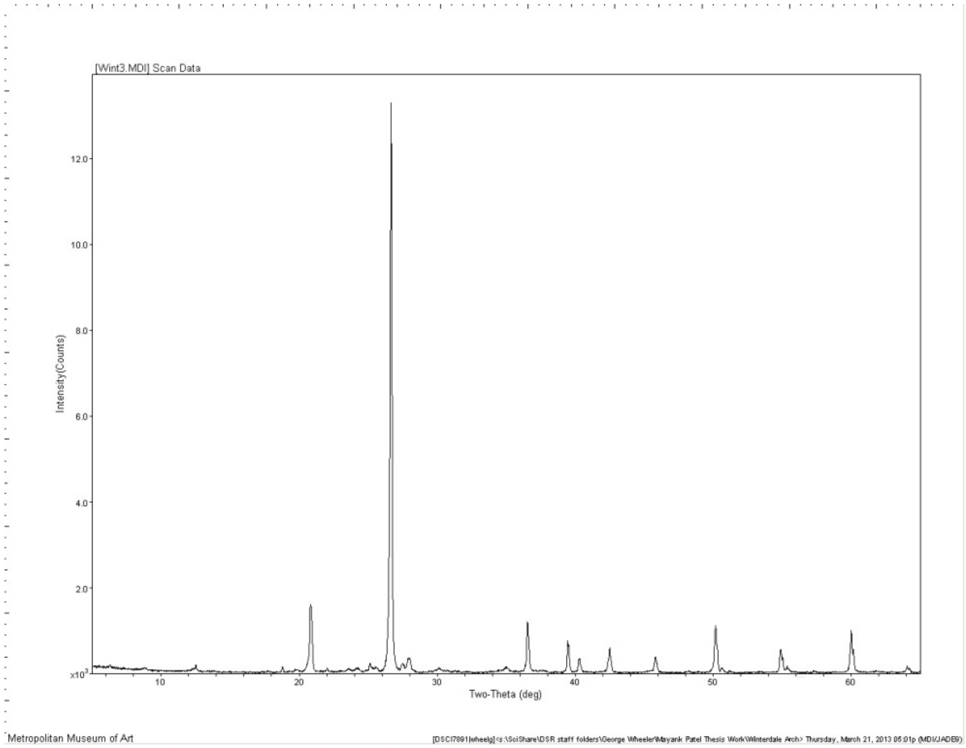


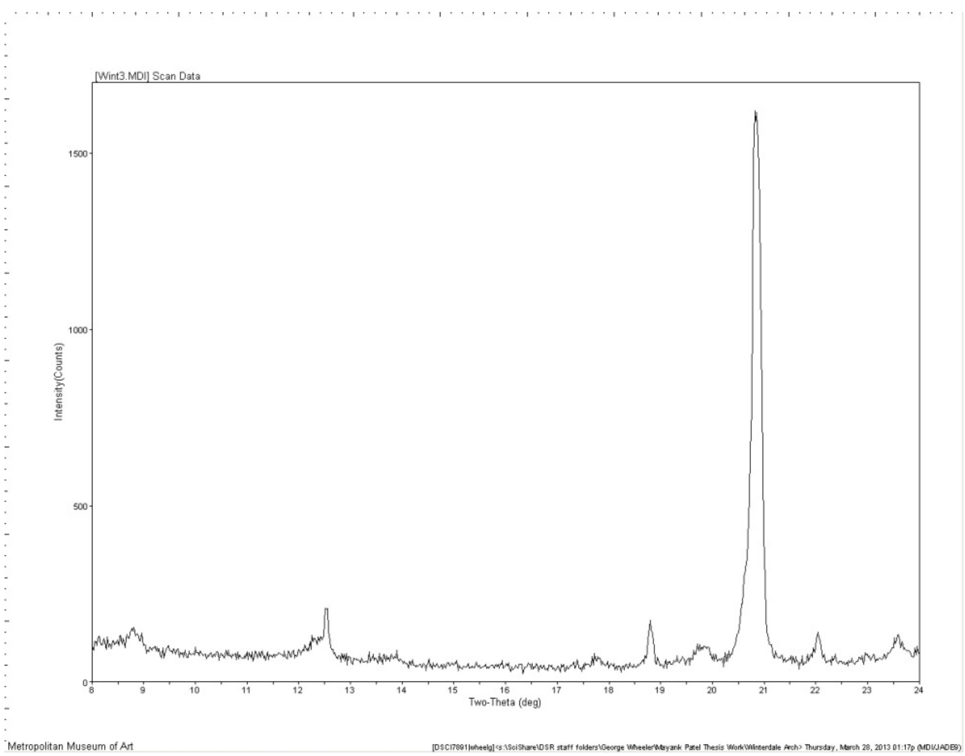
Winterdale Arch 2





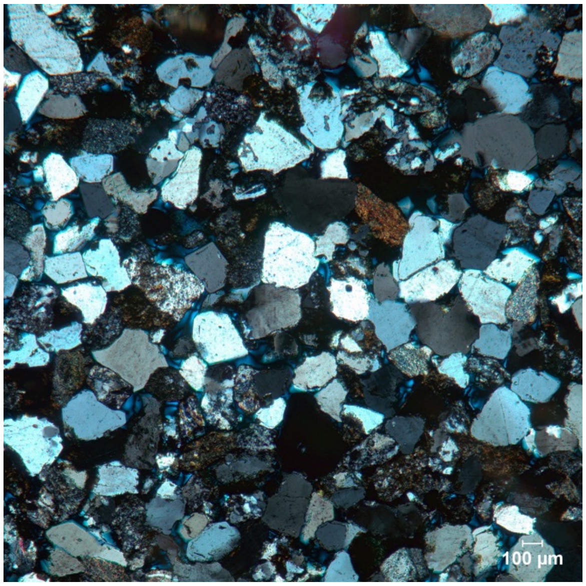
Winterdale Arch 3



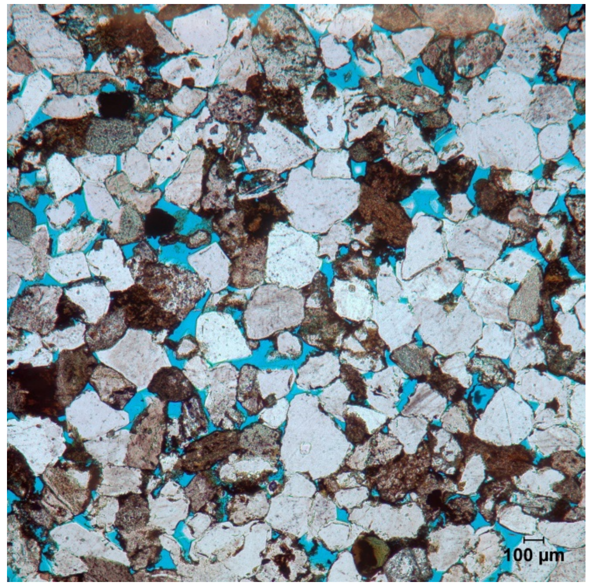


APPENDIX E: Thin Section Images

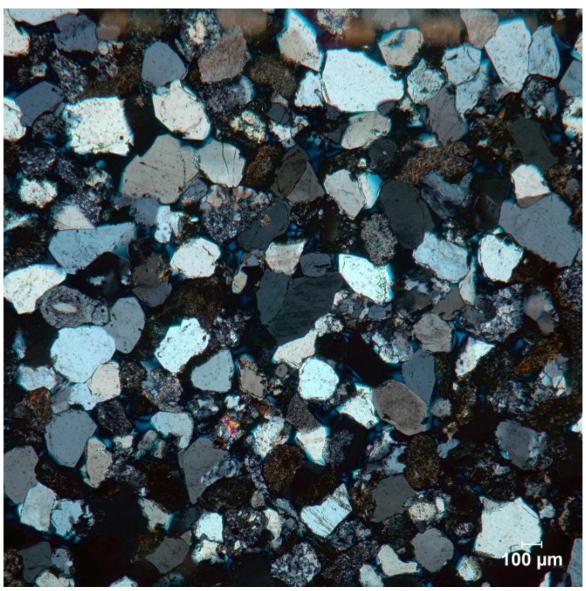
Balcony Bridge 1



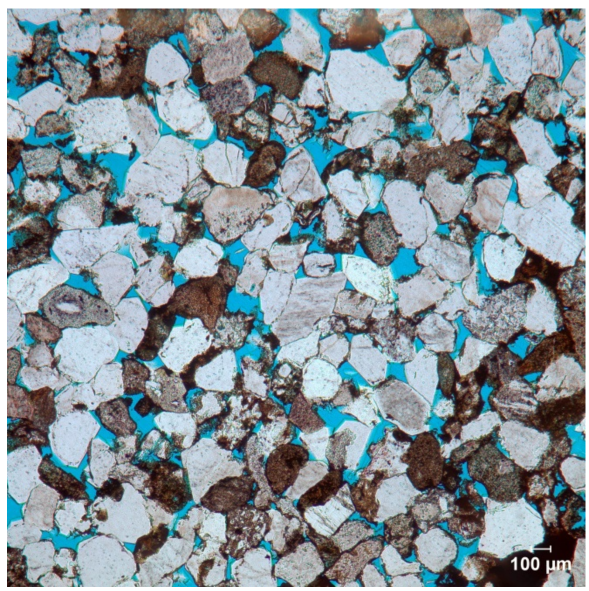
Balcony Bridge 1 [5X, cross-polarized light (XPL)]



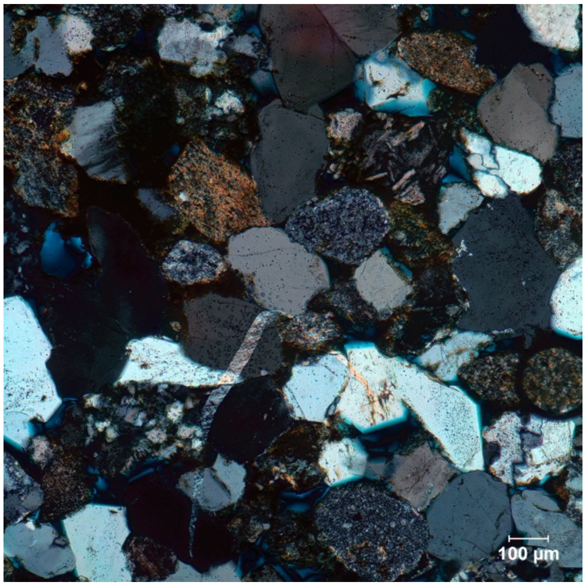
Balcony Bridge 1 [5X, plane-polarized light (PPL)]



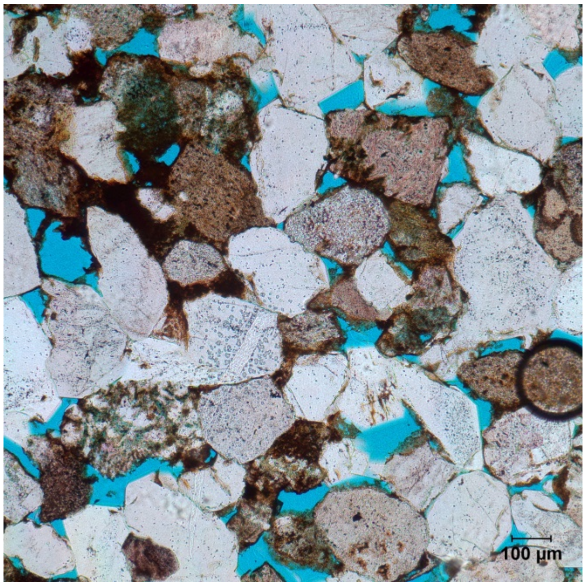
Balcony Bridge 1 (5X, XPL)



Balcony Bridge 1 (5X, PPL)



Balcony Bridge 1 (10X, XPL)



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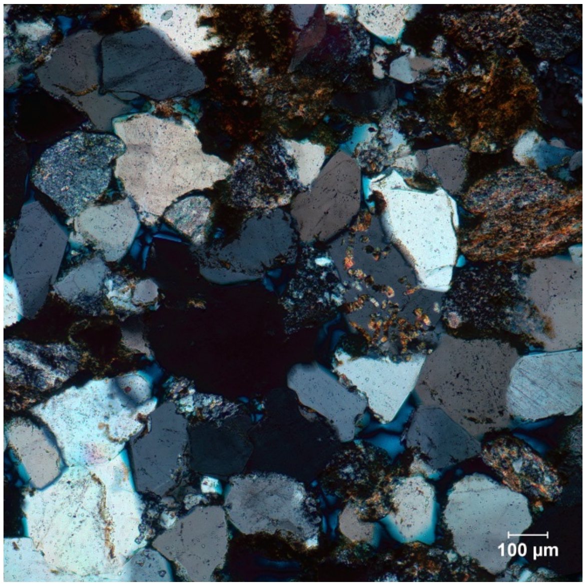

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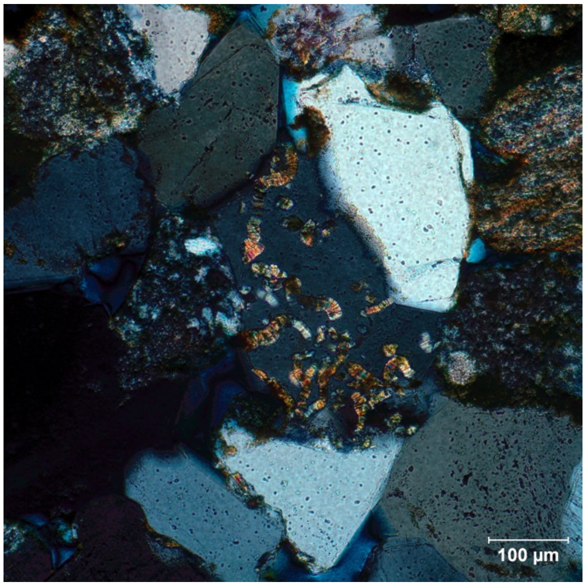
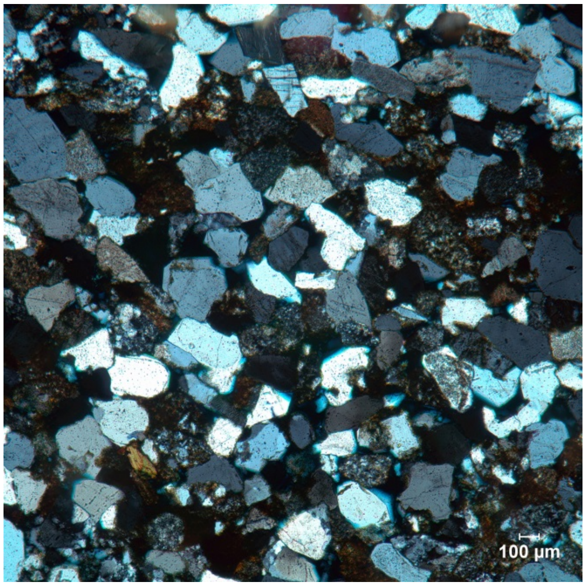
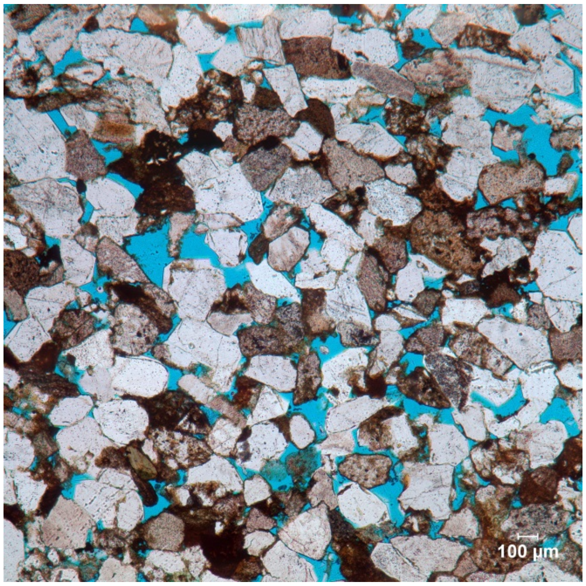


Balcony Bridge 1 (20X, XPL)

Balcony Bridge 2



Balcony Bridge 2 (5X, XPL)



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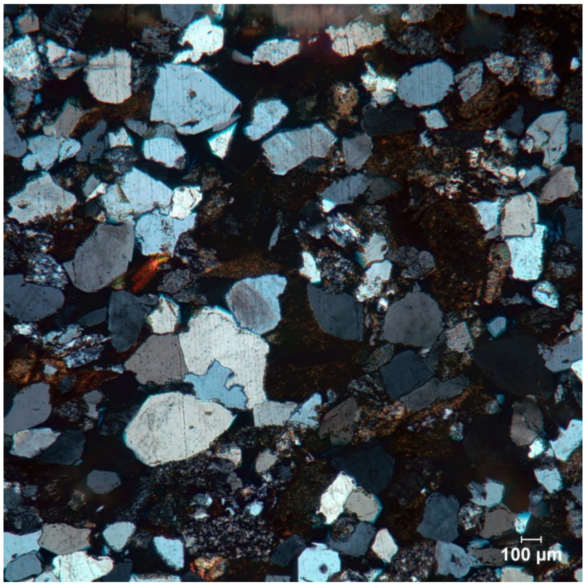

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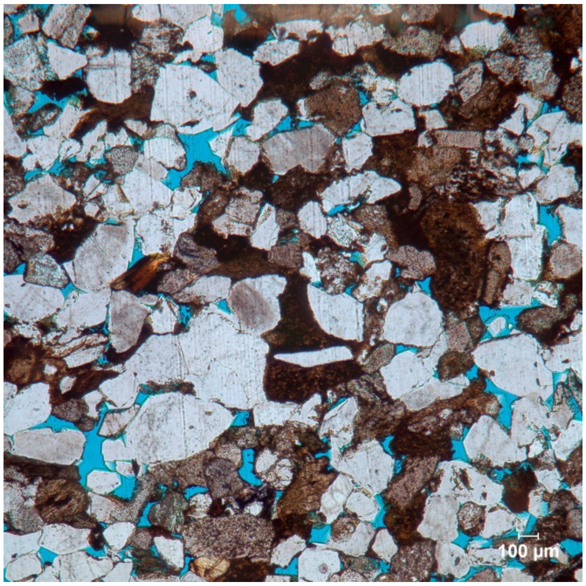

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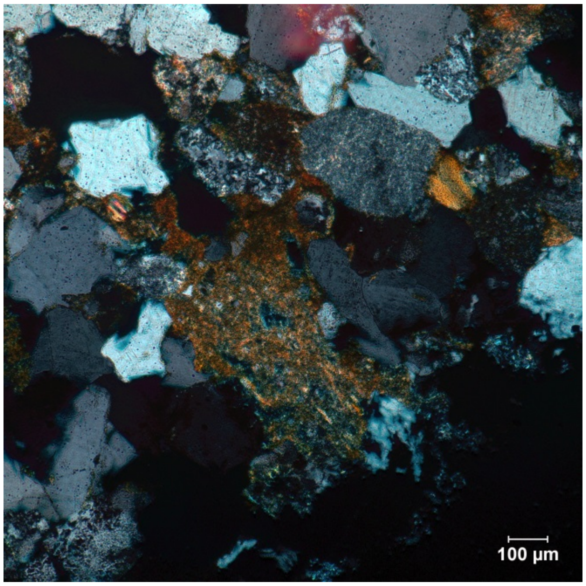
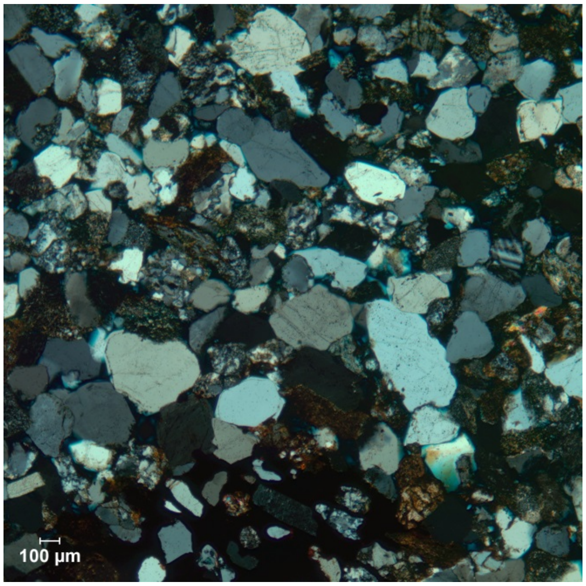
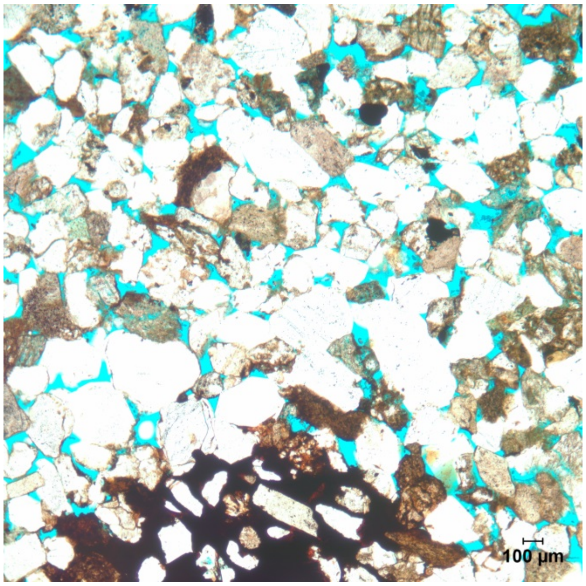


Balcony Bridge 2 (510X, XPL)

Bethesda Terrace 1



Bethesda Terrace 1 (5X, XPL)



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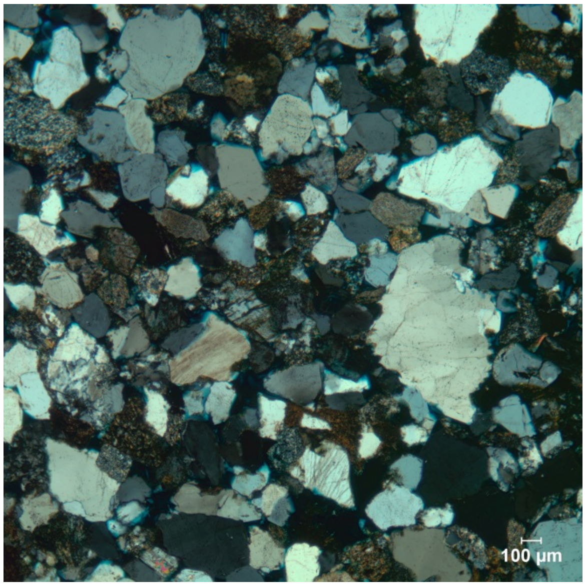

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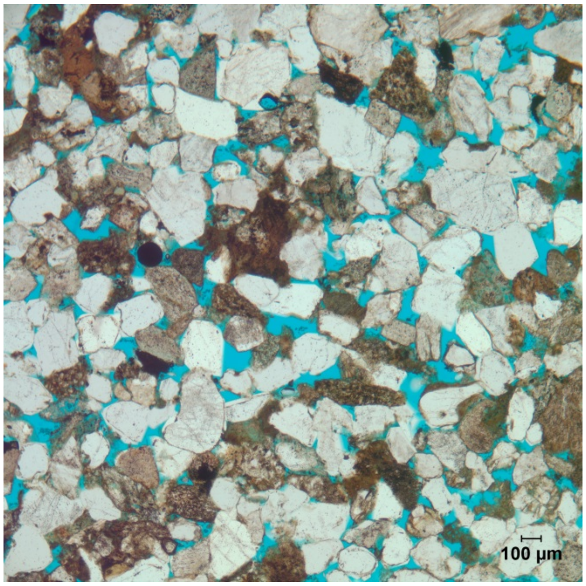

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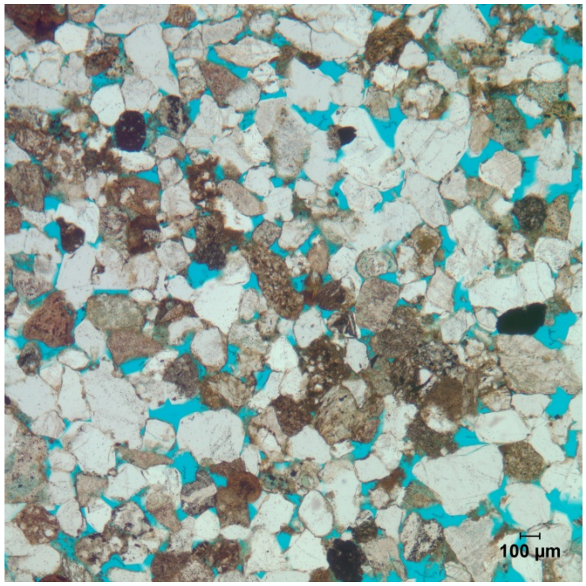
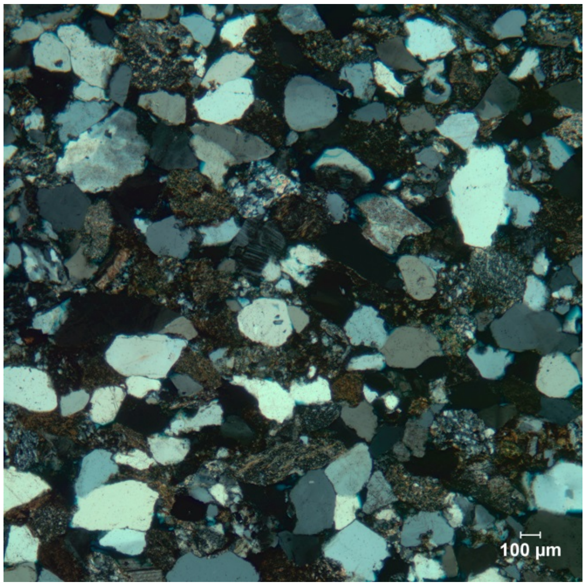


Bethesda Terrace 1 (5X, PPL)

Bethesda Terrace 2



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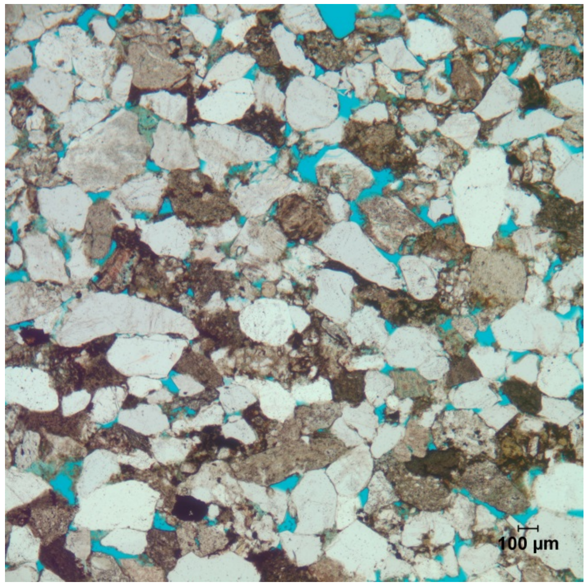

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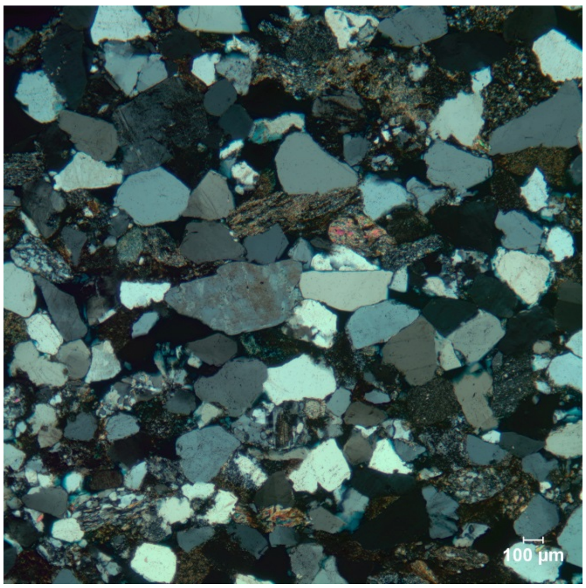

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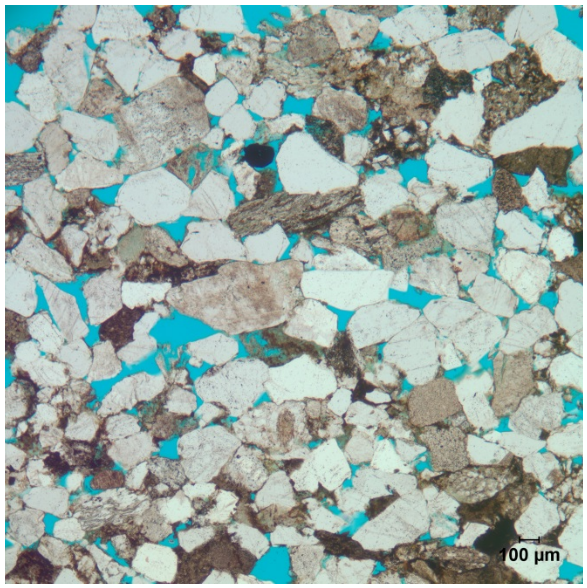

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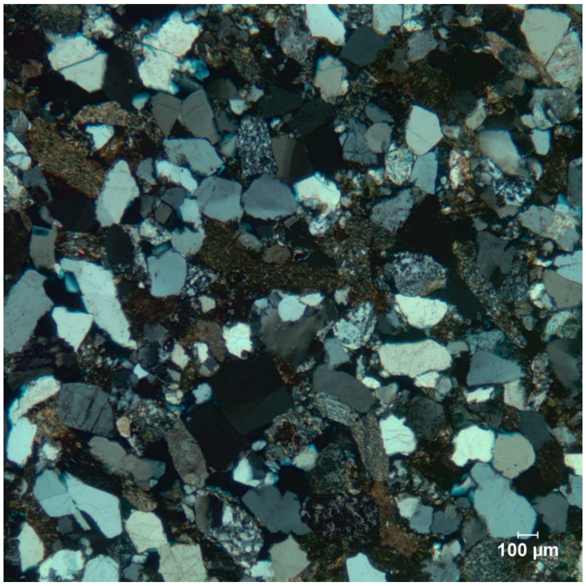

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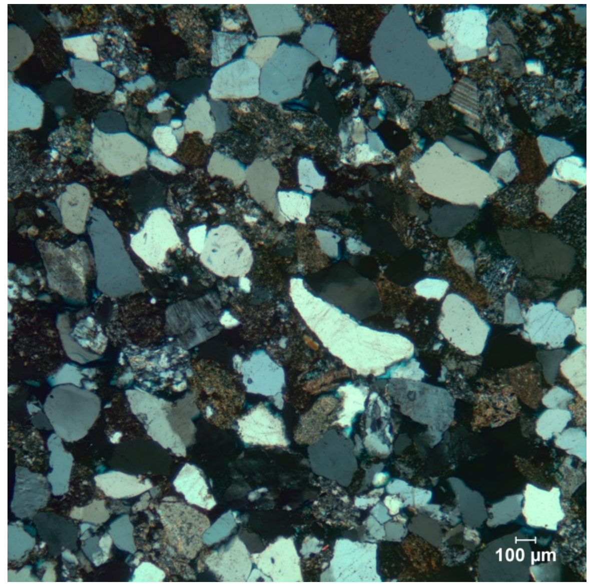
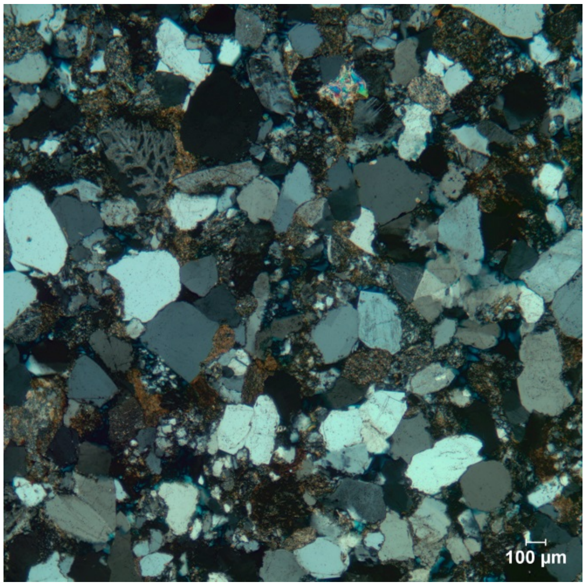


Bethesda Terrace 2 (5X, XPL)

Bethesda Terrace 6



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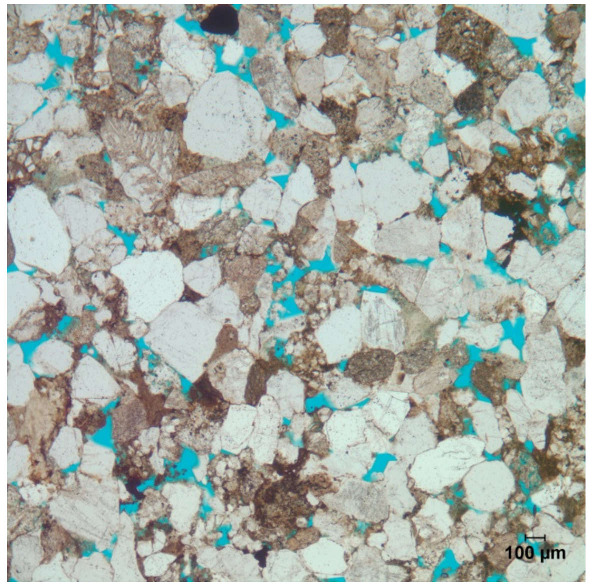

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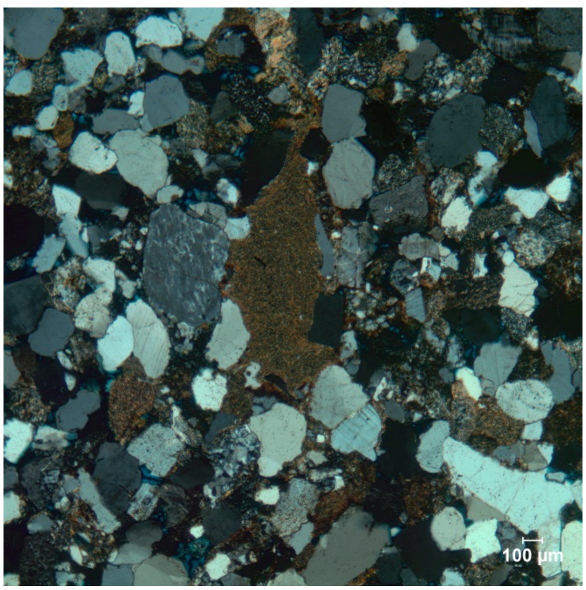

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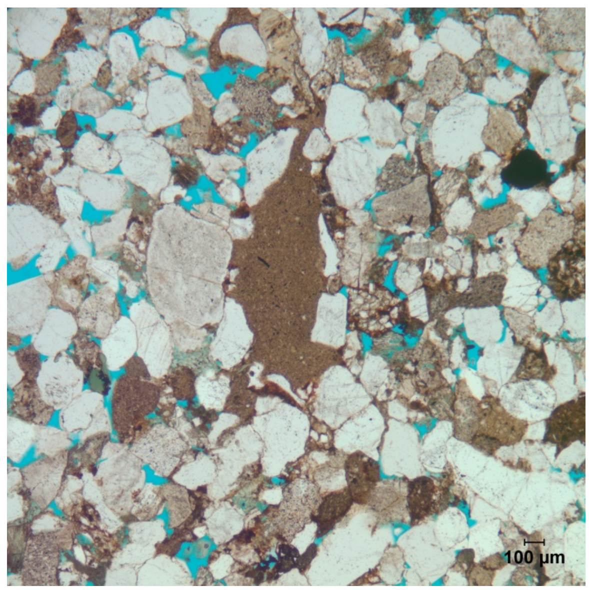

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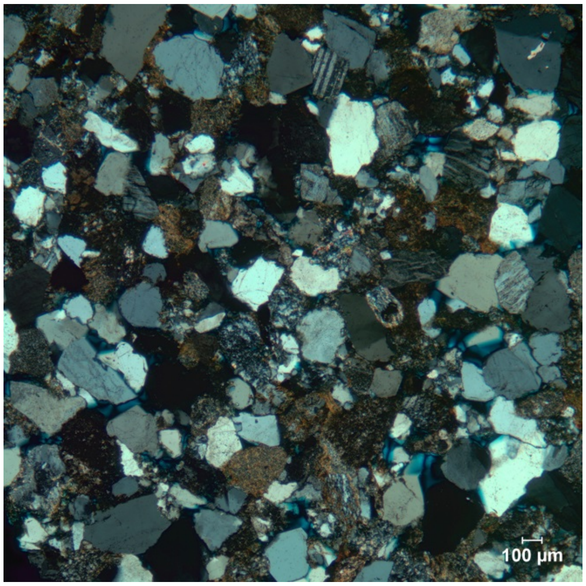

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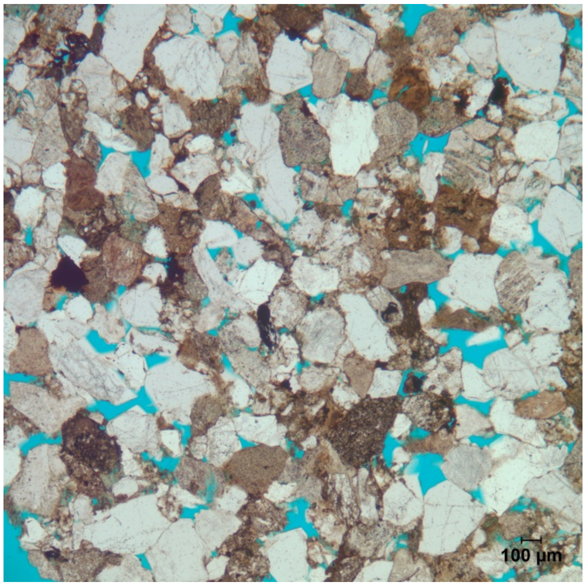

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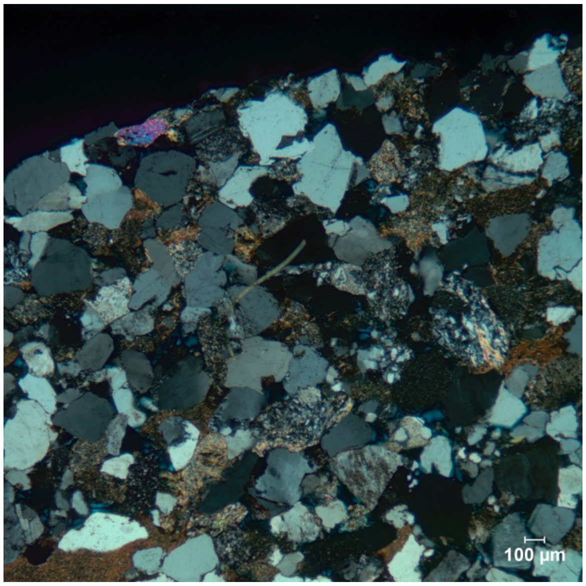

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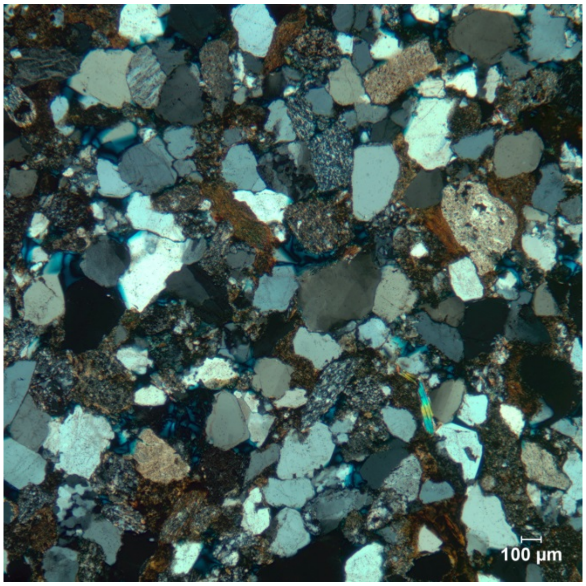
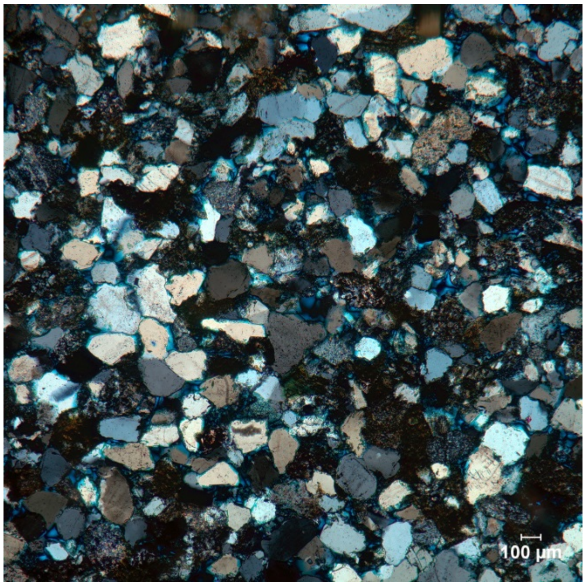


Bethesda Terrace 6 (5X, XPL)

Bethesda Terrace 9



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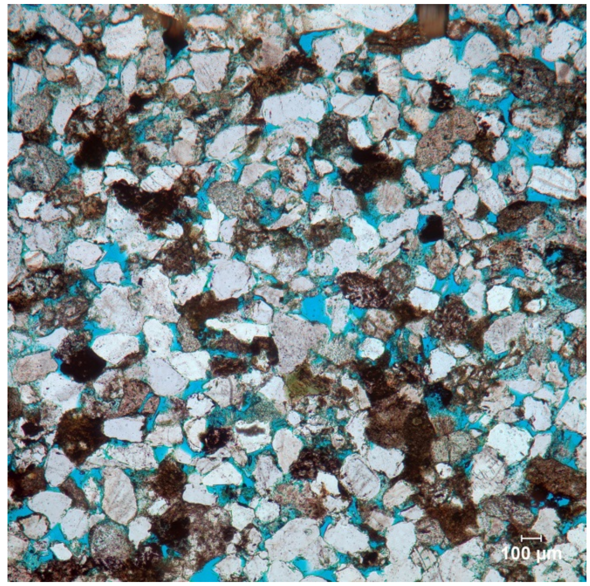

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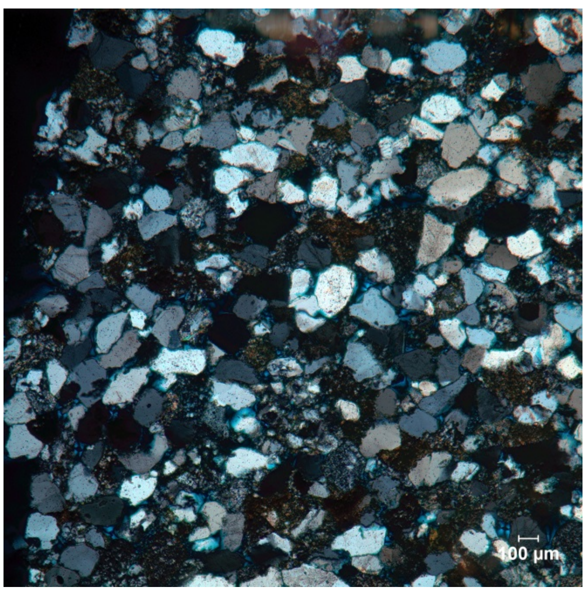

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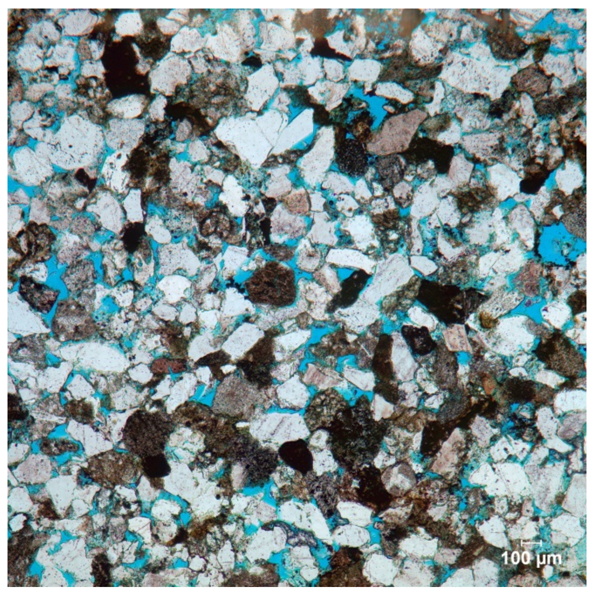

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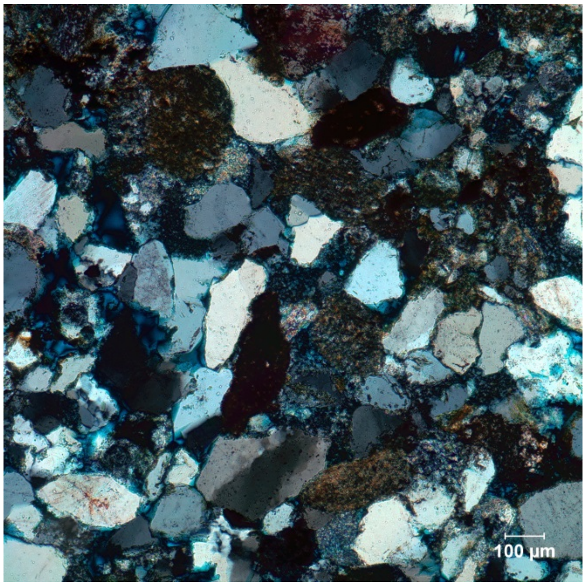

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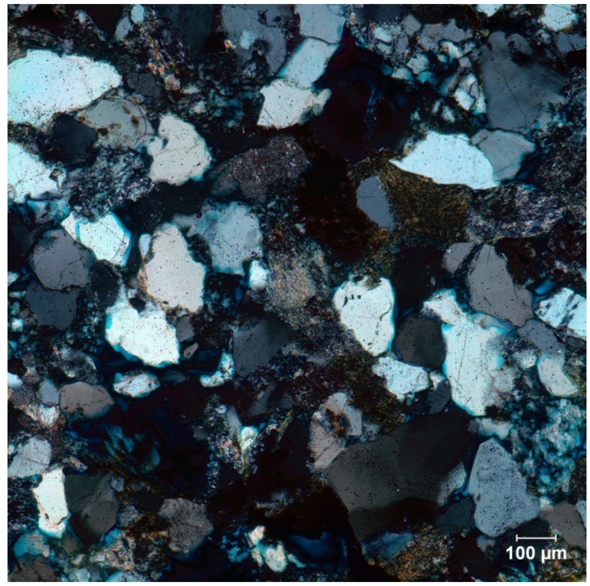
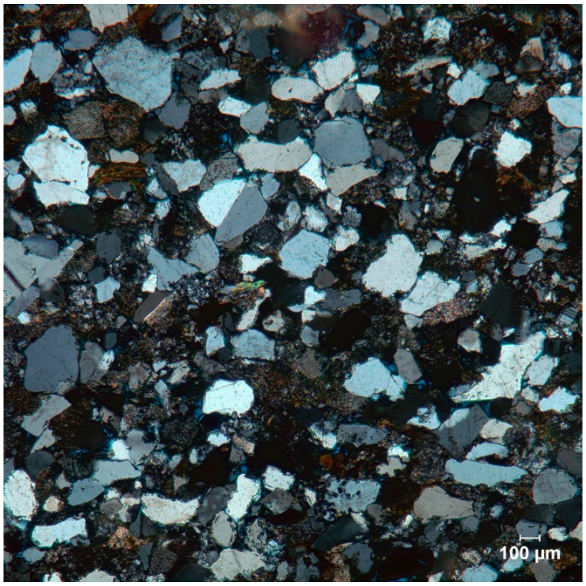


Bethesda Terrace 9 (10X, XPL)

Bethesda Terrace 10



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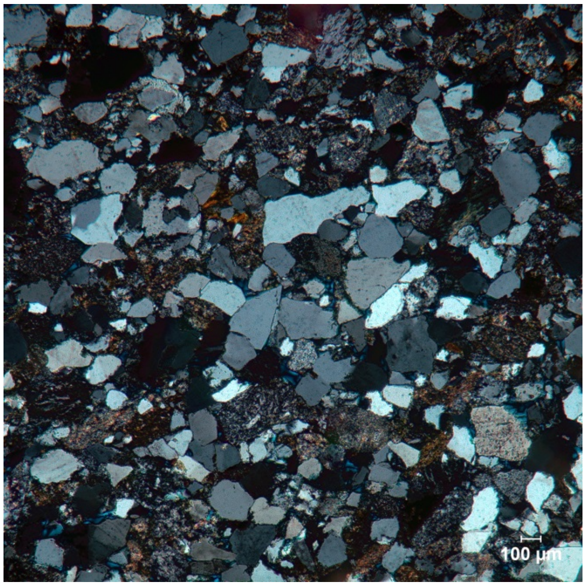

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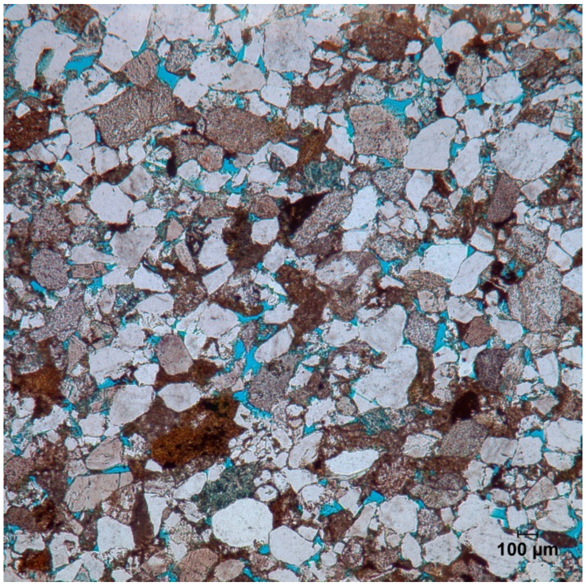

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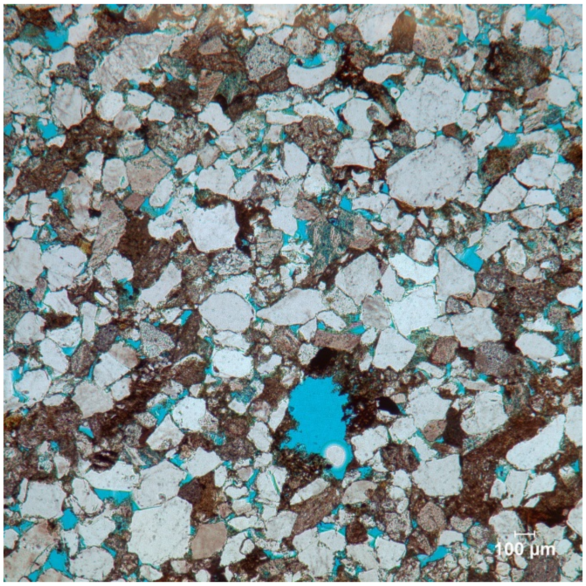

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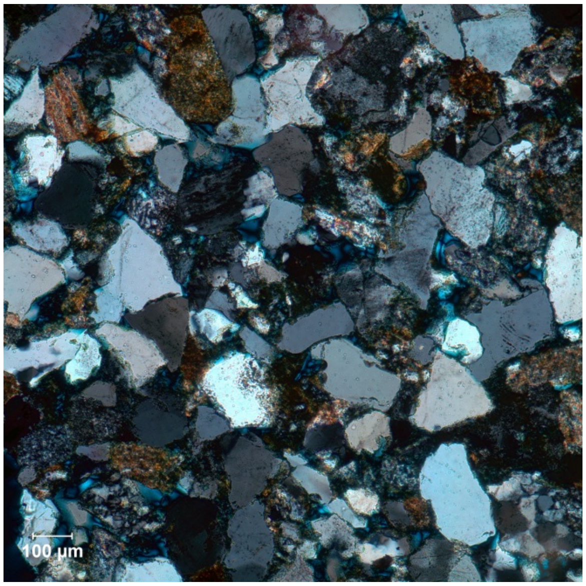

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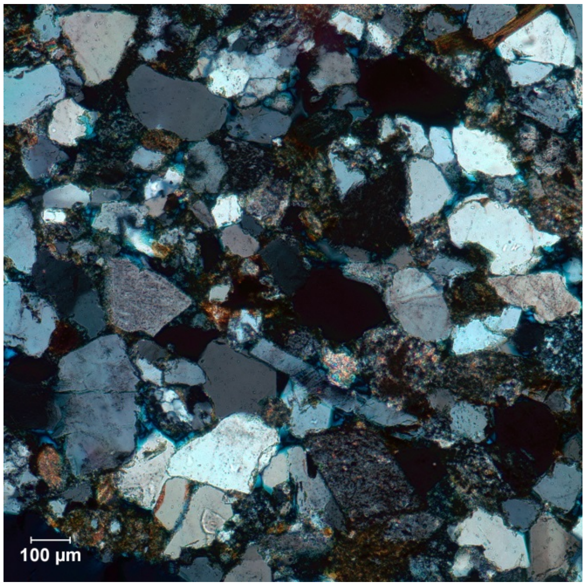

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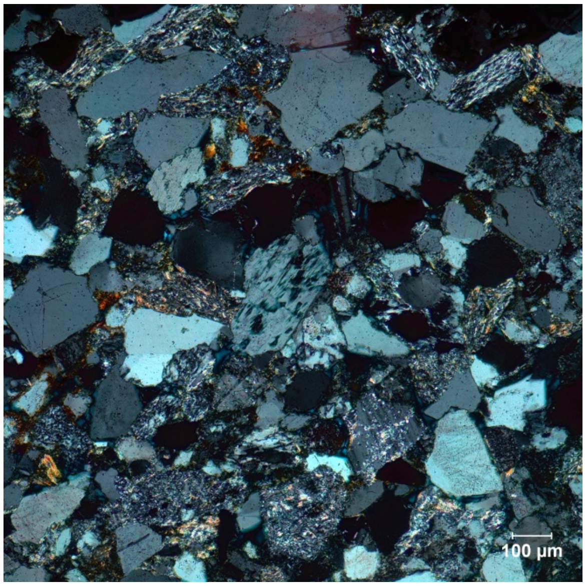
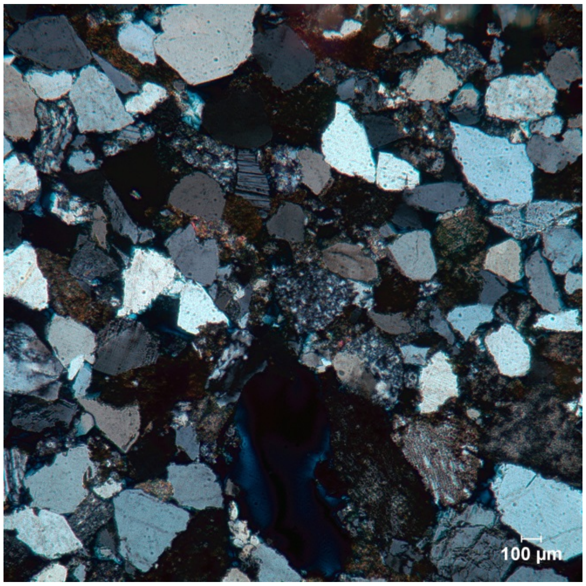
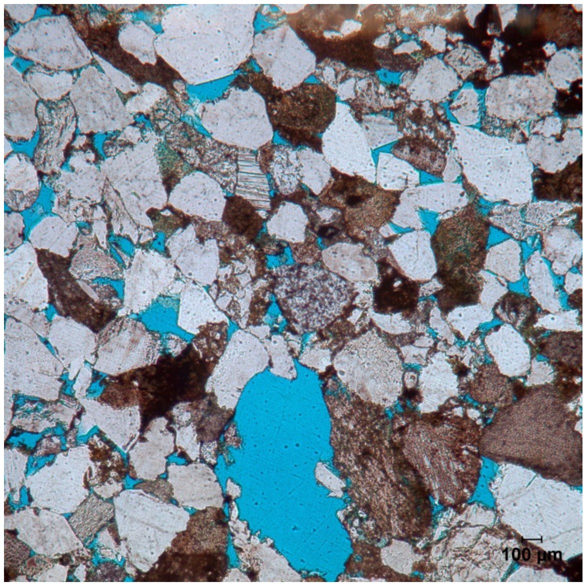


Bethesda Terrace 10 (10X, XPL)

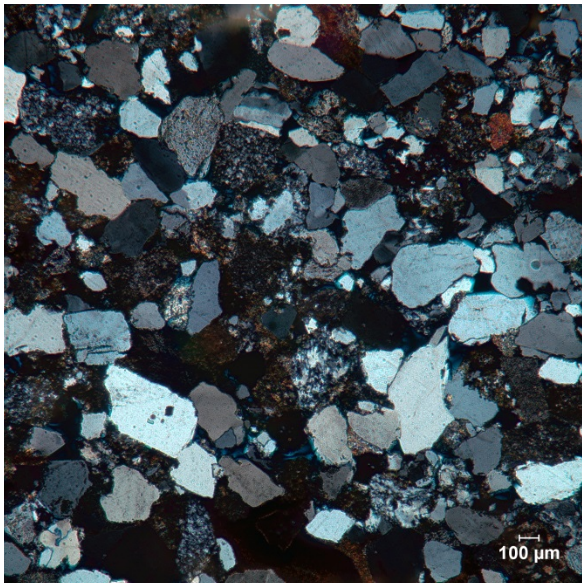
Dalehead Arch 4



Dalehead Arch 4 (5X, XPL)



Dalehead Arch 4 (5X, PPL)



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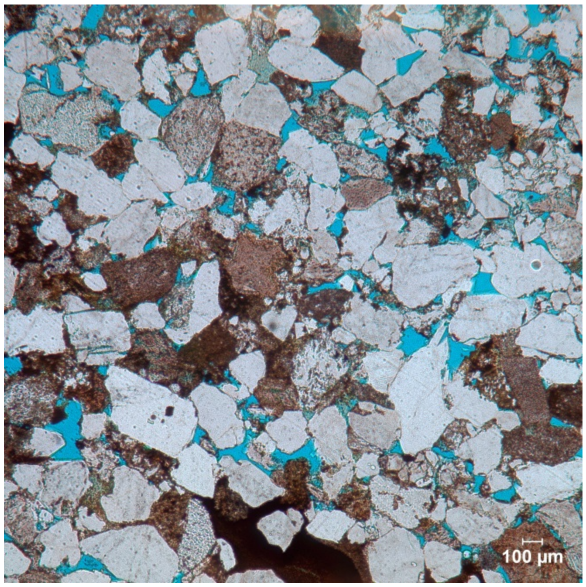
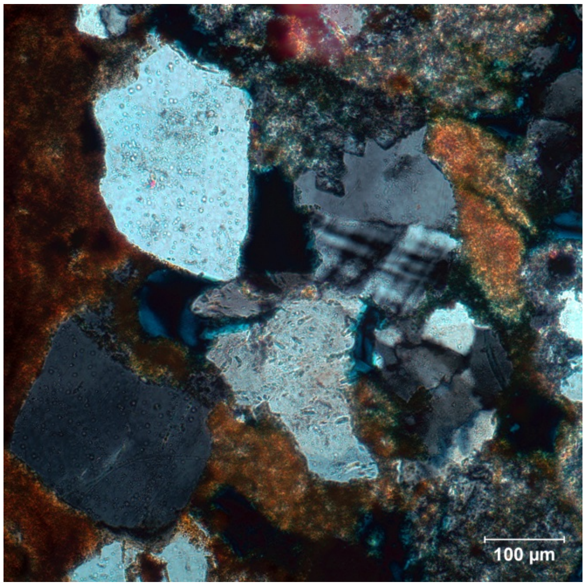
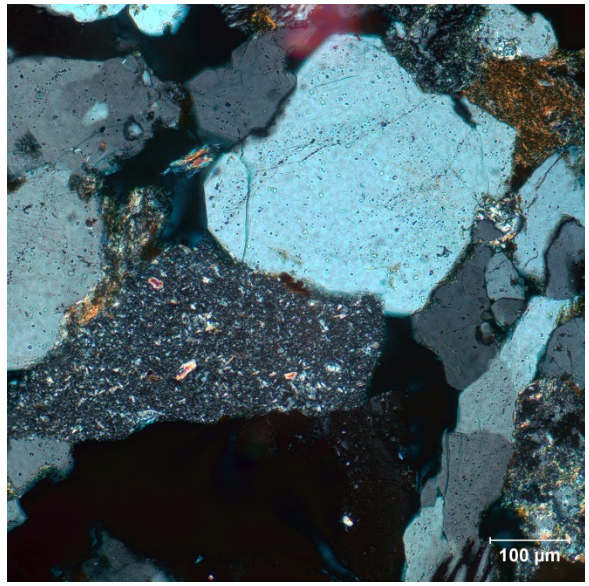


Dalehead Arch 4 (5X, PPL)



Dalehead Arch 4 (20X, XPL)



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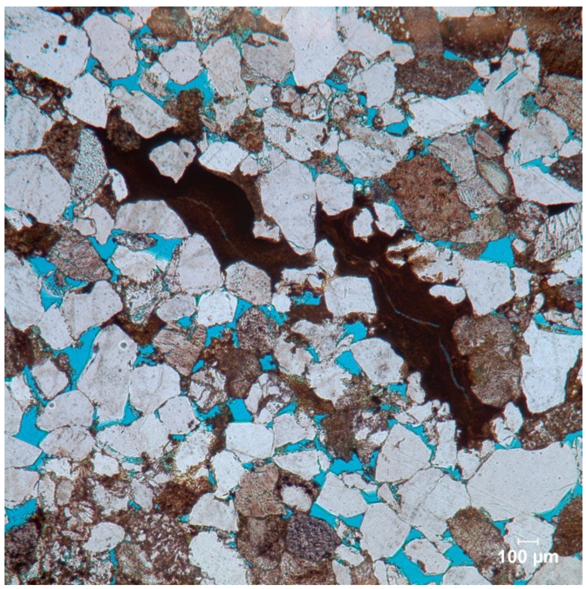
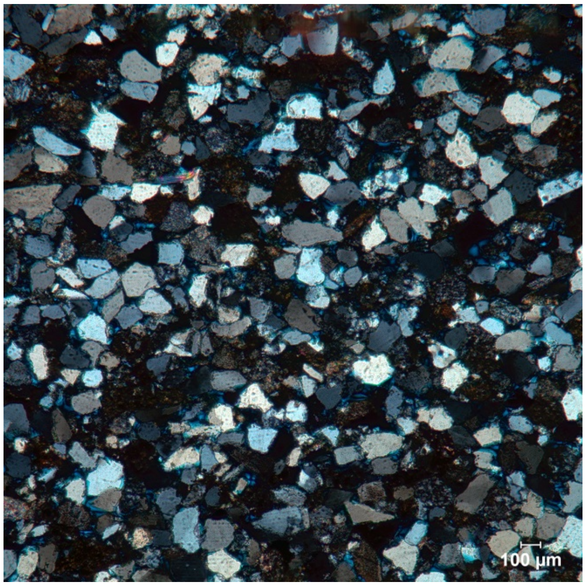


Dalehead Arch 4 (5X, PPL)

Dalehead Arch 5



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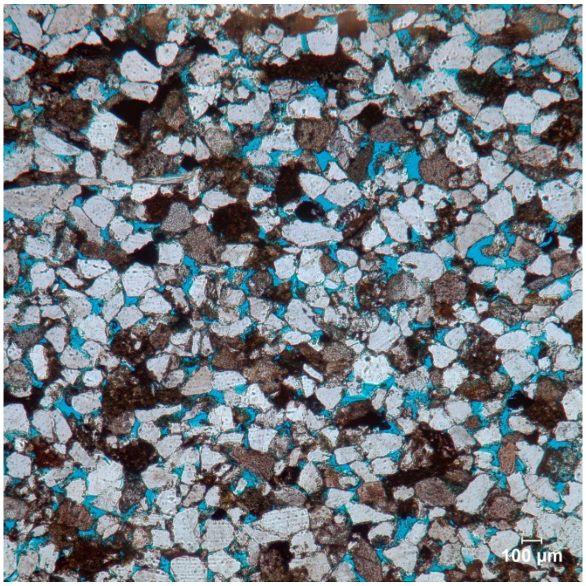

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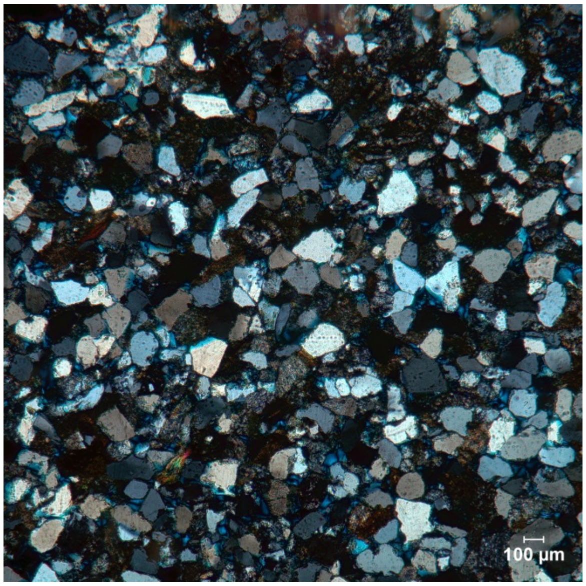

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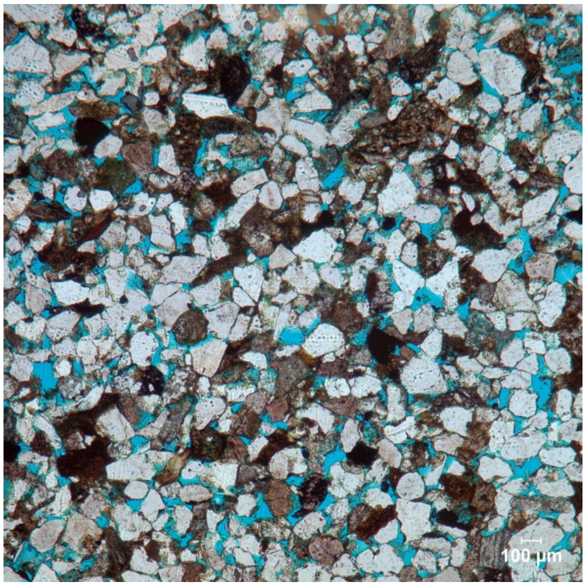

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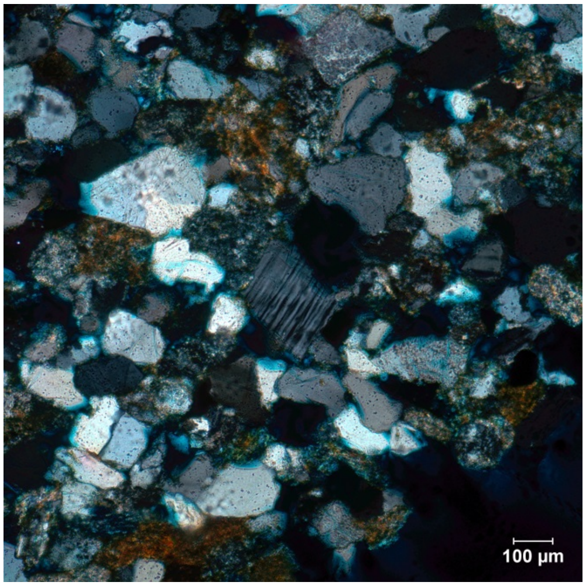

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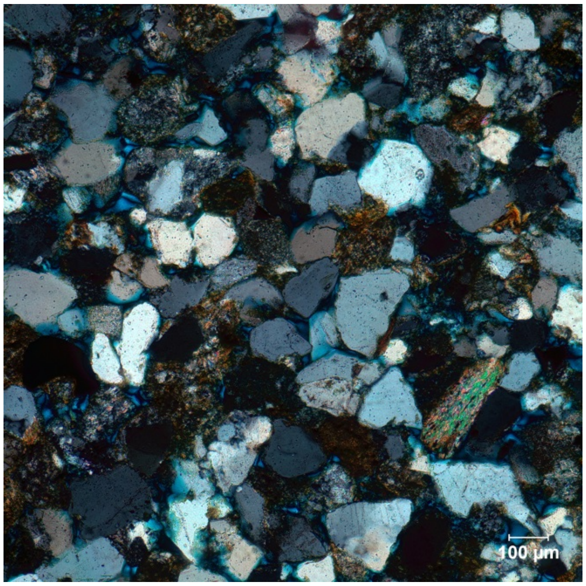
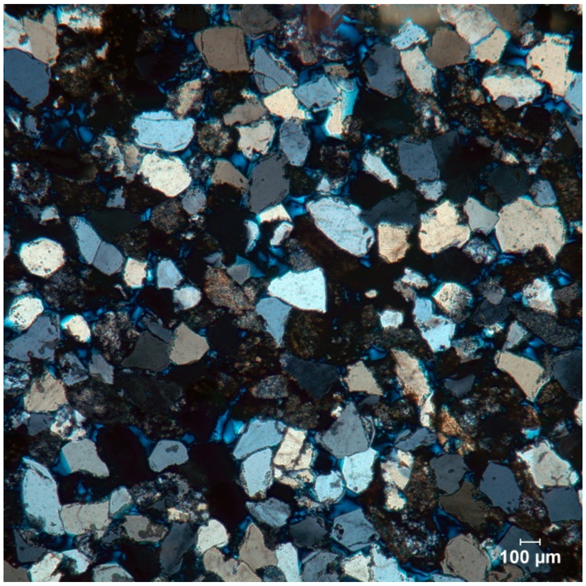
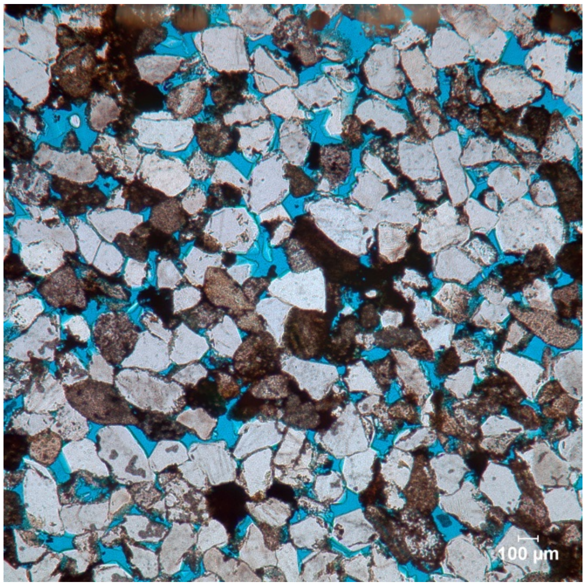


Dalehead Arch 5 (10X, XPL)

Denesmouth Arch 4



Denesmouth Arch 4 (5X, XPL)



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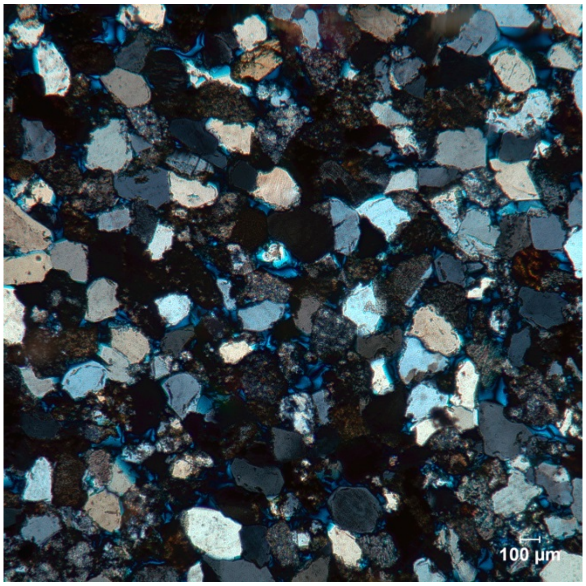

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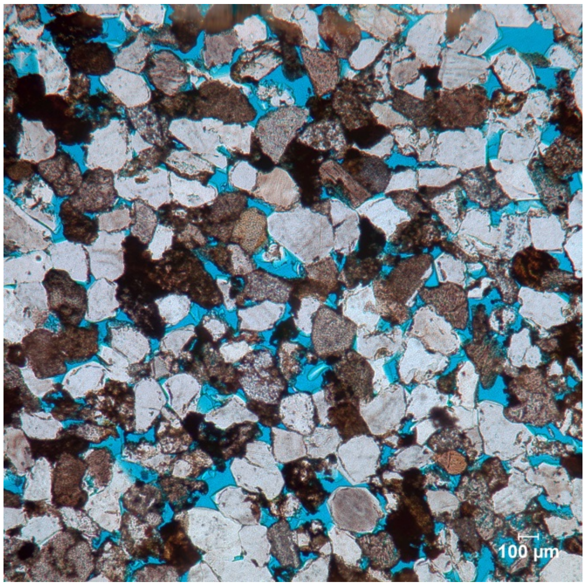

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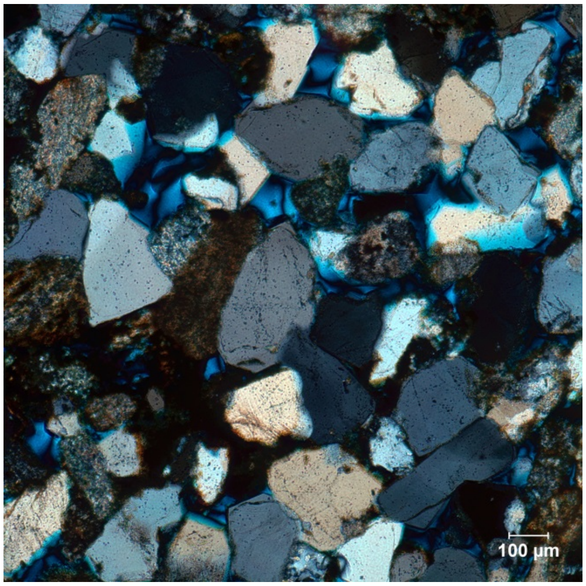

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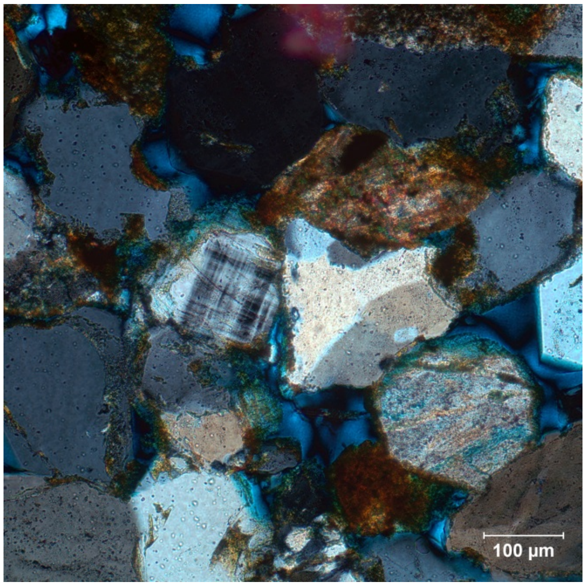

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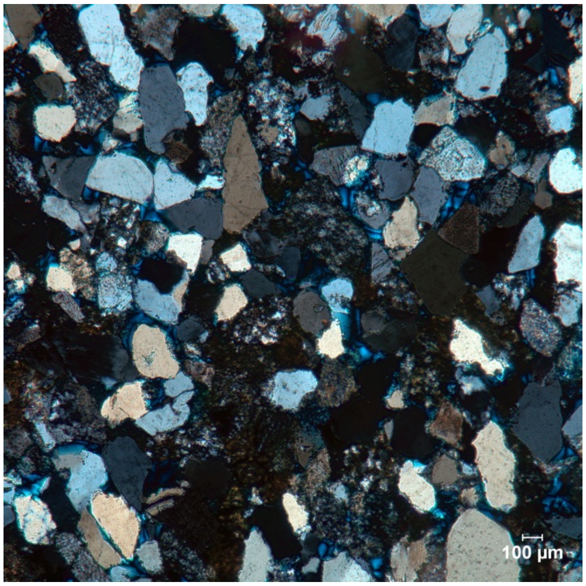
Denesmouth Arch 5



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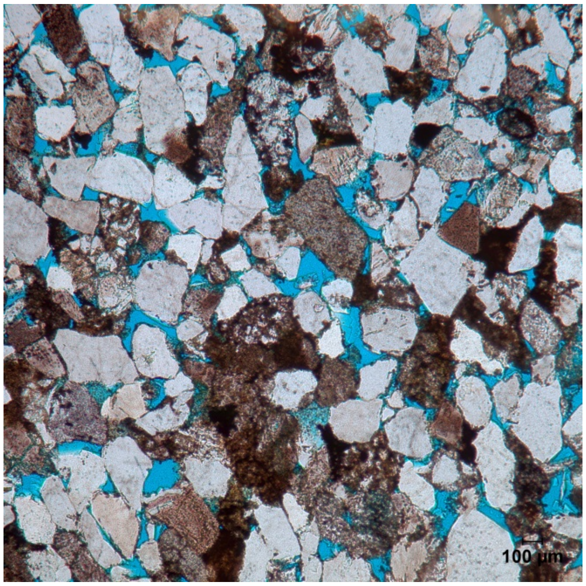

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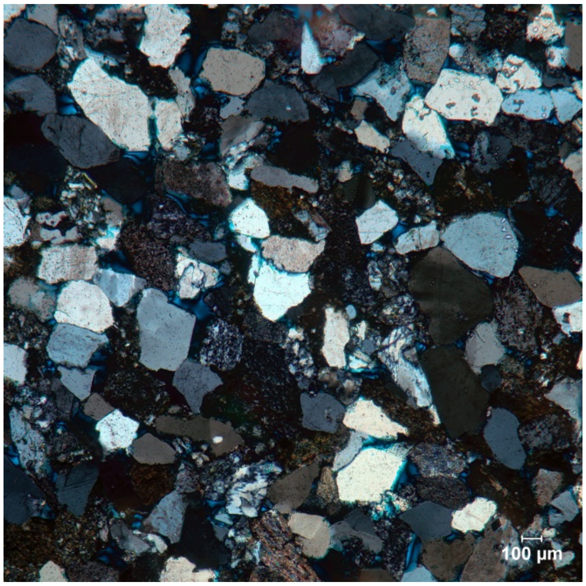

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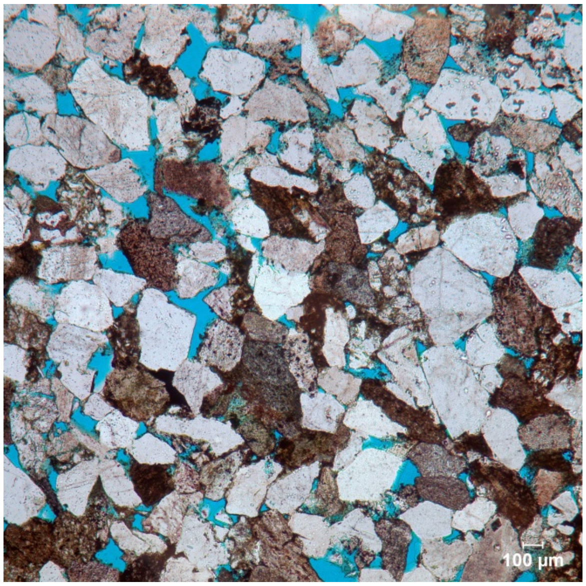

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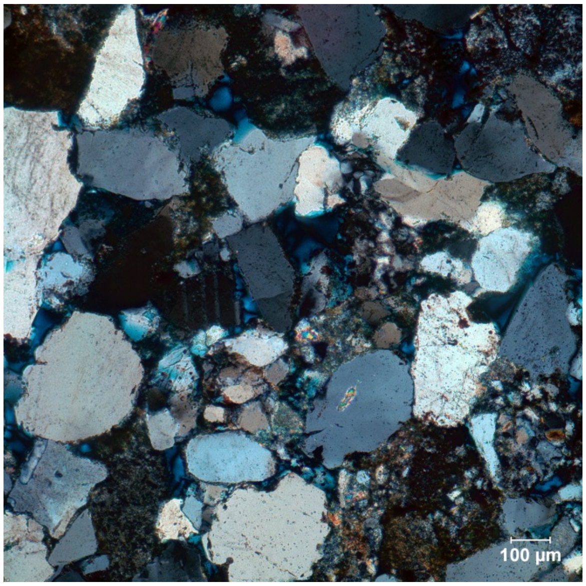

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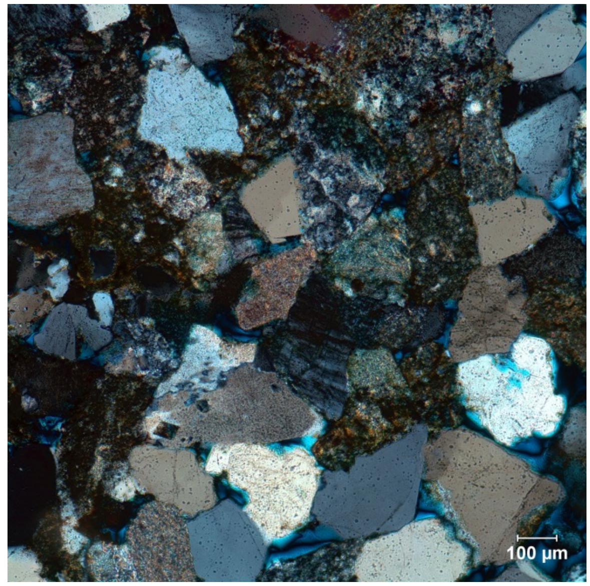
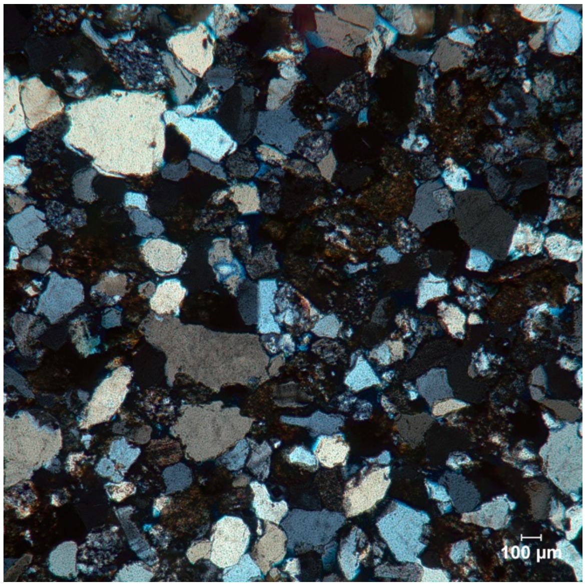


Denesmouth Arch 5 (10X, XPL)

Dorchester



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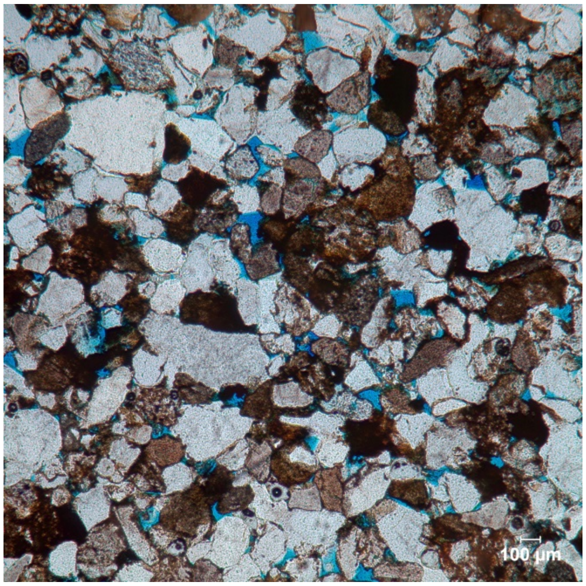

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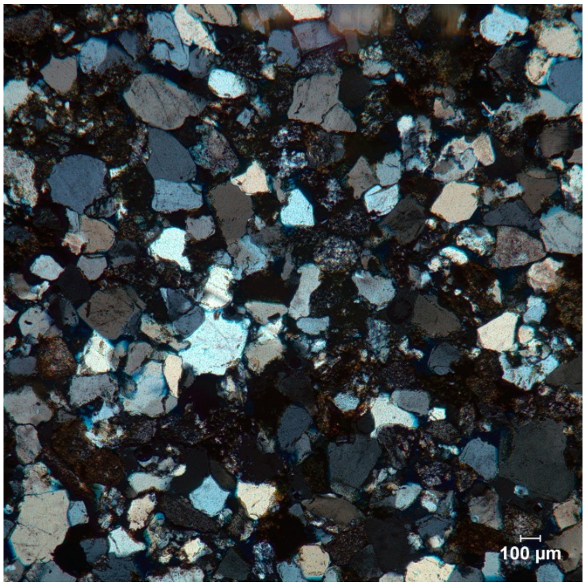

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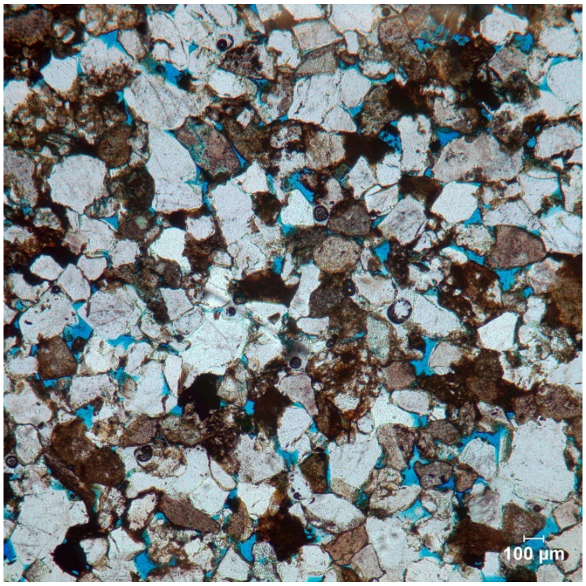

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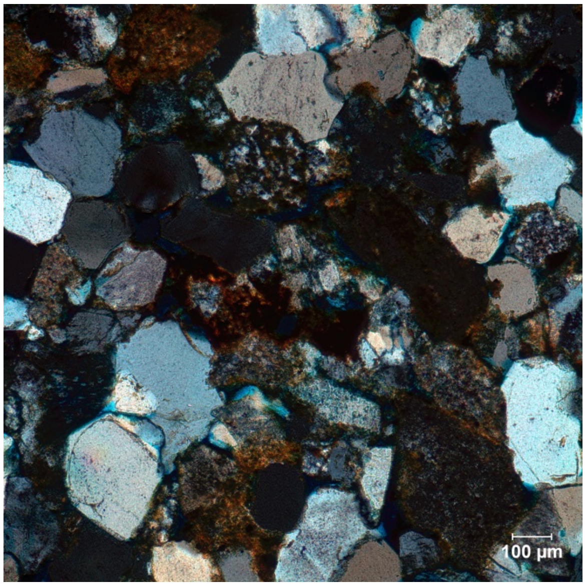

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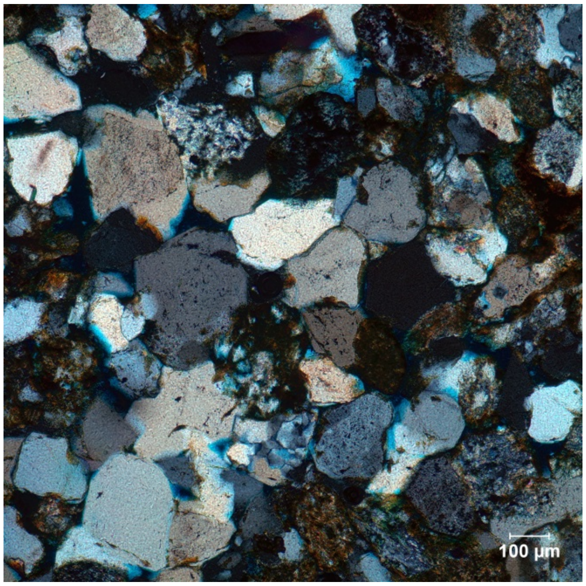

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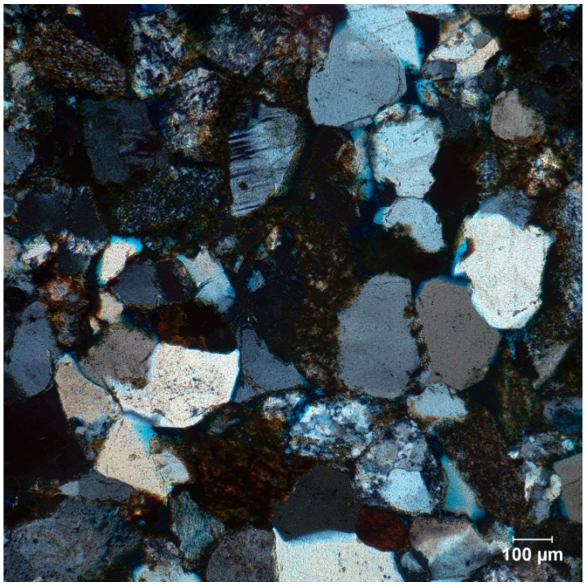

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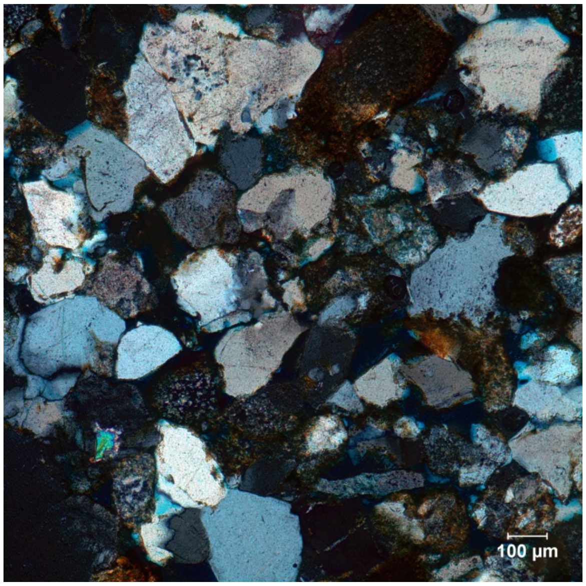

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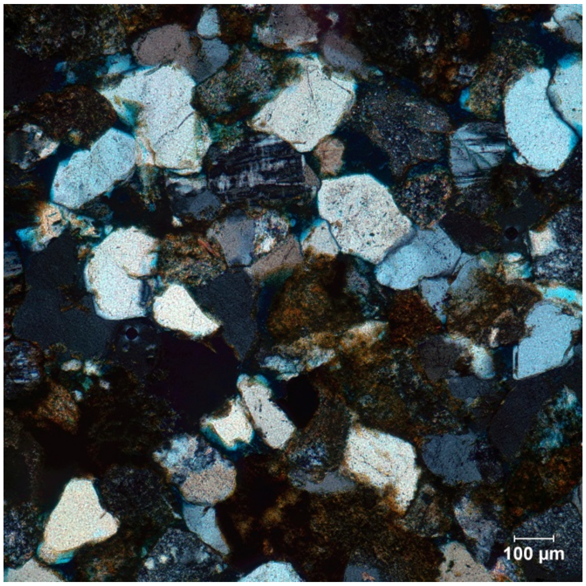

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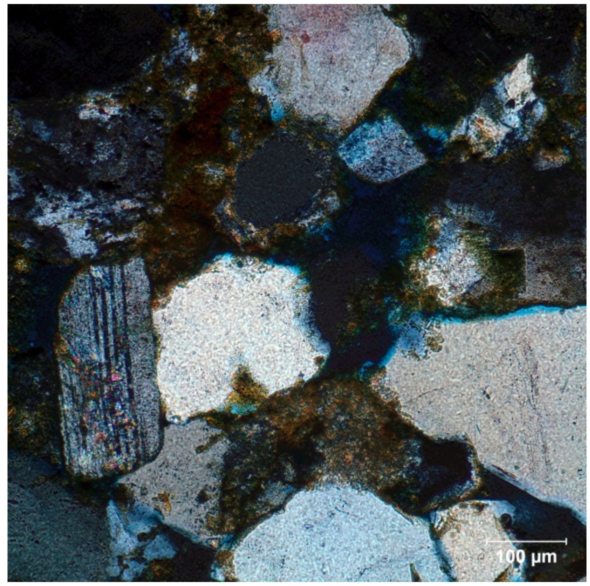
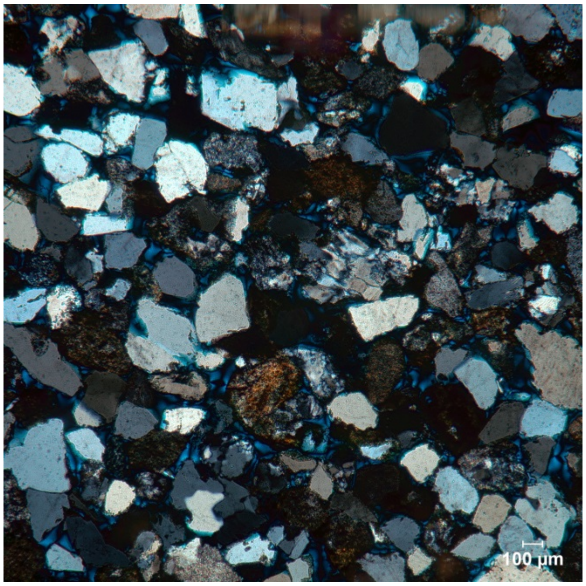
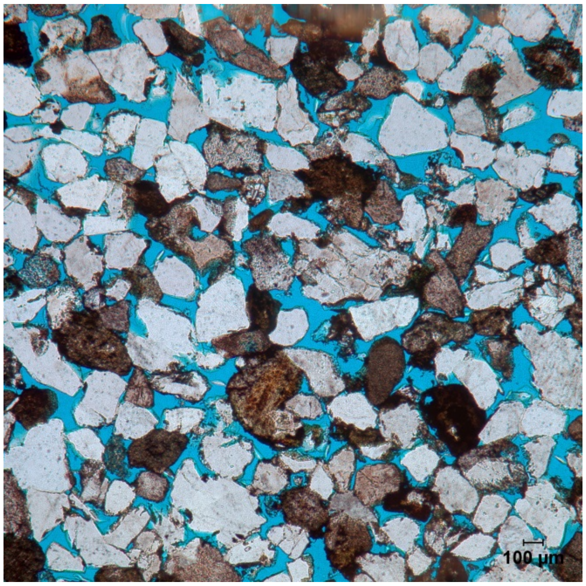


Dorchester (20X, XPL)

Driprock Arch 1



Driprock Arch 1 (5X, XPL)



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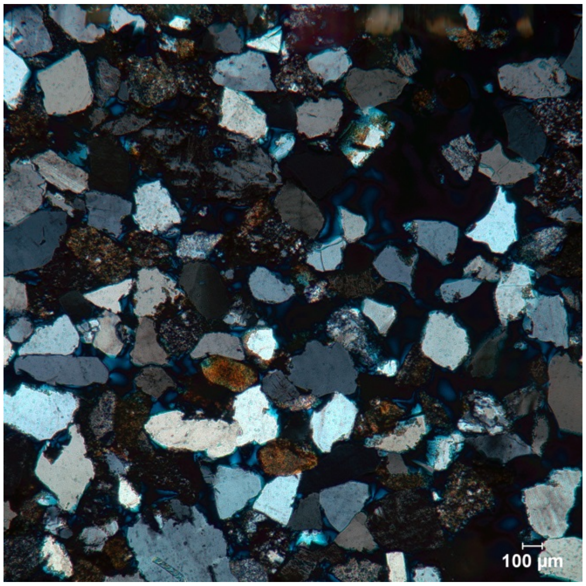

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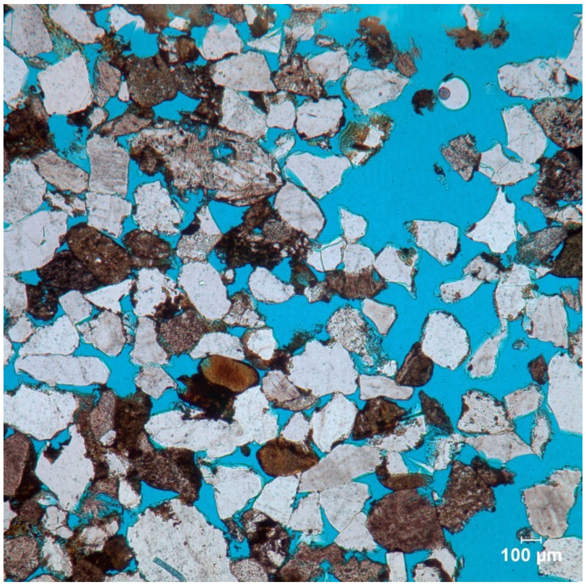

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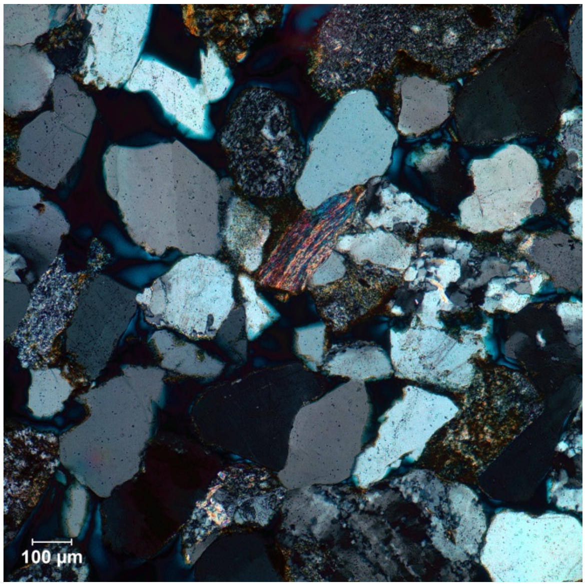

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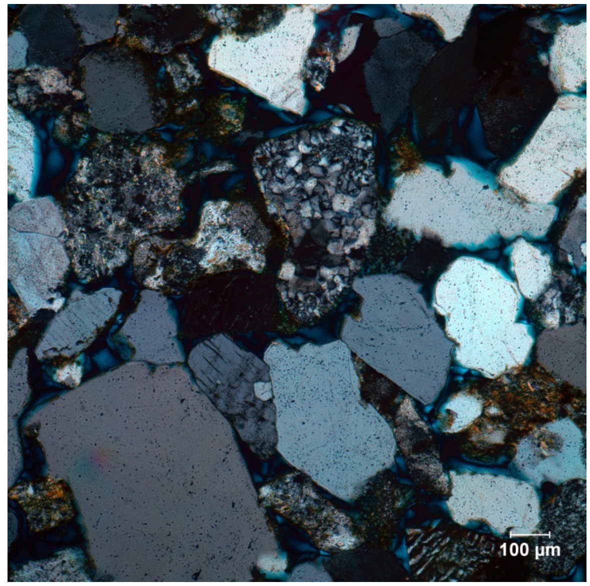

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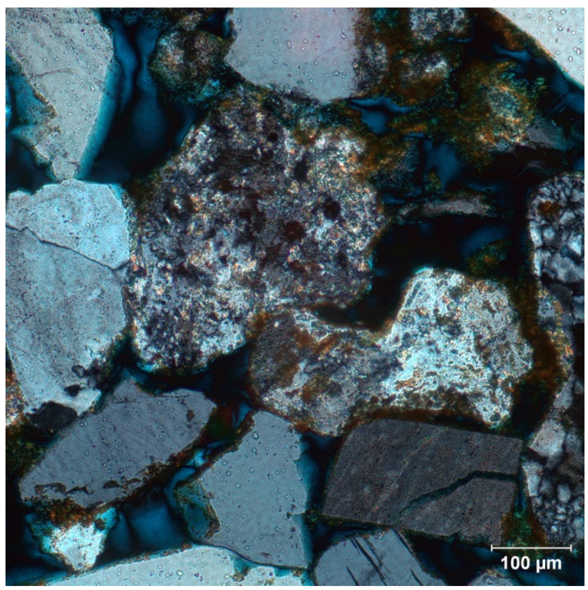
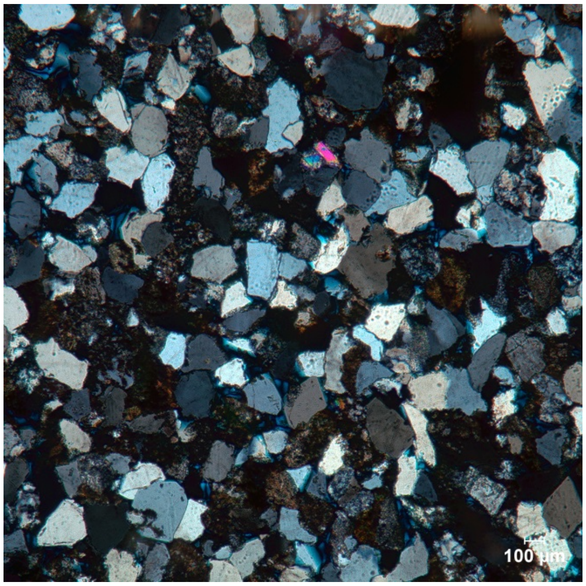
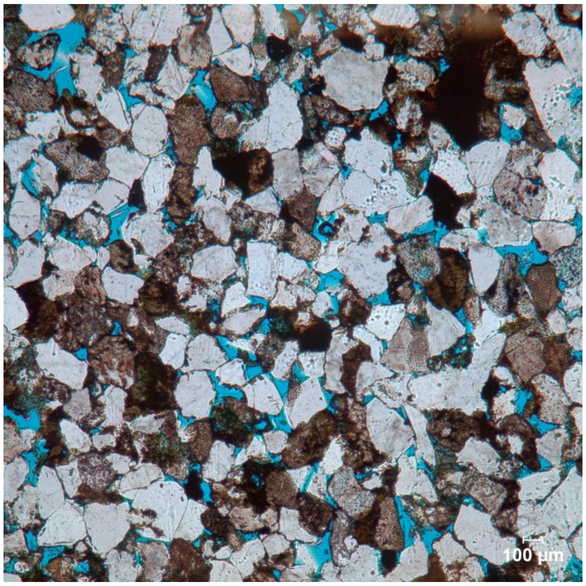


Driprock Arch 1 (20X, XPL)

Driprock Arch 2



Driprock Arch 2 (5X, XPL)



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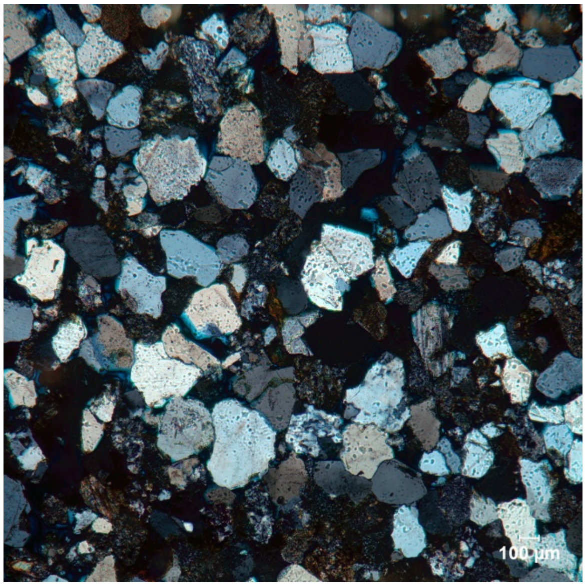

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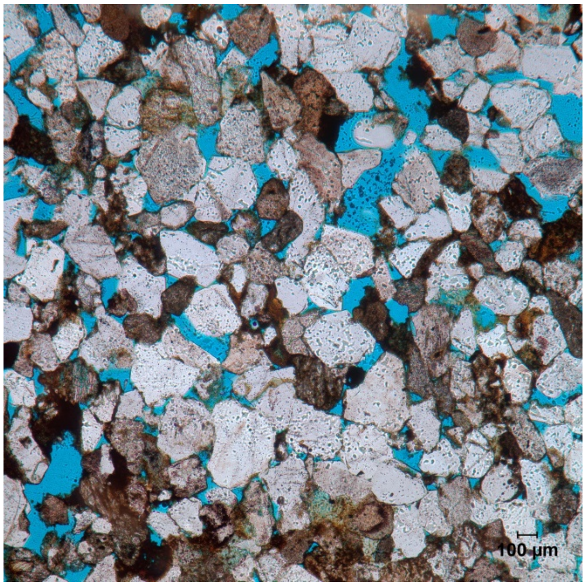

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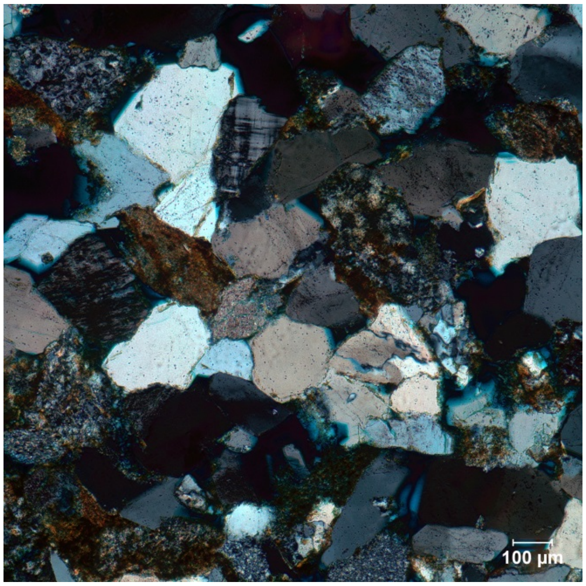

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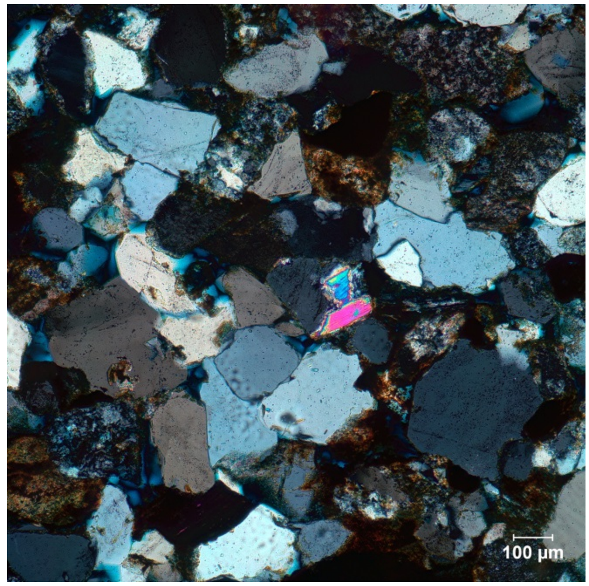
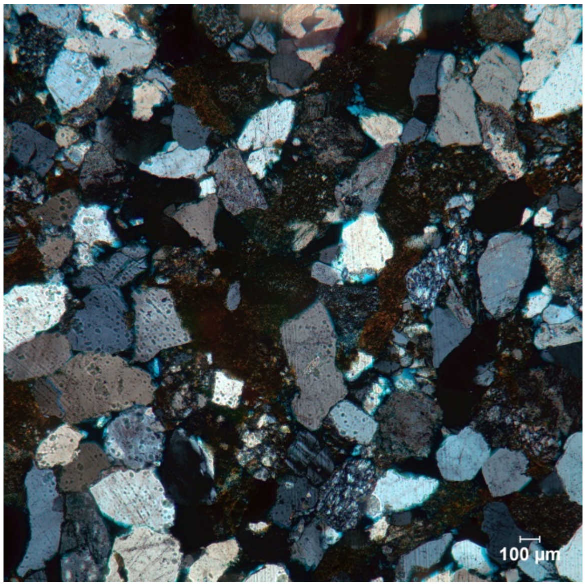
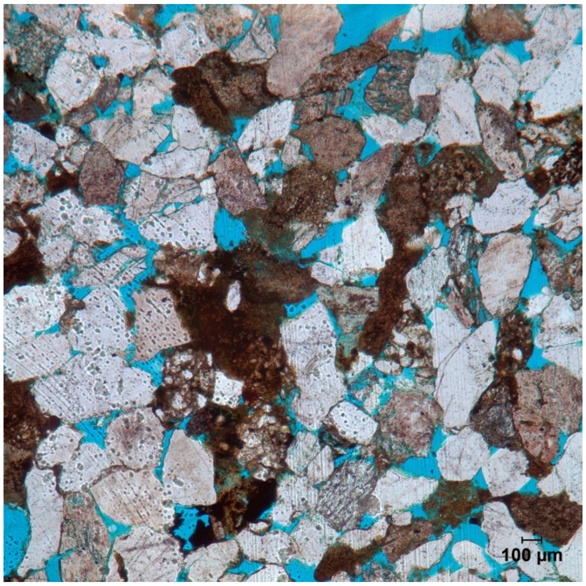


Driprock Arch 2 (10X, XPL)

Glade Arch 4



Glade Arch 4 (5X, XPL)



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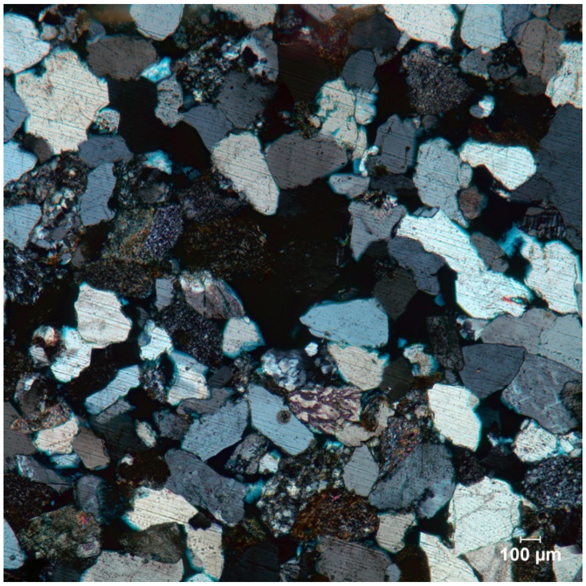

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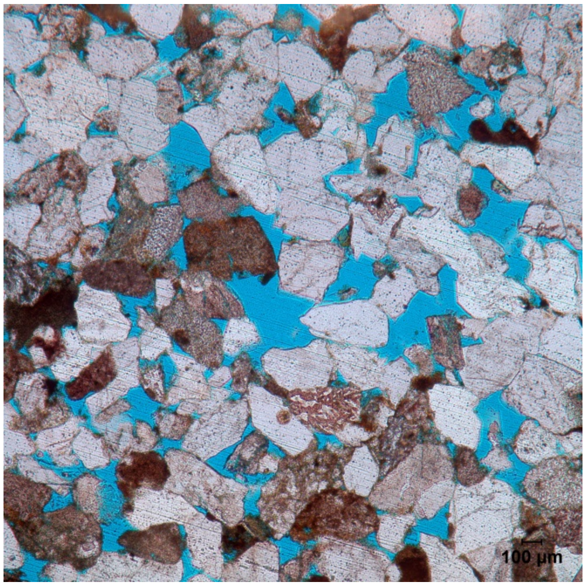

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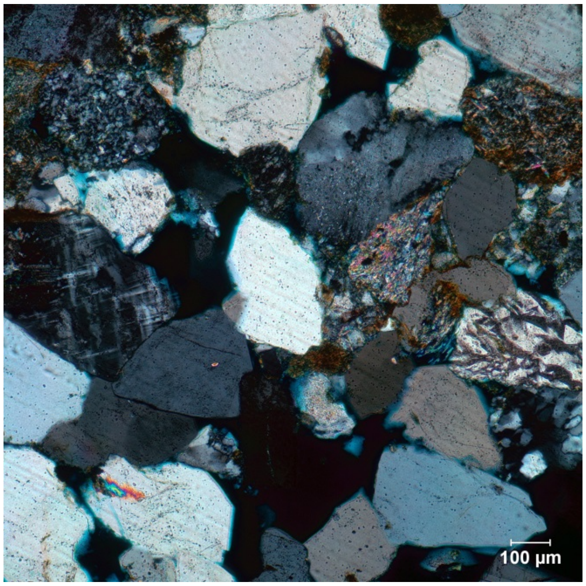

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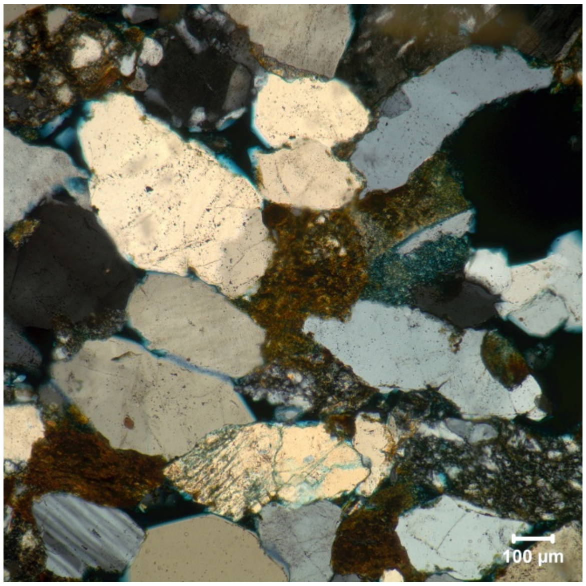

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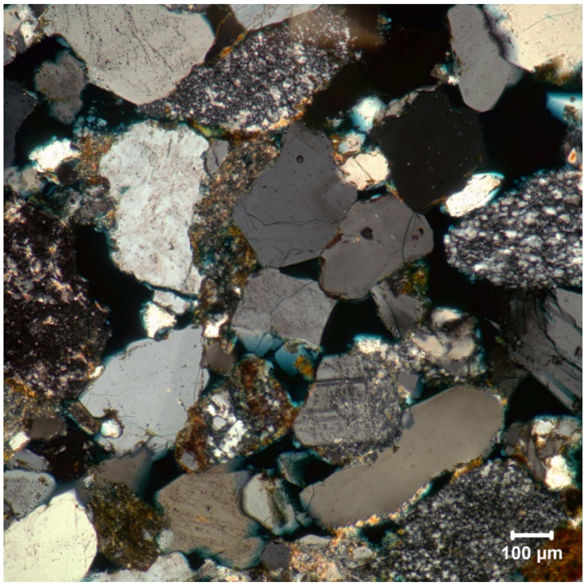

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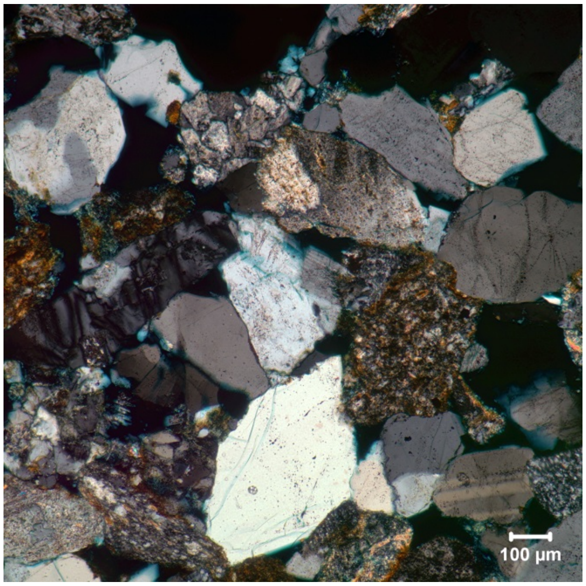

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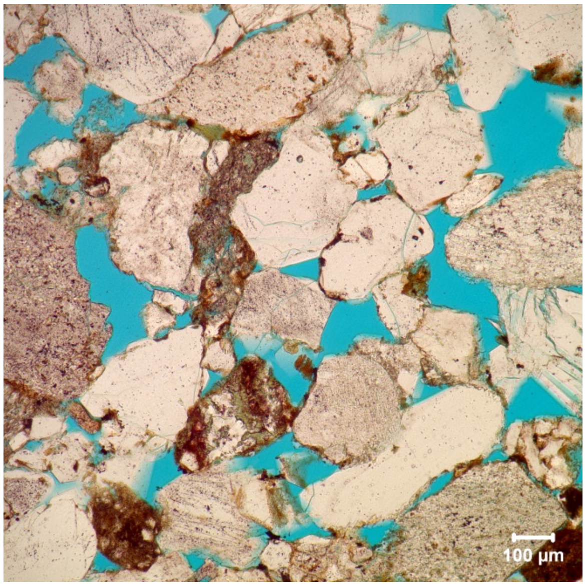

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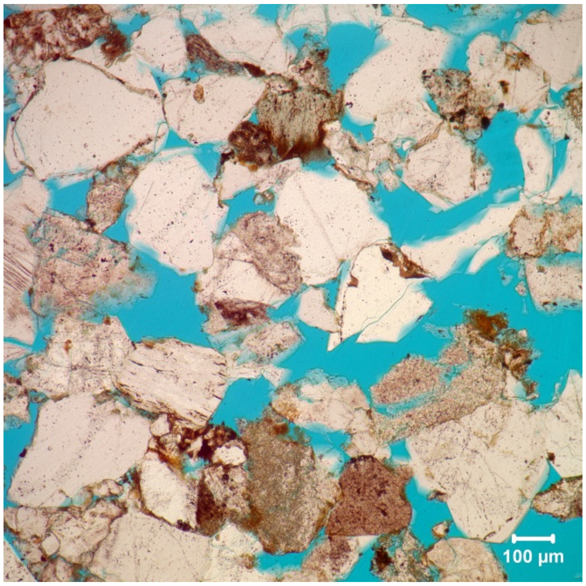

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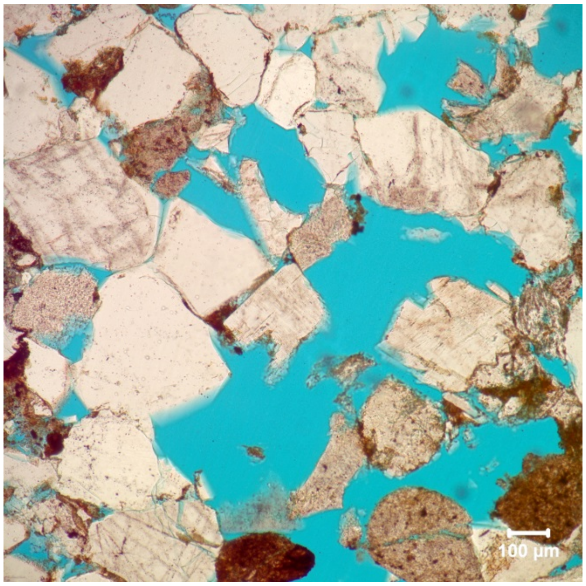

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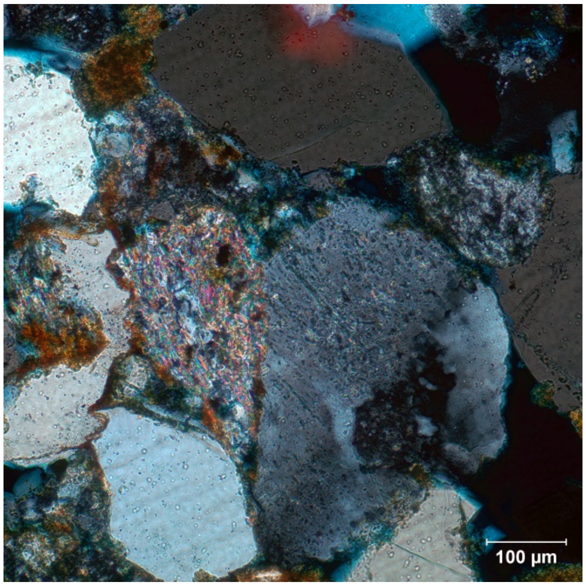
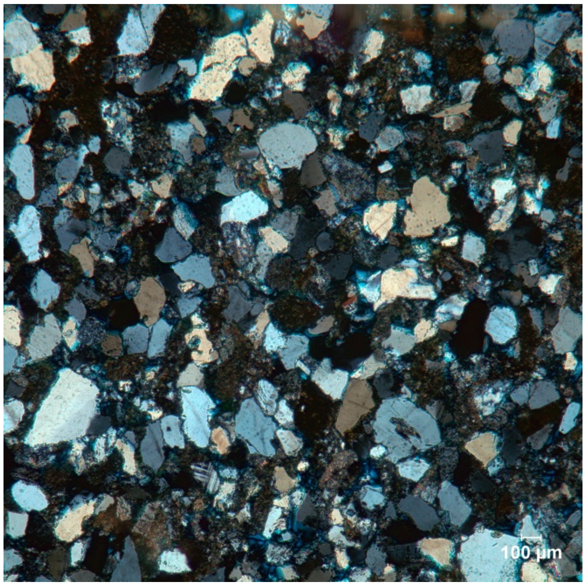


Glade Arch 4 (20X, XPL)

Glade Arch 5



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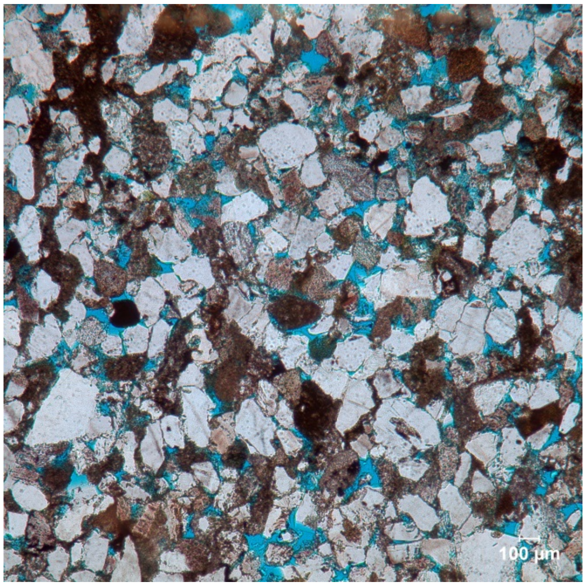

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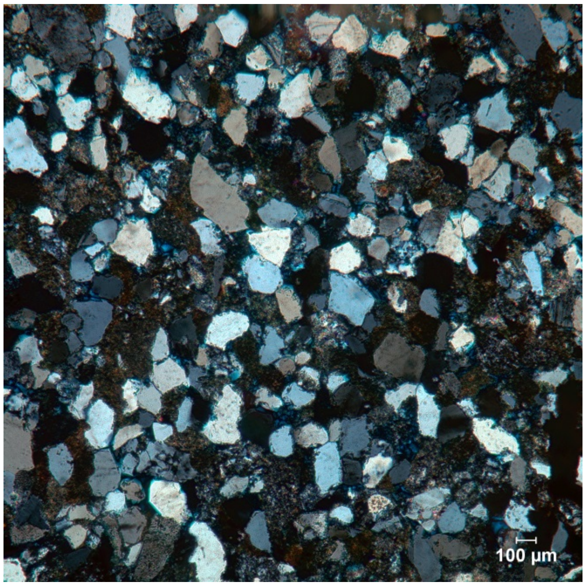

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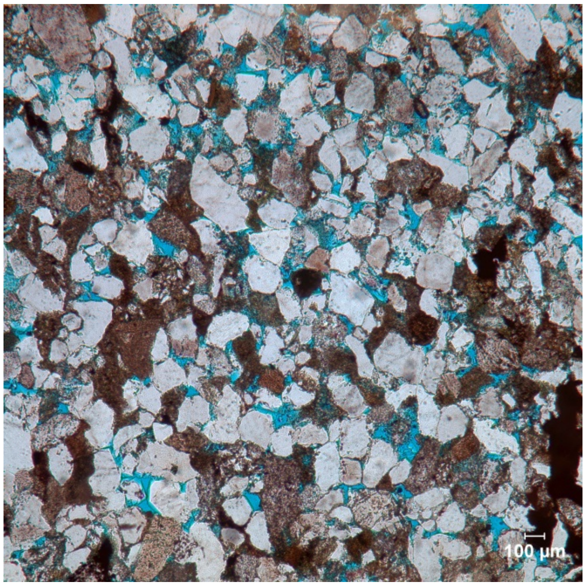

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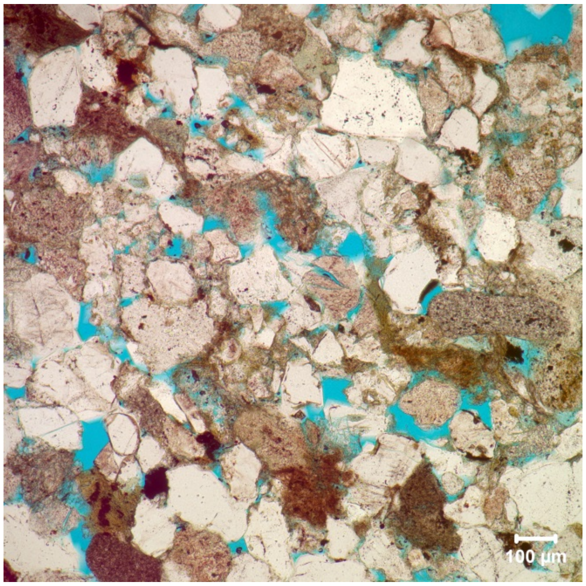

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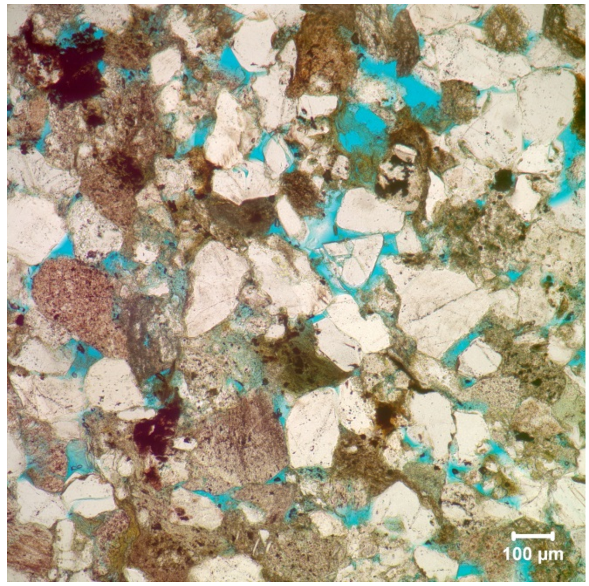

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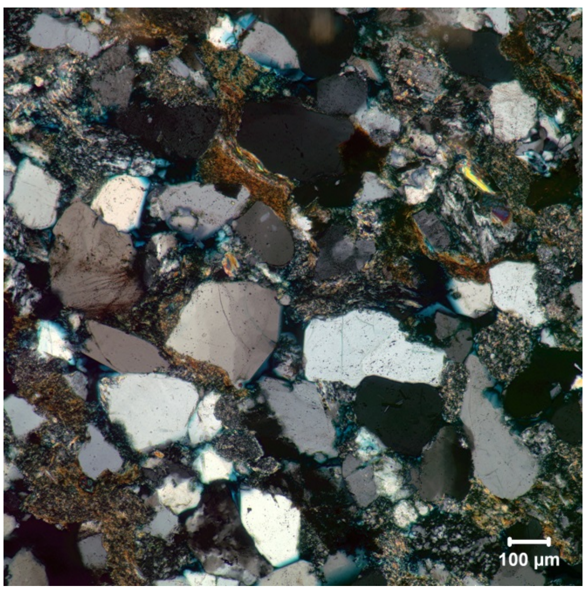

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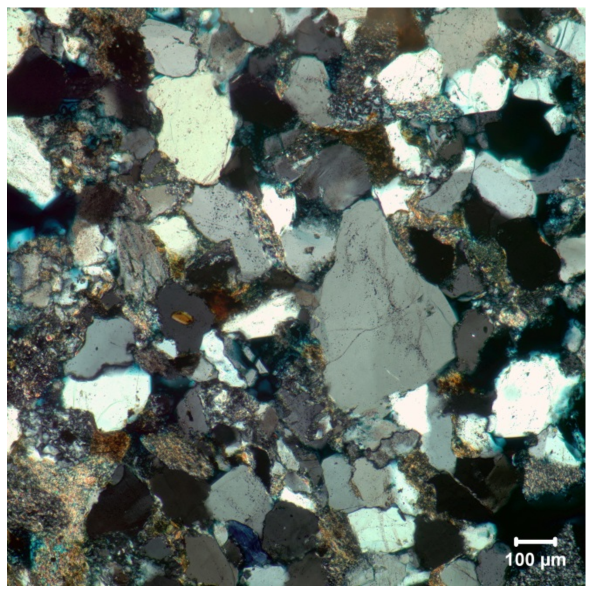

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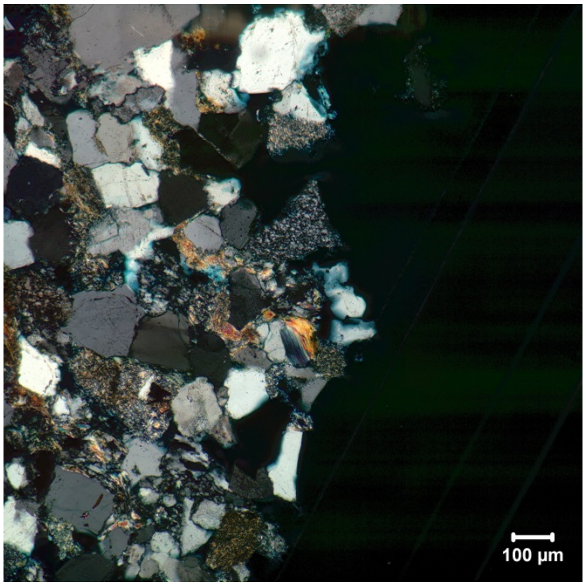

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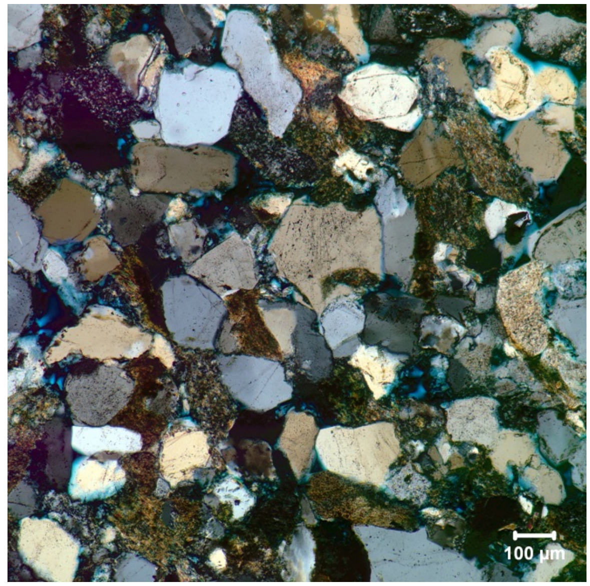

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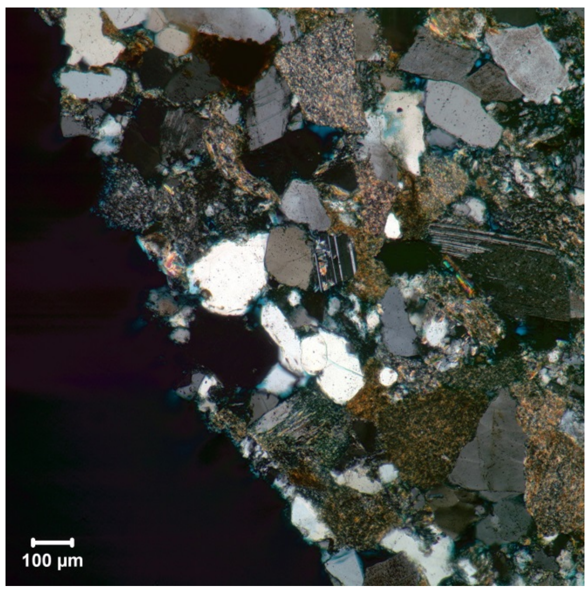
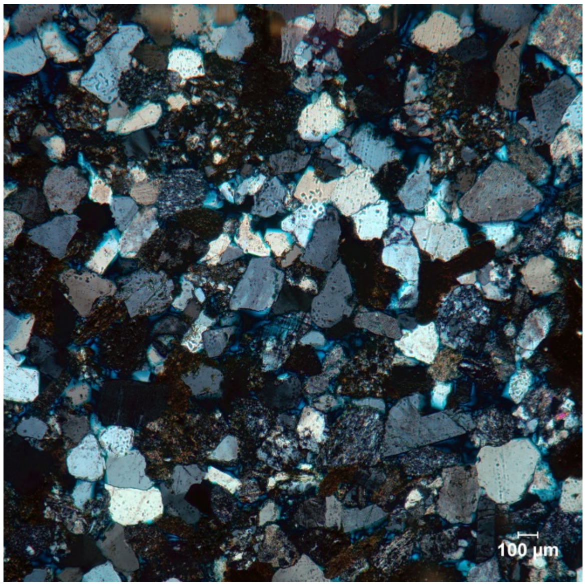
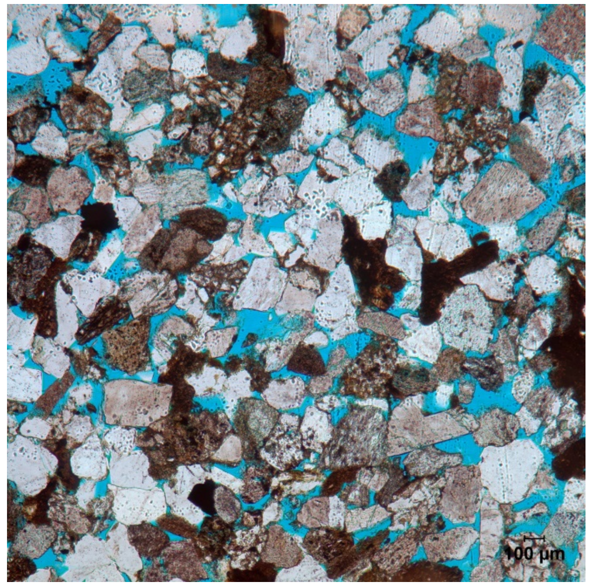


Glade Arch 5 (10X, XPL)

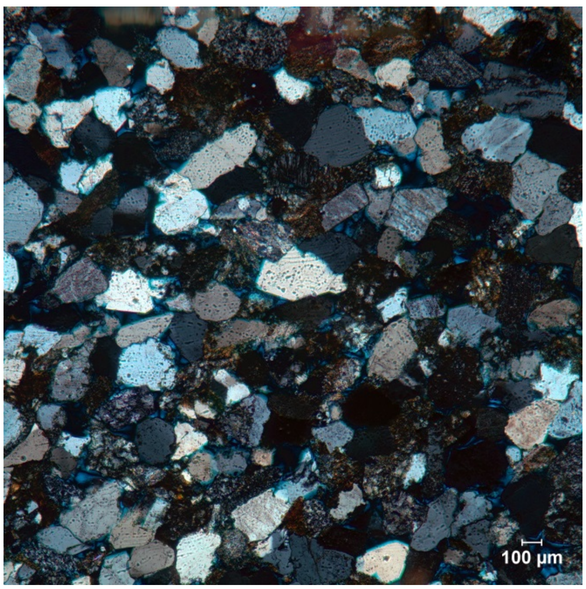
Green Gap Arch 2



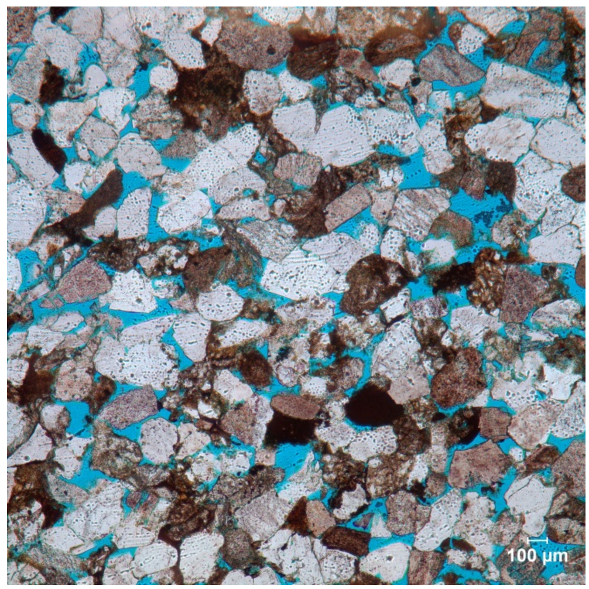
Green Gap Arch 2 (5X, XPL)



Green Gap Arch 2 (5X, PPL)



Green Gap Arch 2 (5X, XPL)



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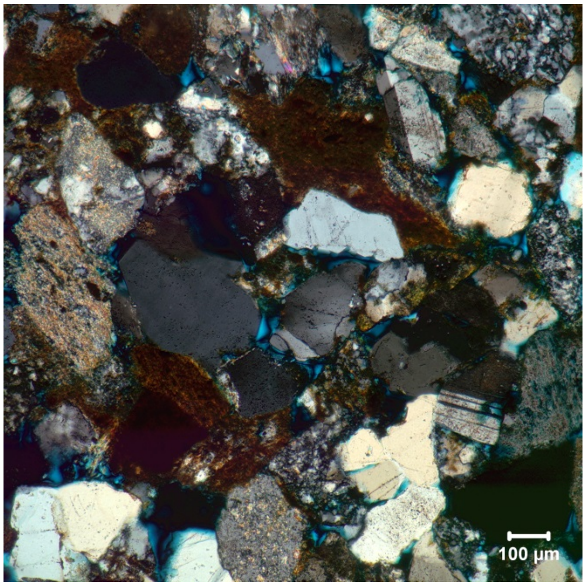

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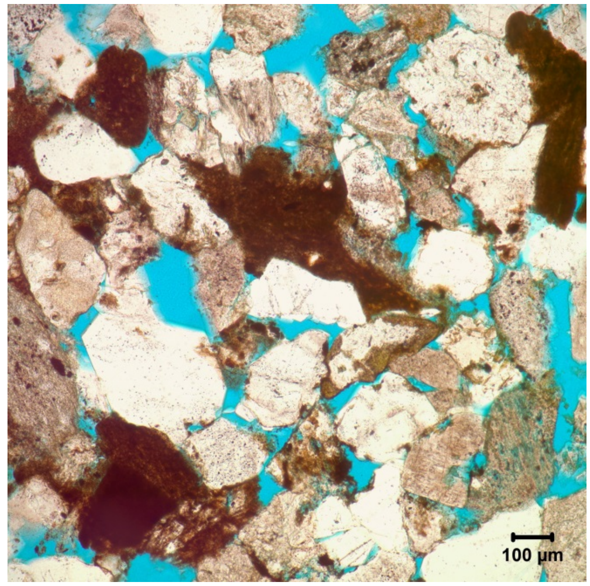

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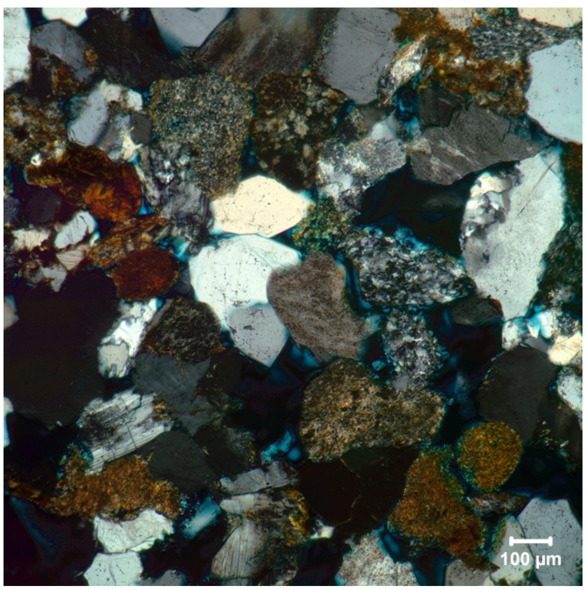

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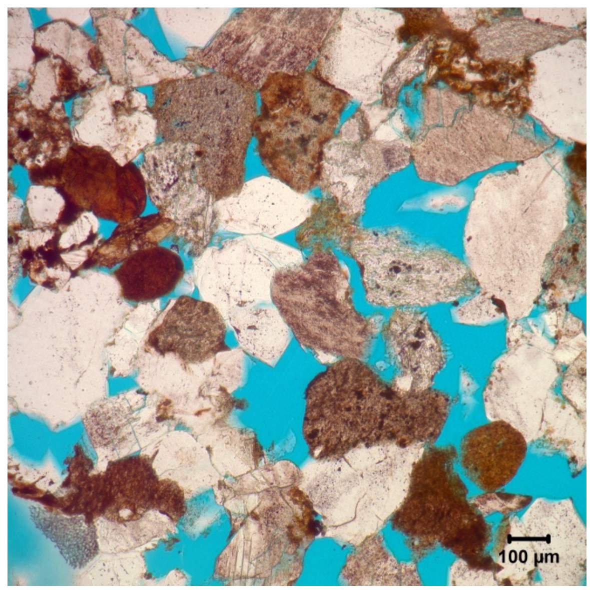

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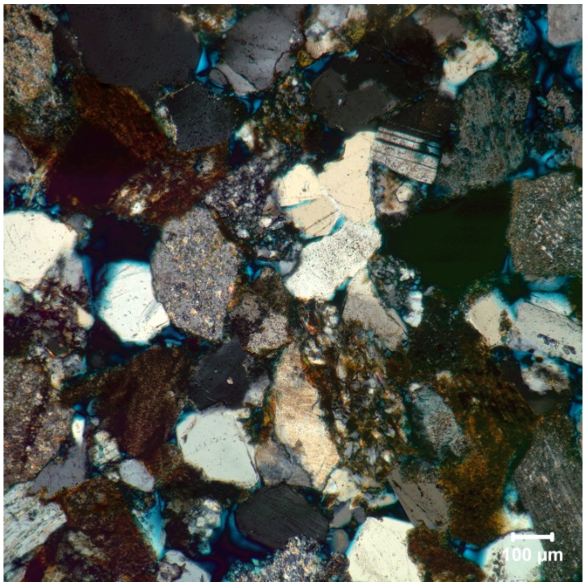

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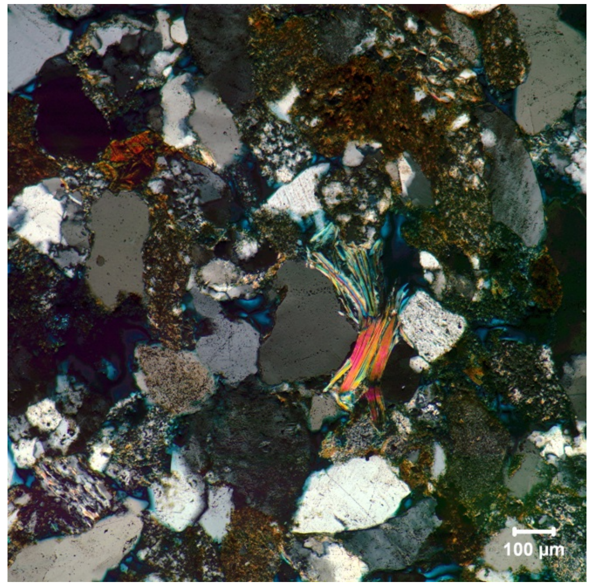

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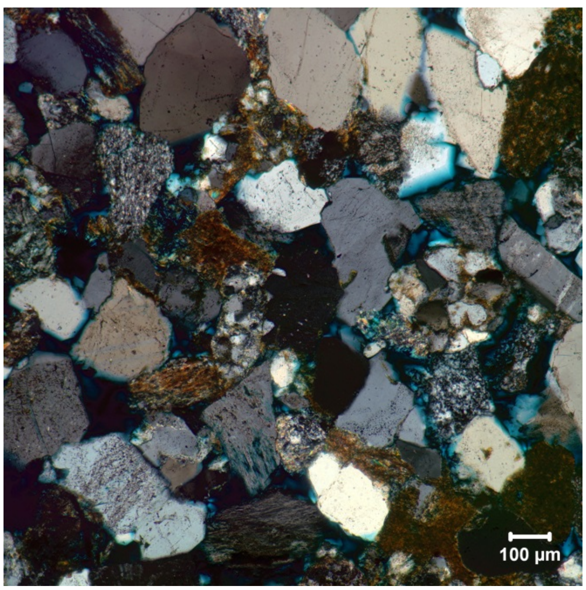

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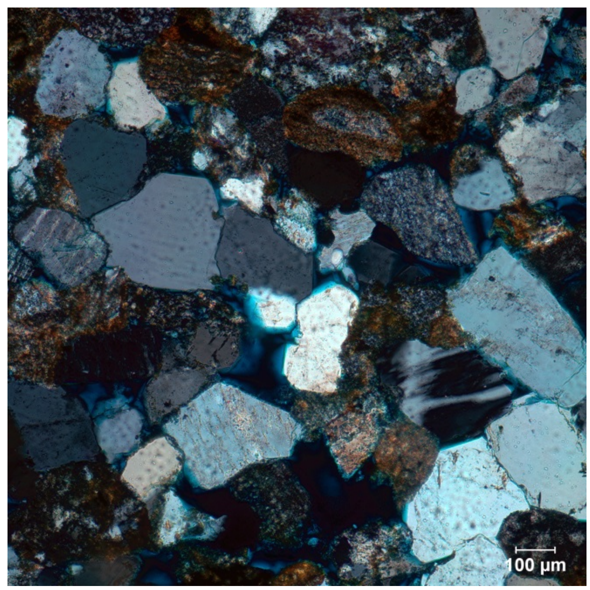

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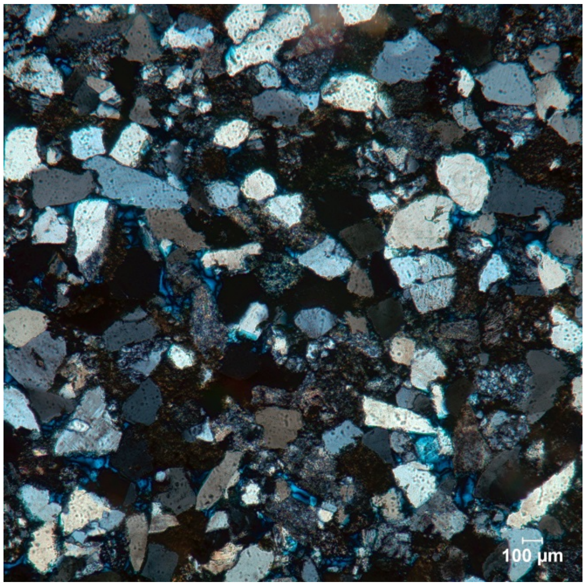
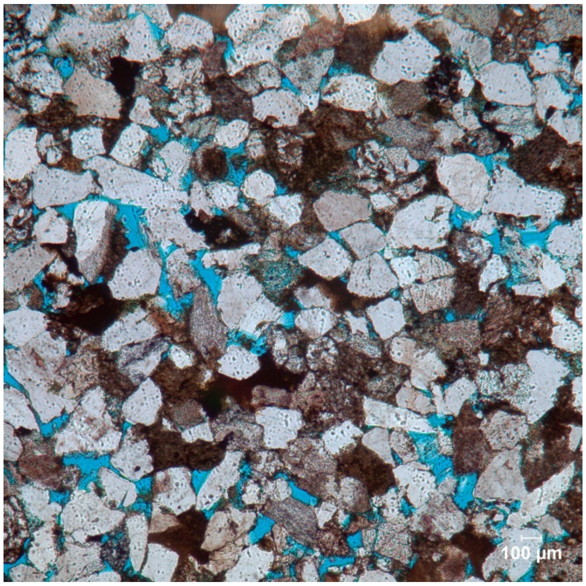
Green Gap Arch 3



Green Gap Arch 3 (5X, XPL)



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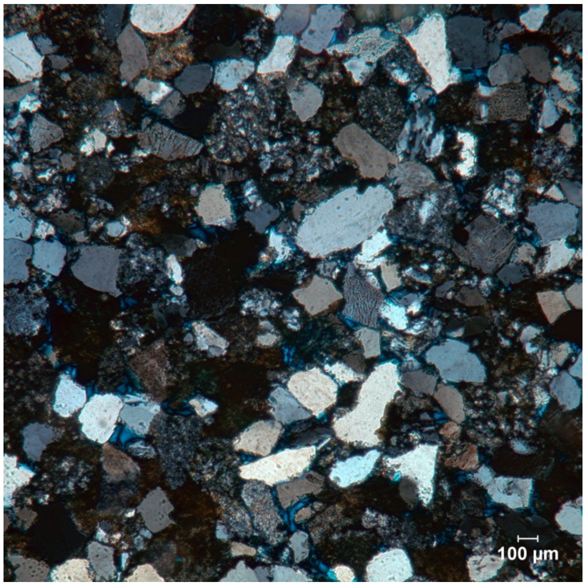

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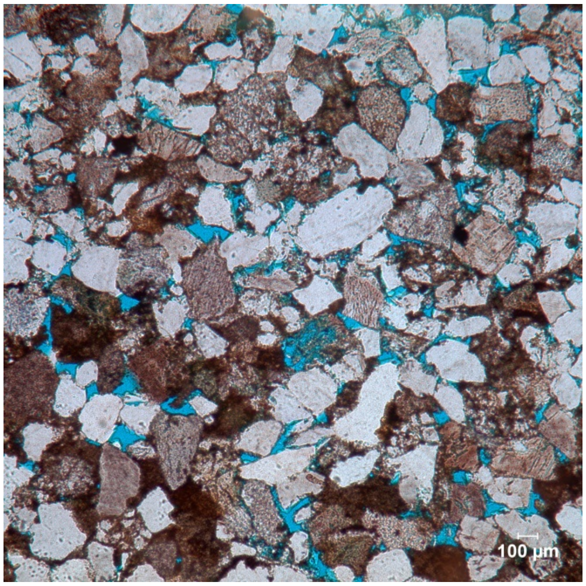

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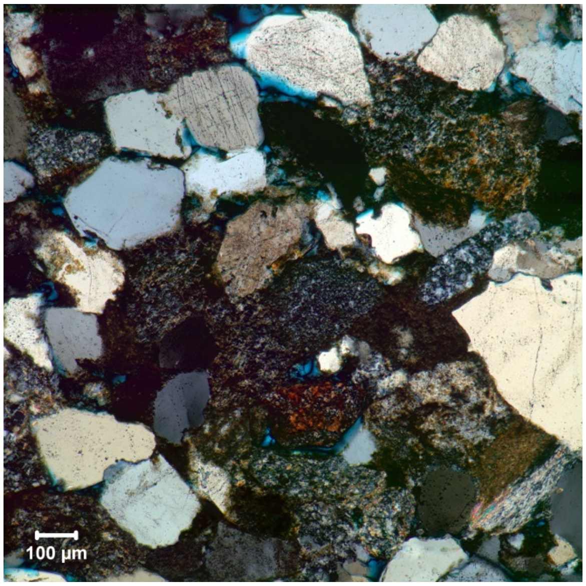

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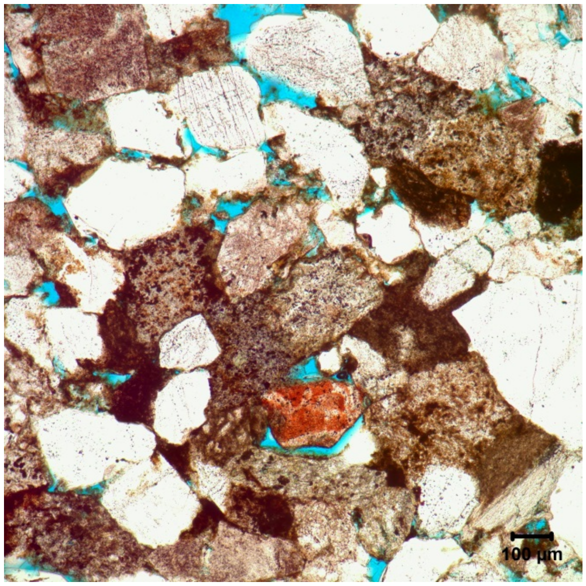

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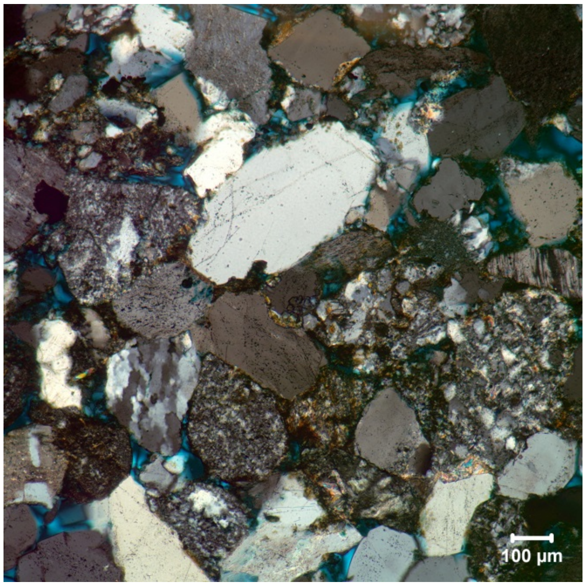

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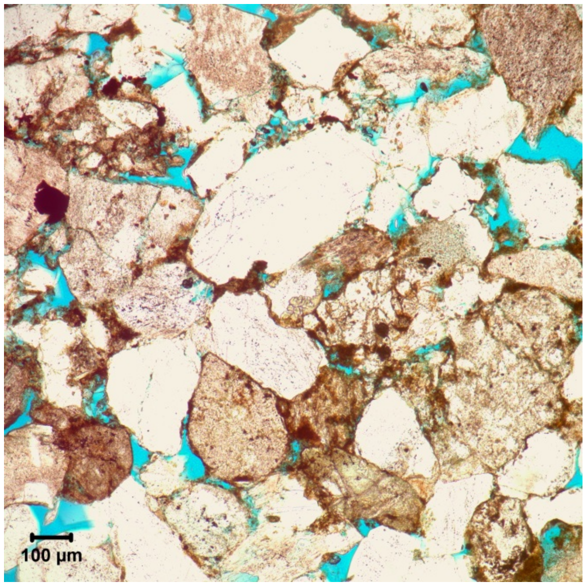

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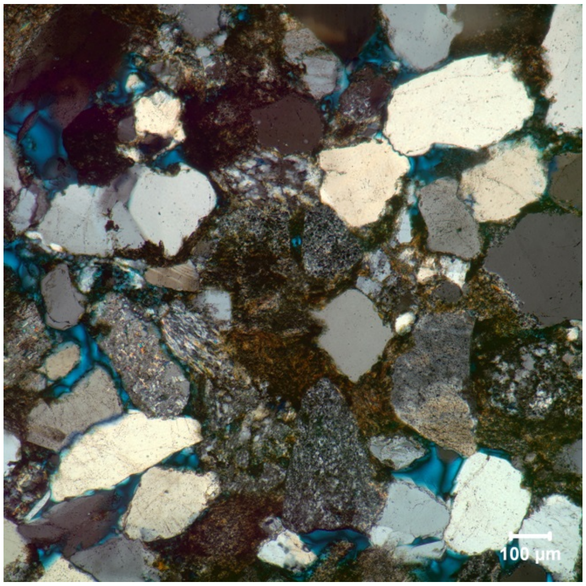

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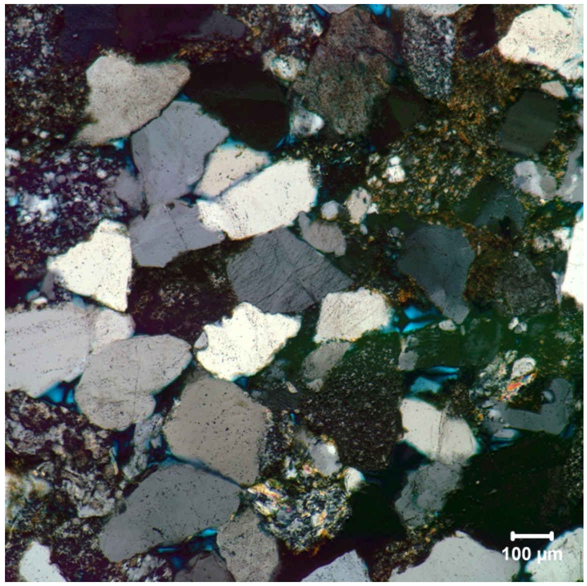

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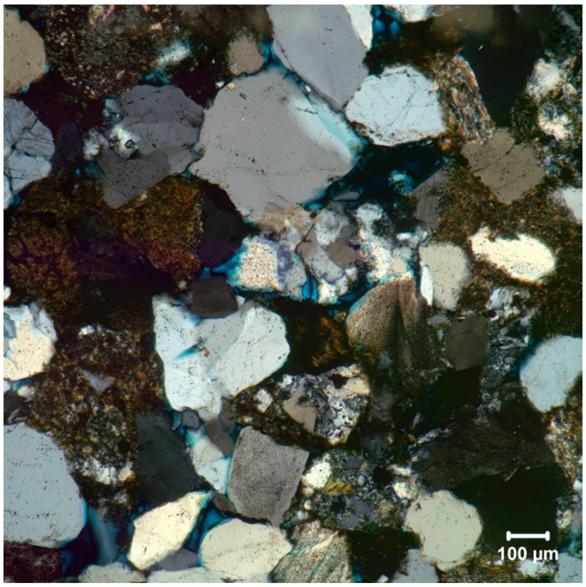

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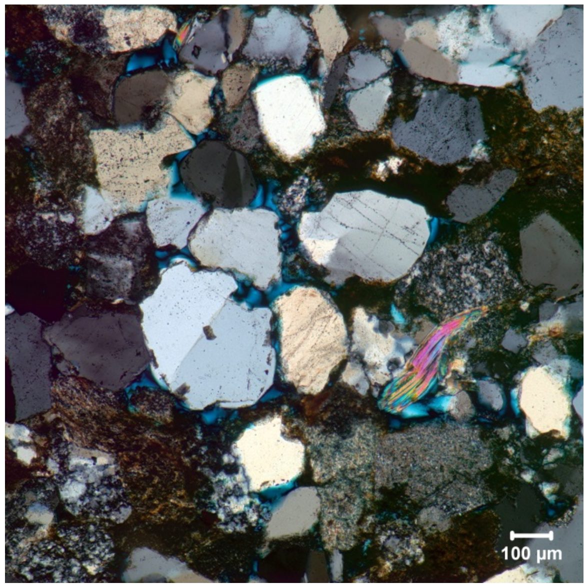
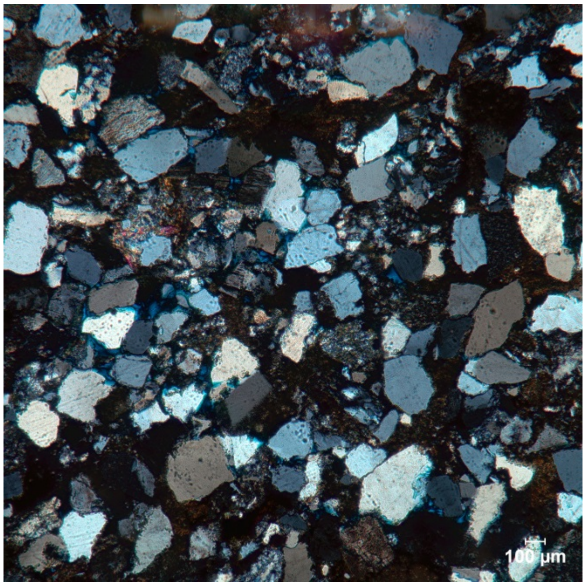
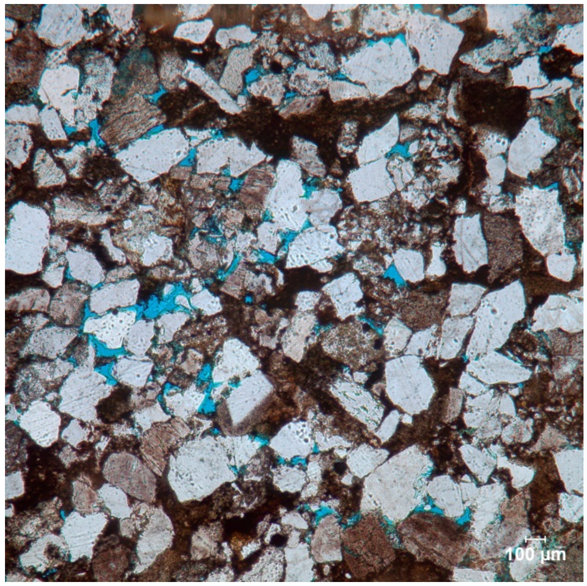


Green Gap Arch 3 (10X, XPL)

Greyshot Arch 1



Greyshot Arch 1 (5X, XPL)



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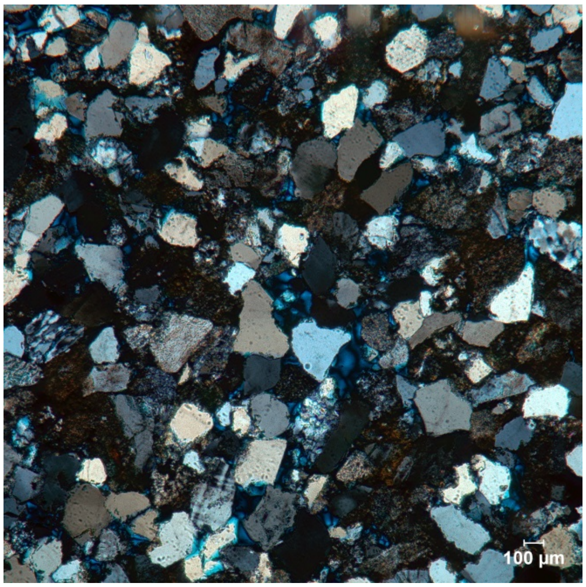

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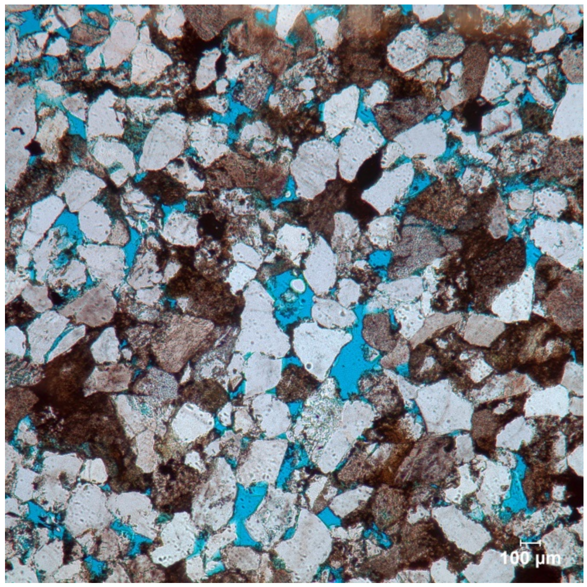

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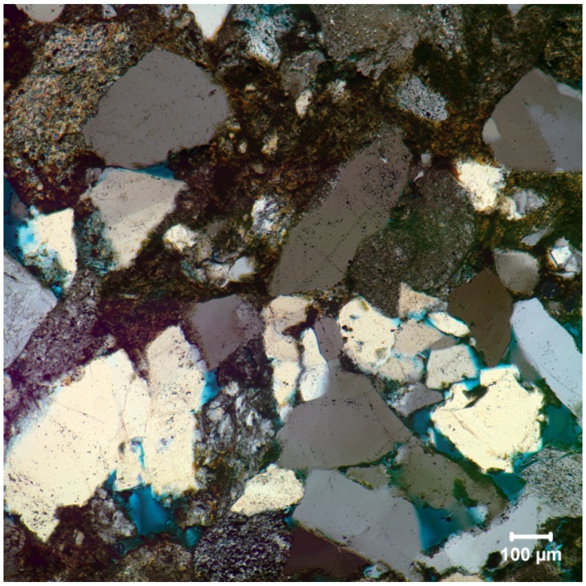

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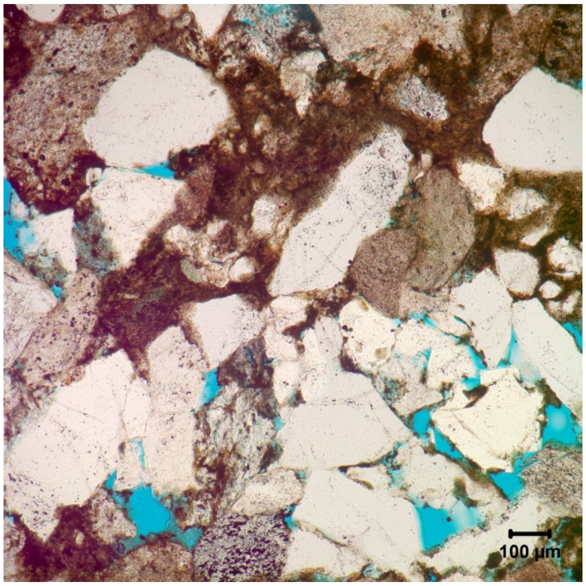

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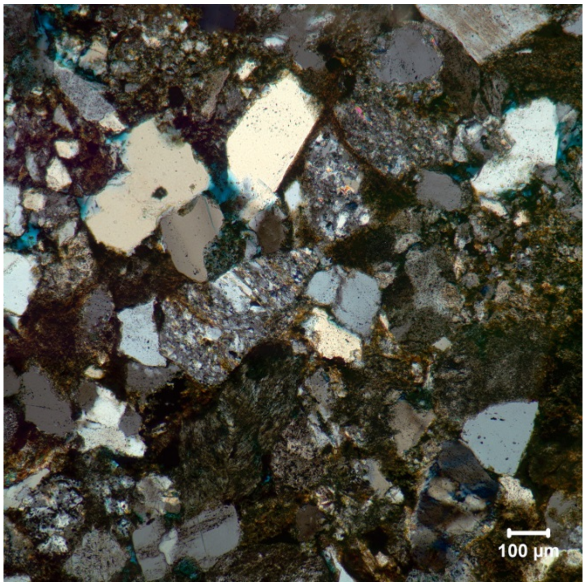

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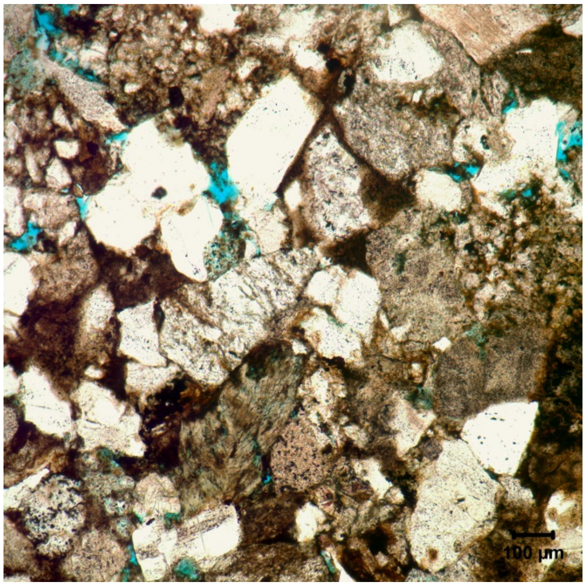

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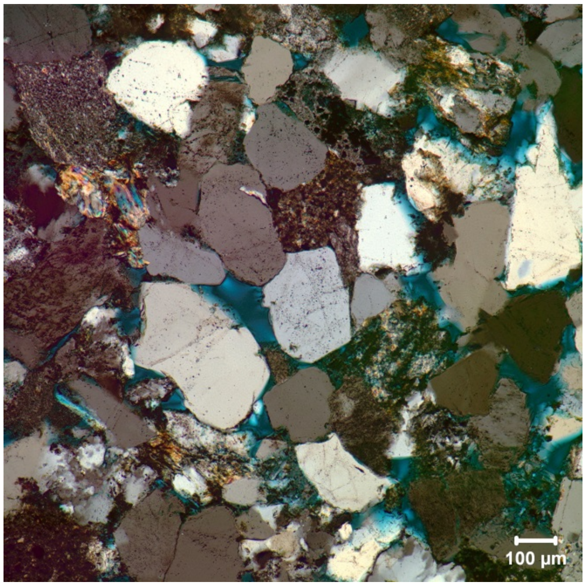

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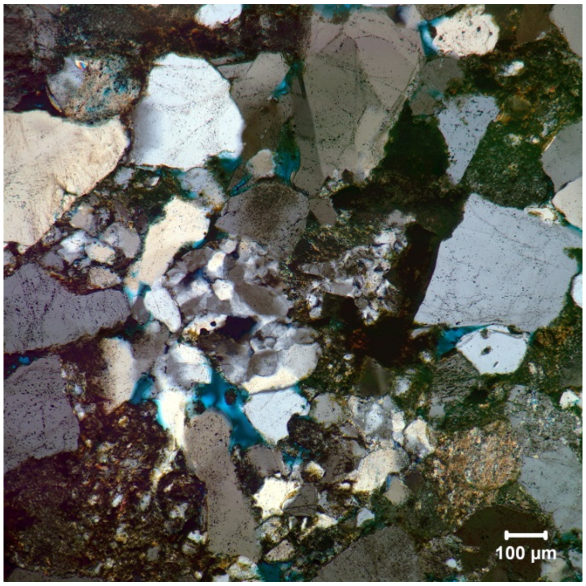

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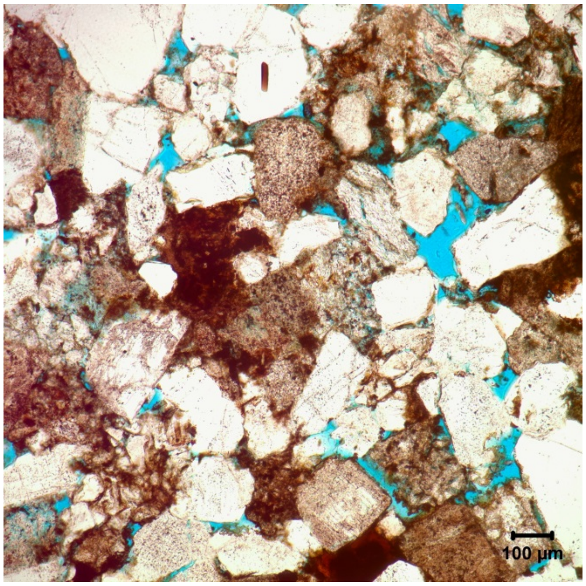
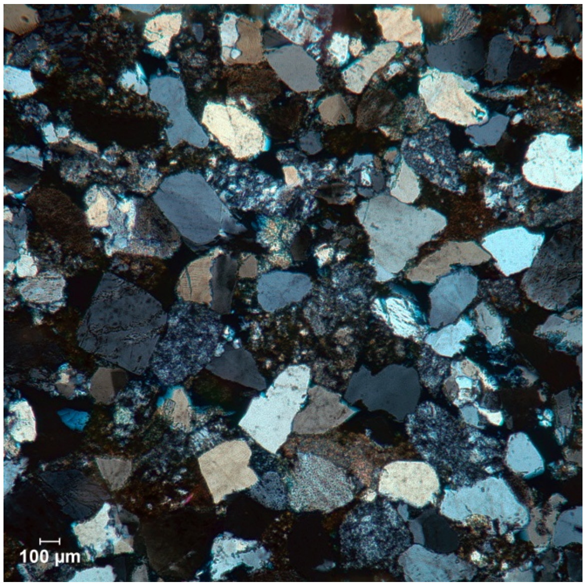


Greyshot Arch 1 (10X, PPL)

Greyshot Arch 2



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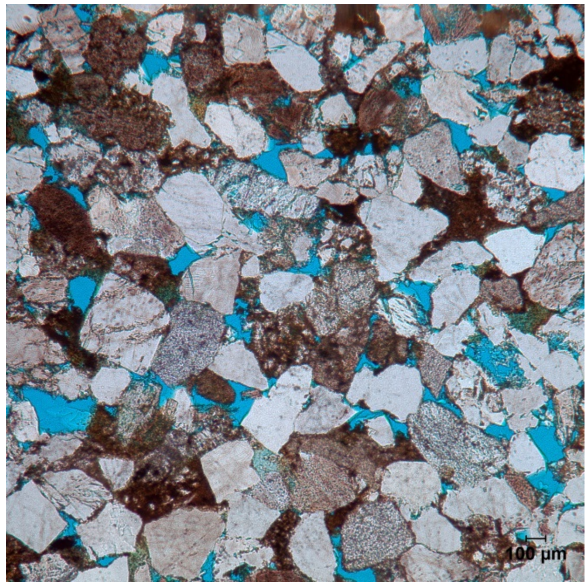

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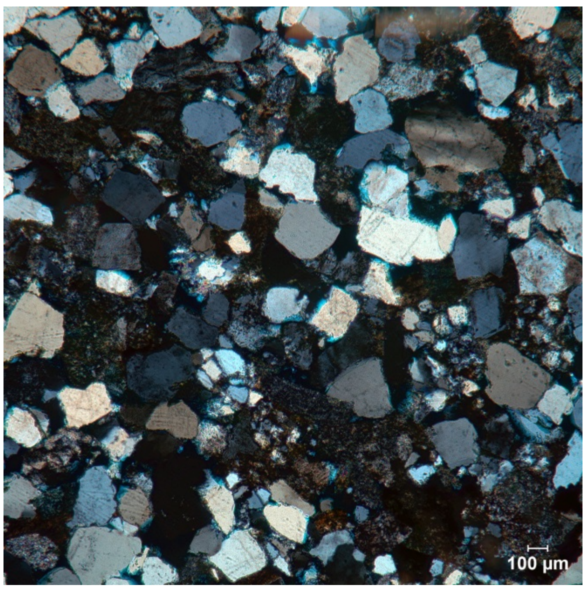

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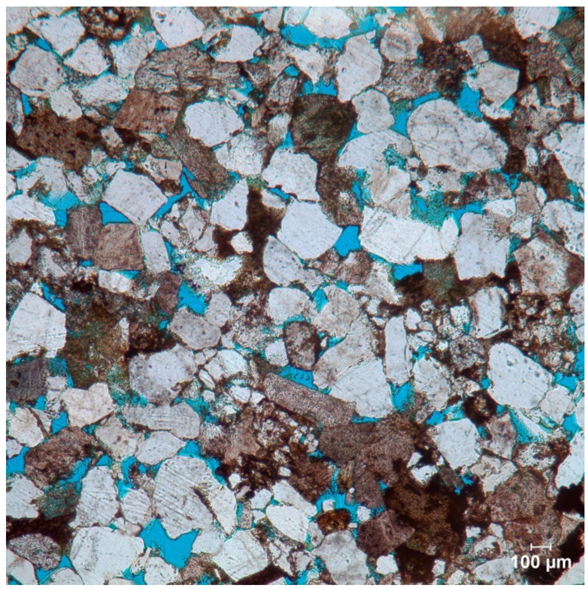

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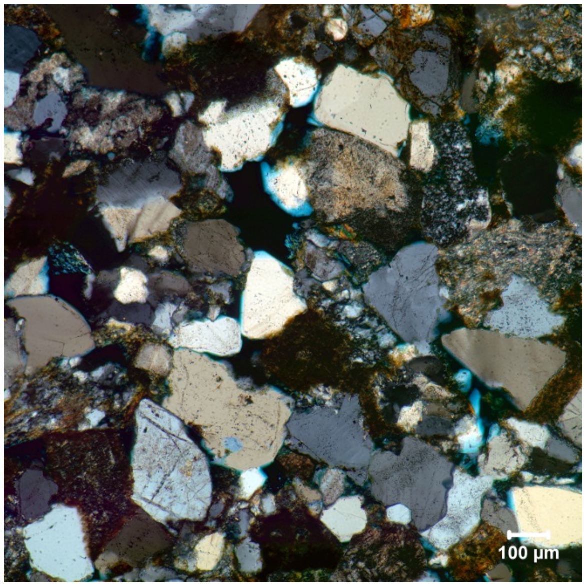

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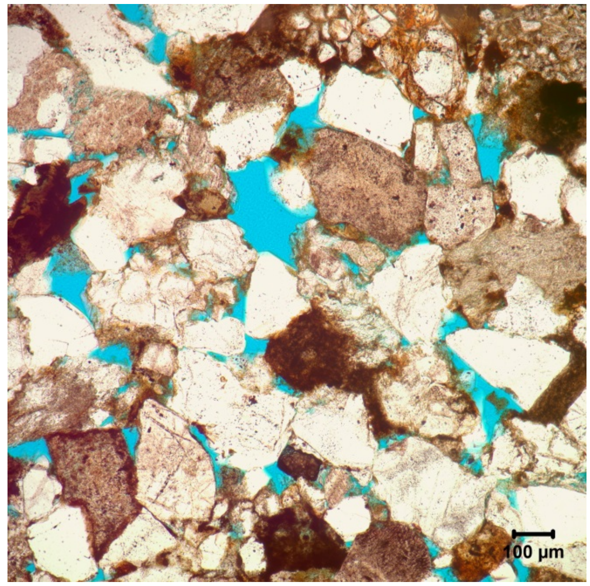
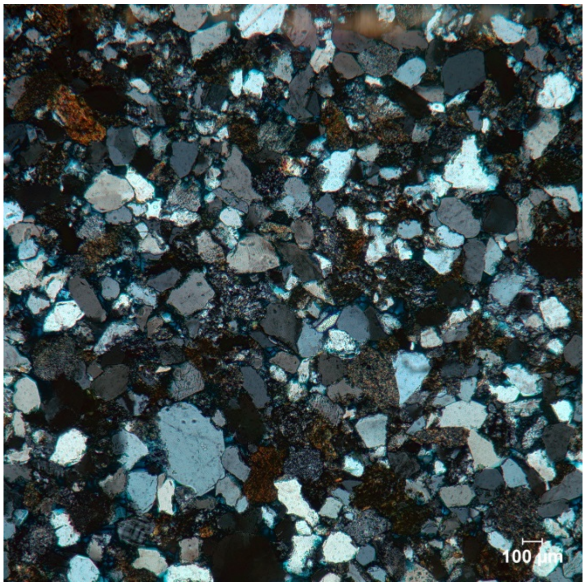
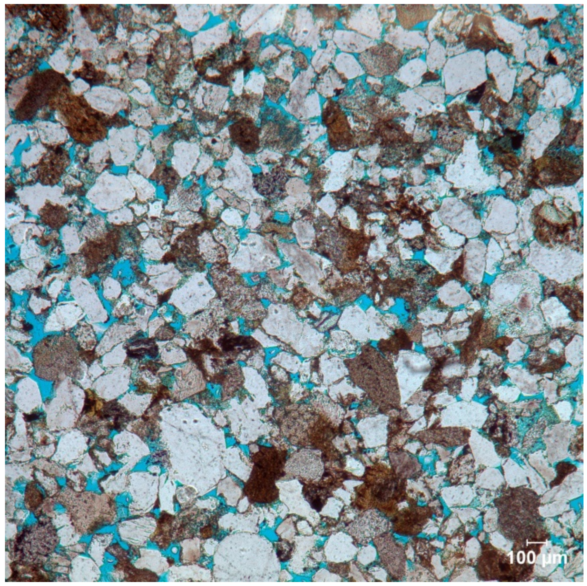


Greyshot Arch 2 (10X, PPL)

Wallace



Wallace (5X, XPL)



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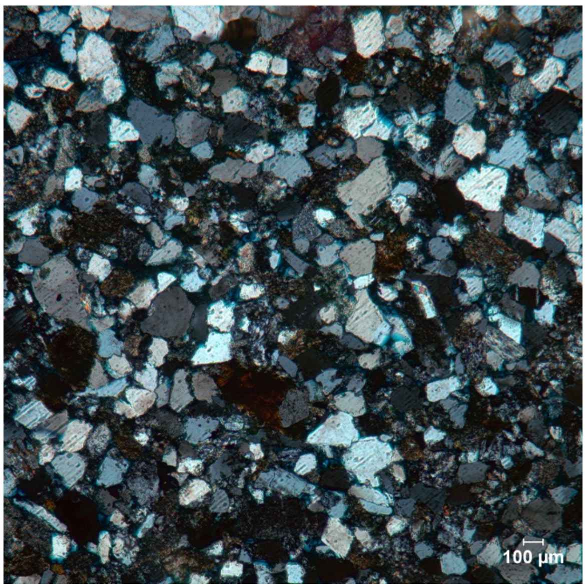

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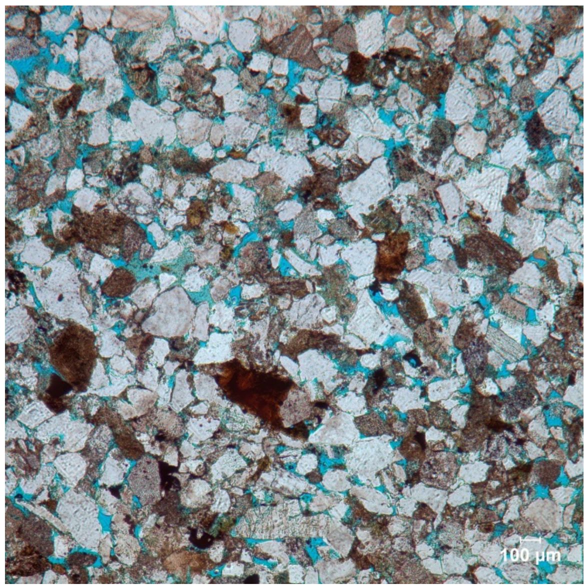

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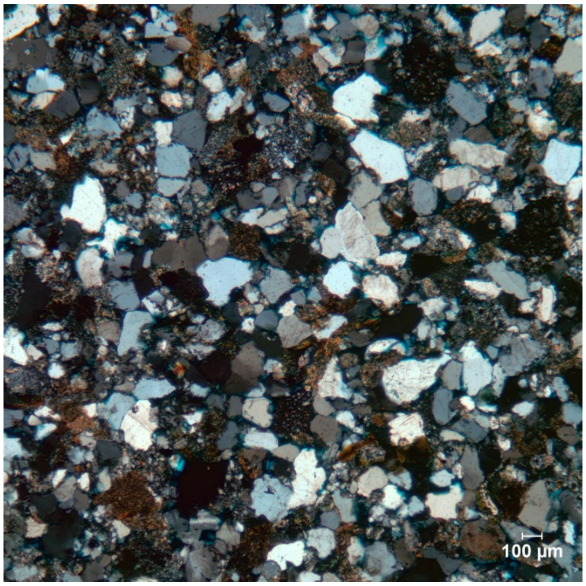

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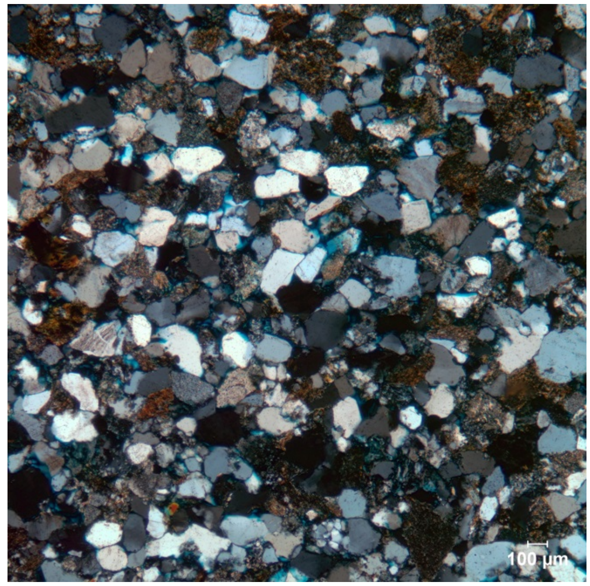

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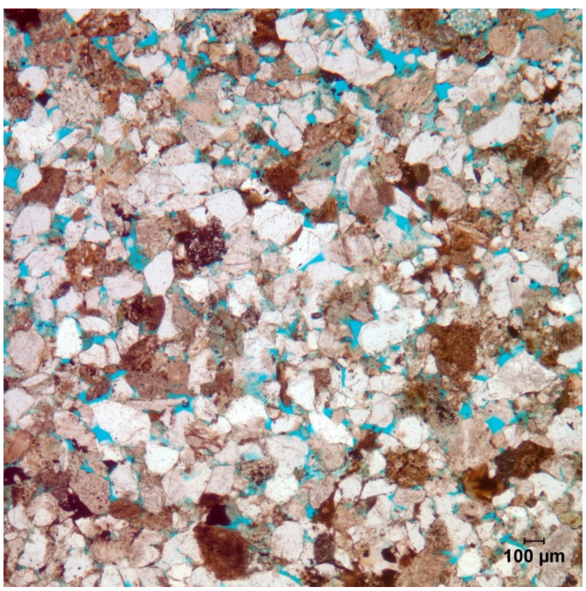

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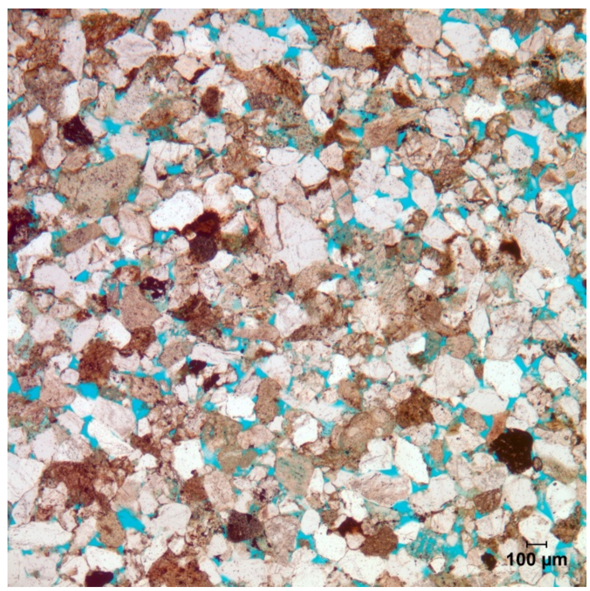

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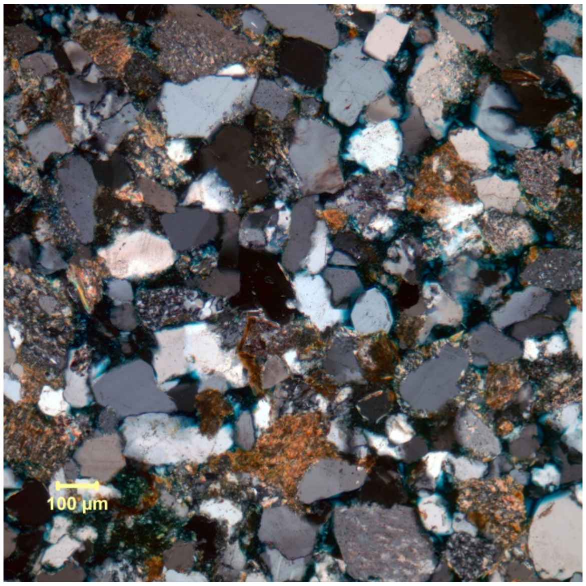

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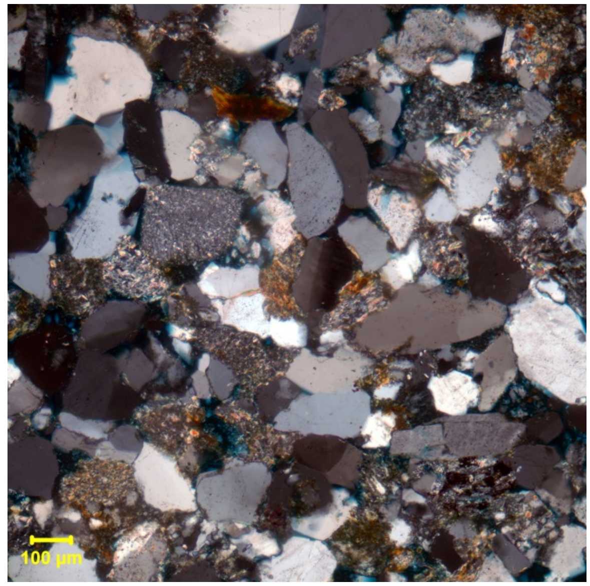

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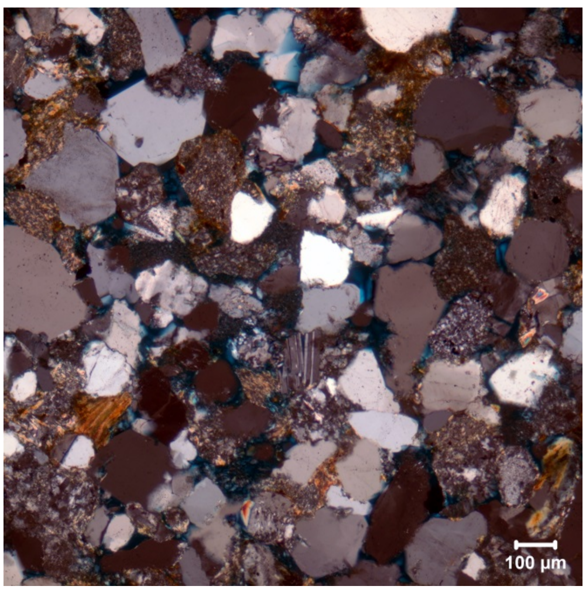

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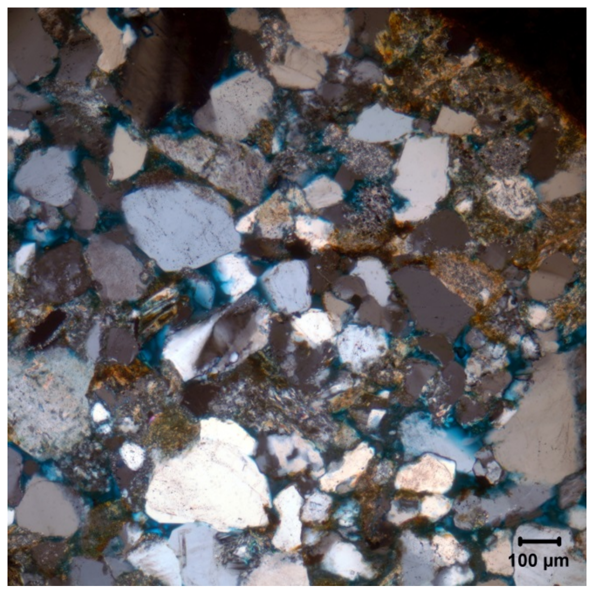
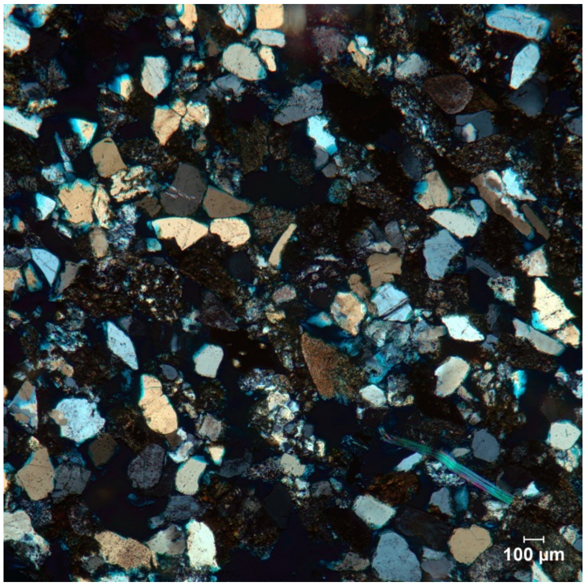
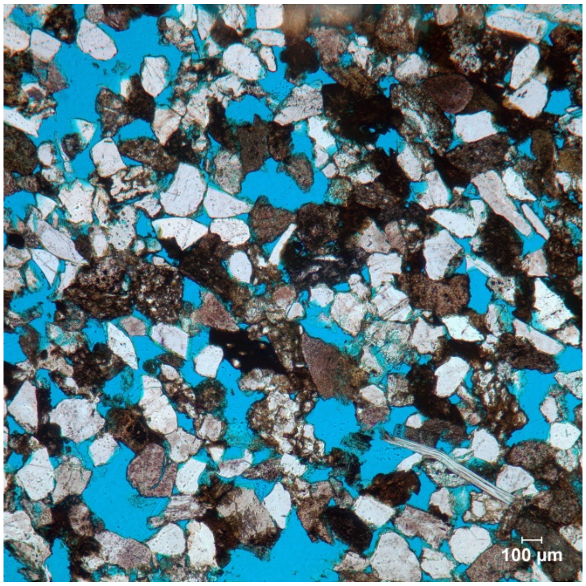


Wallace (10X, XPL)

Willowdell Arch 4



Willowdell Arch 4 (5X, XPL)



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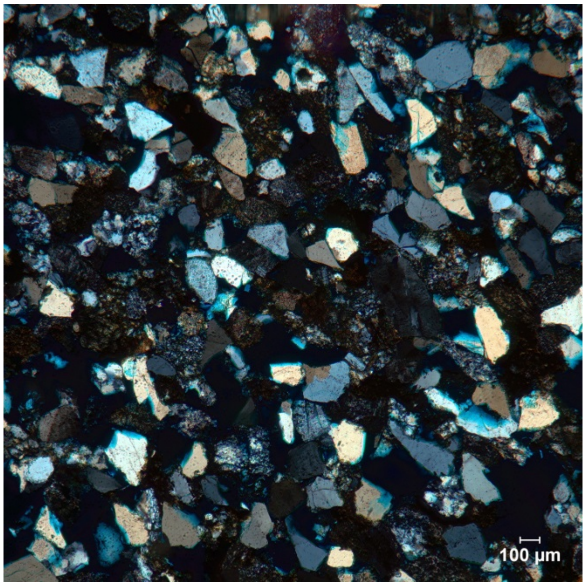

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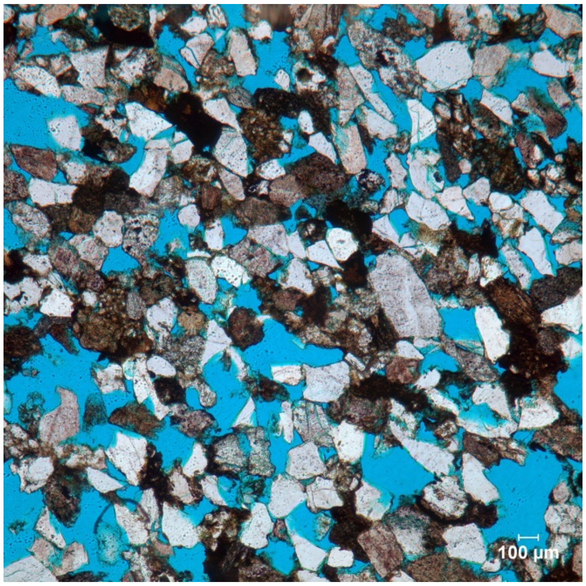

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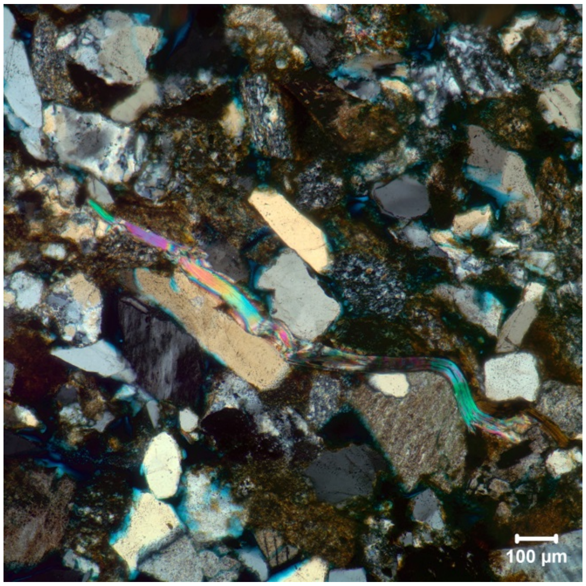

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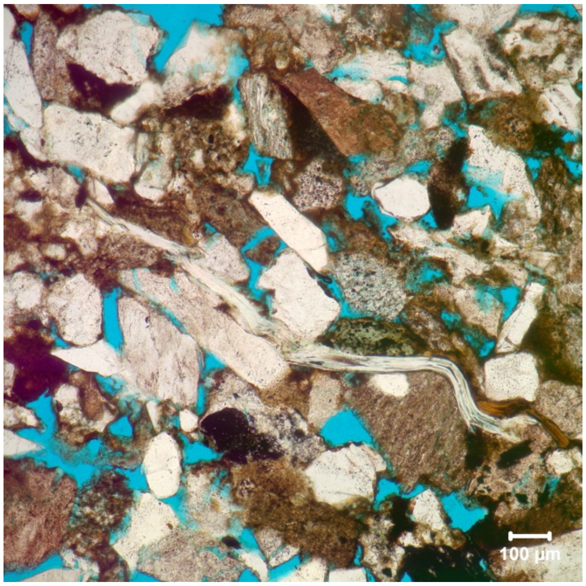

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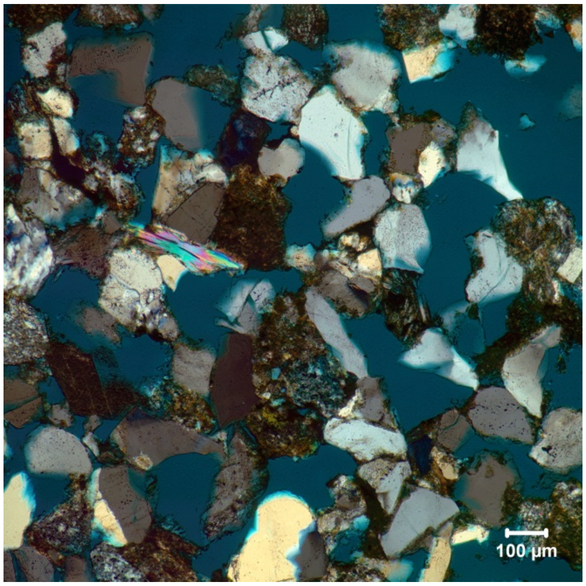

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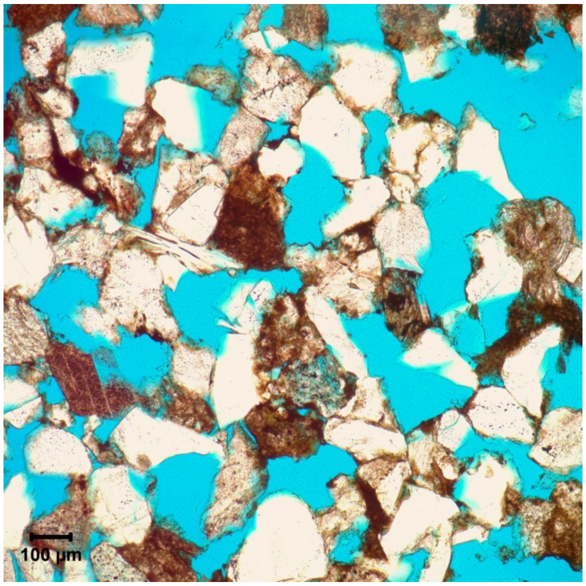

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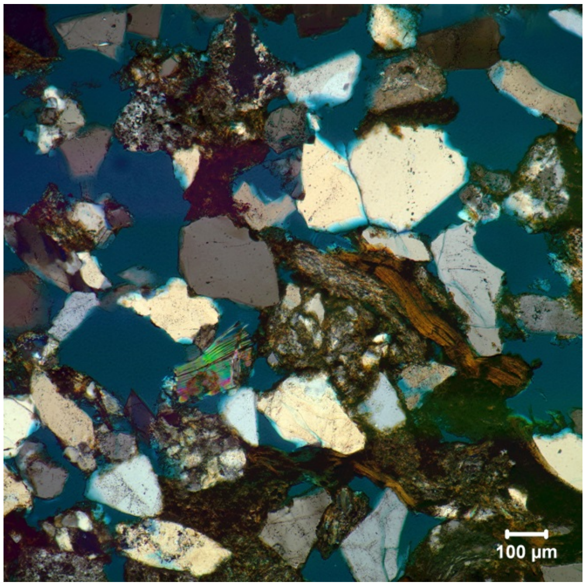

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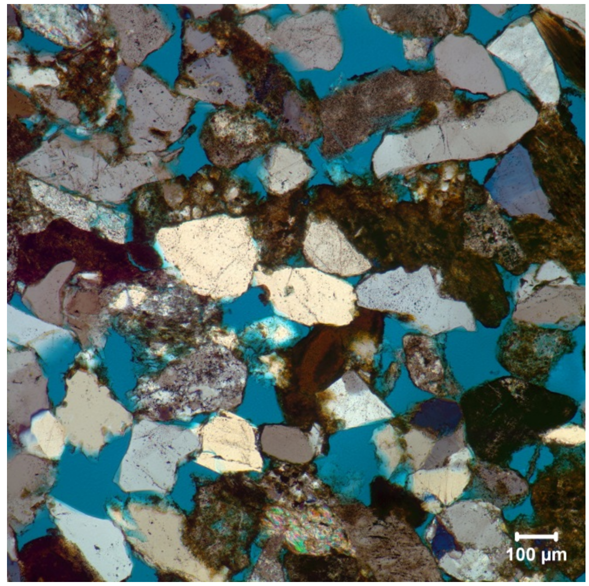

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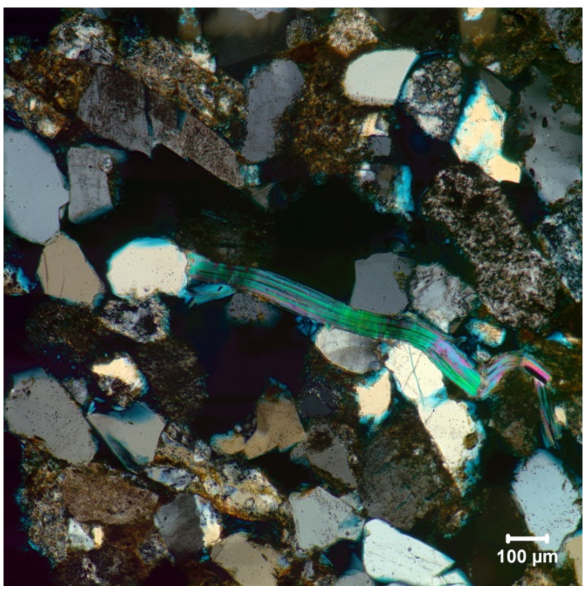

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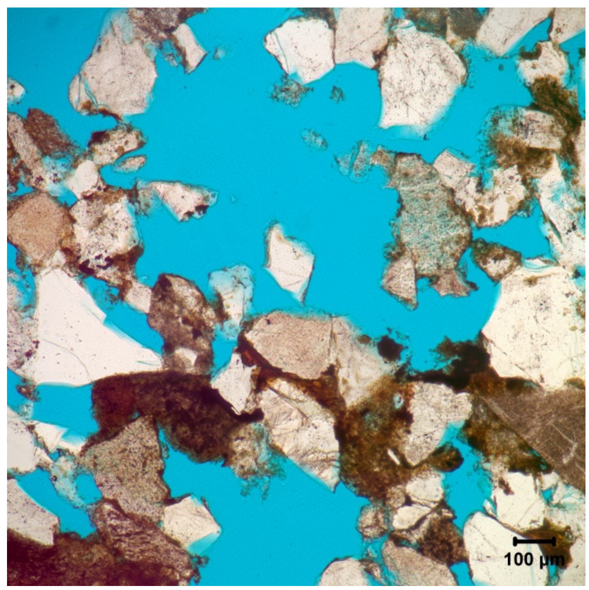
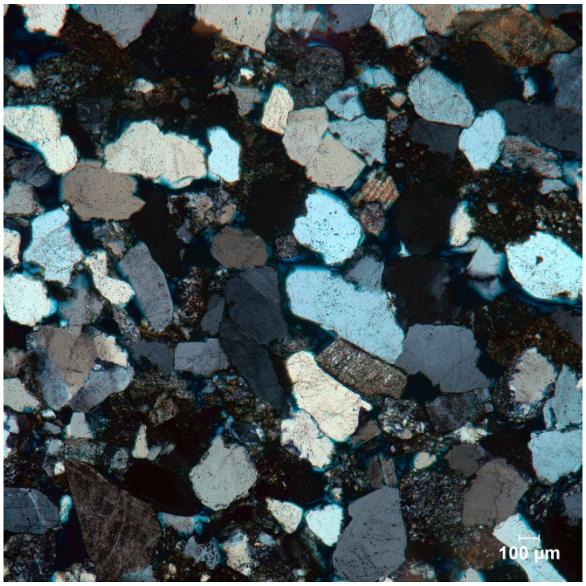
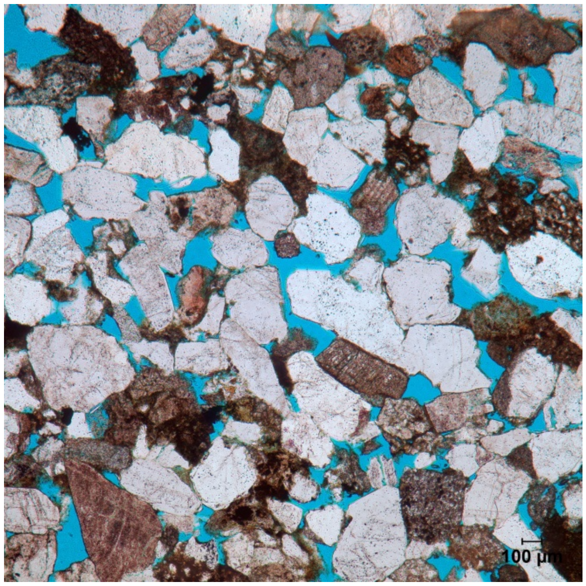


Willowdell Arch 4 (10X, PPL)

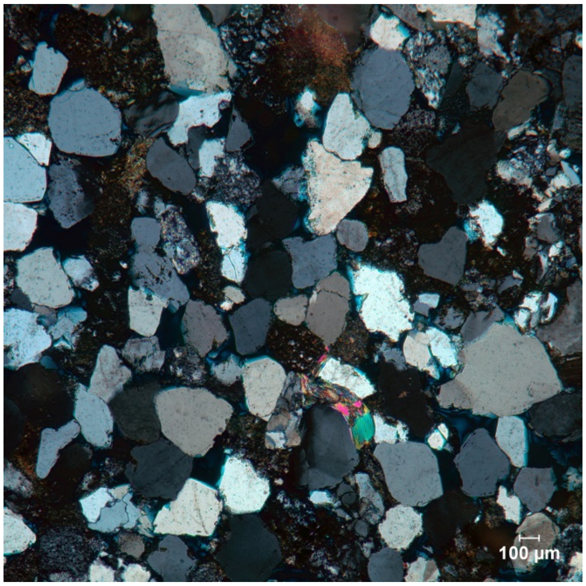
Willowdell Arch 5



Willowdell Arch 5 (5X, XPL)



Willowdell Arch 5 (5X, PPL)



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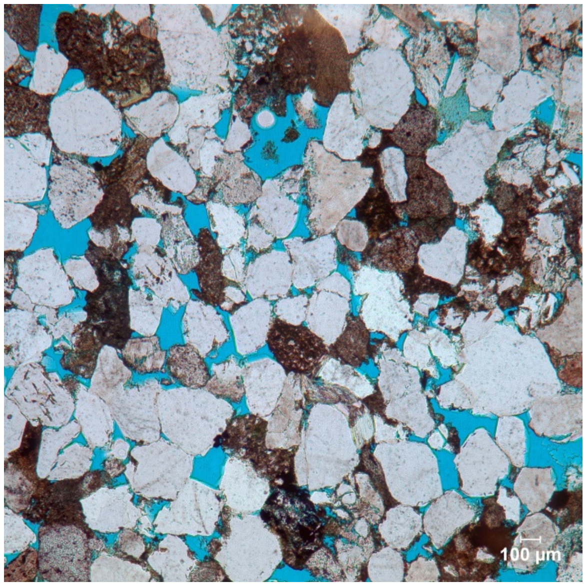

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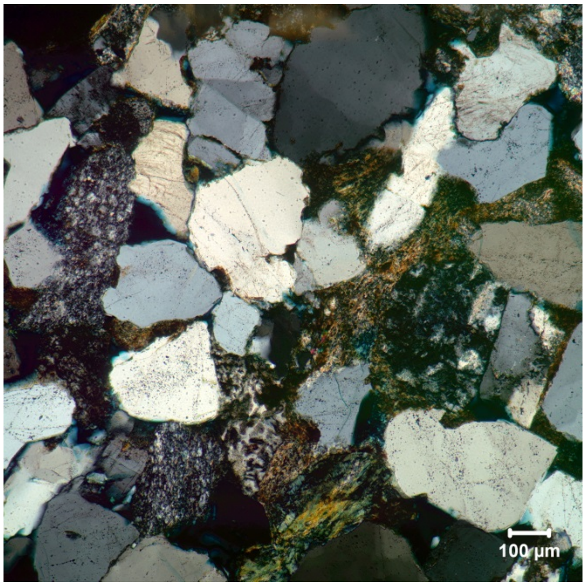
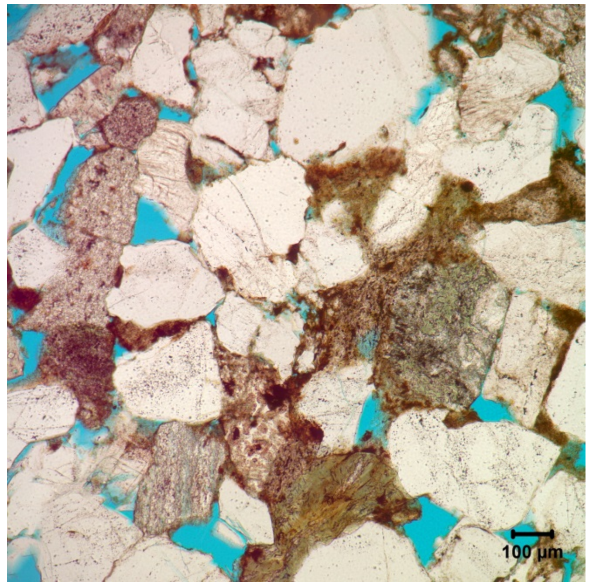
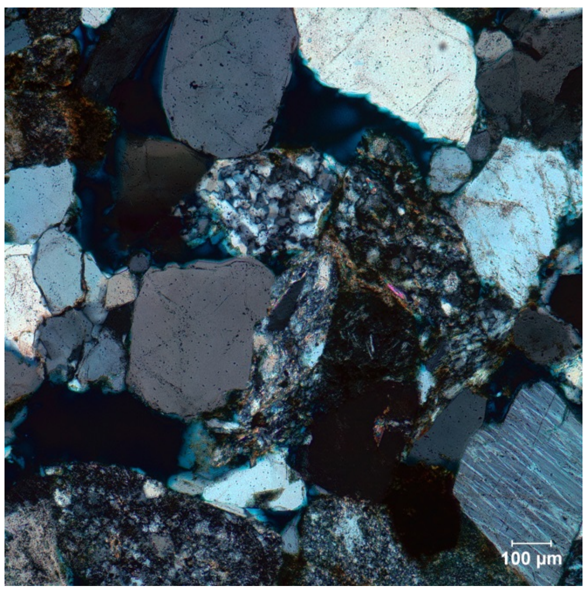


Willowdell Arch 5 (10X, XPL)

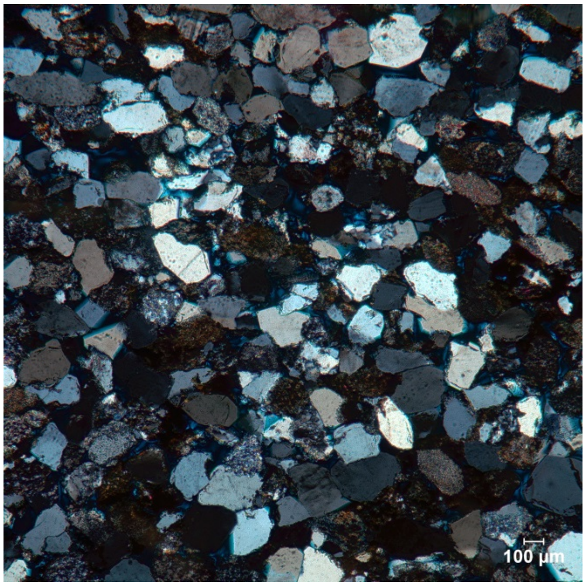


Willowdell Arch 5 (10X, PPL)

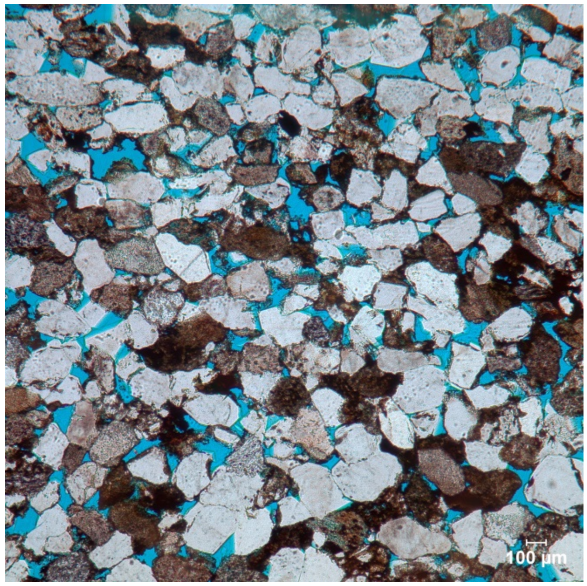


Willowdell Arch 5 (10X, XPL)

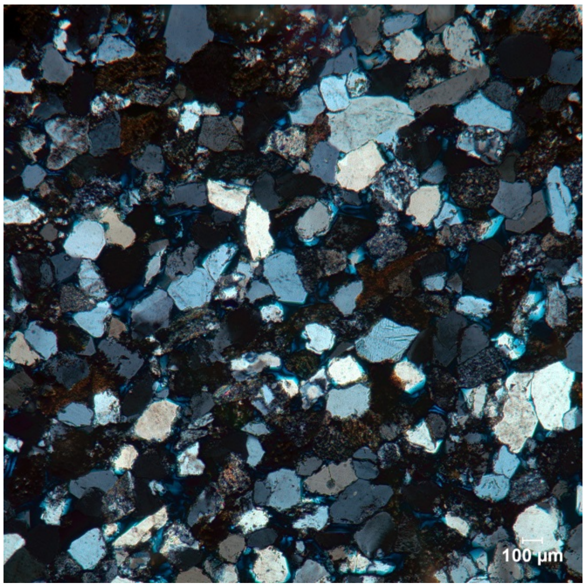
Winterdale Arch 2



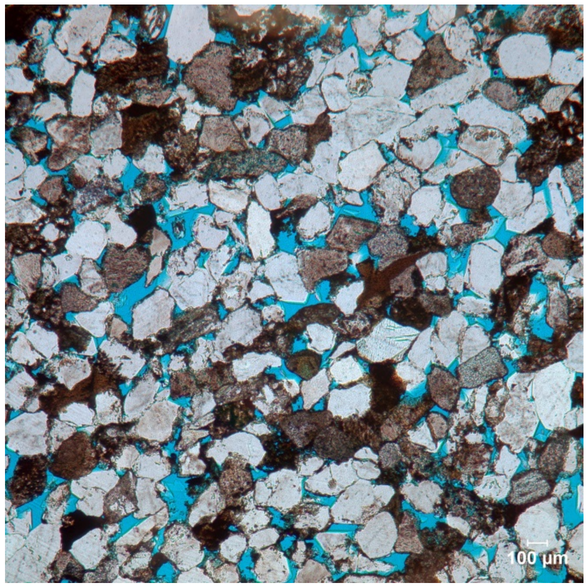
Winterdale Arch 2 (5X, XPL)



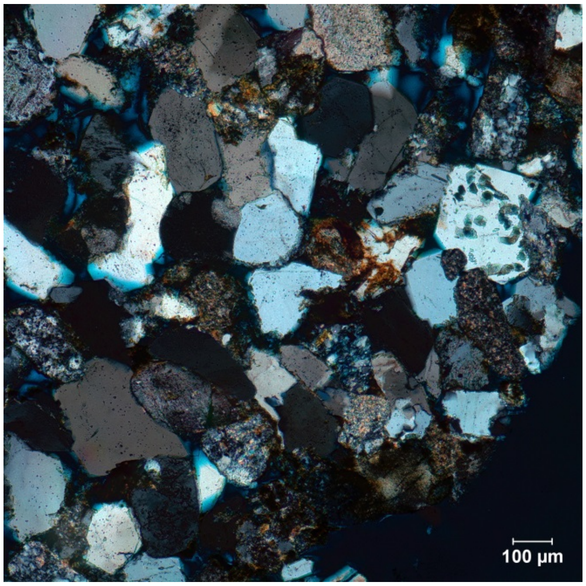
Winterdale Arch 2 (5X, PPL)



Winterdale Arch 2 (5X, XPL)



Winterdale Arch 2 (5X, PPL)



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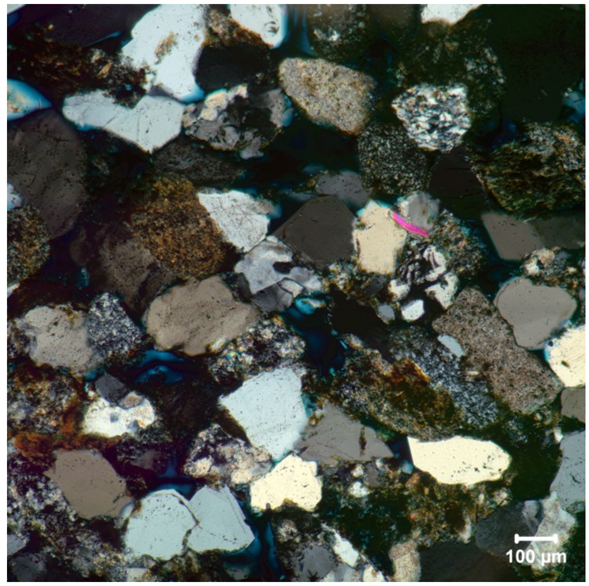
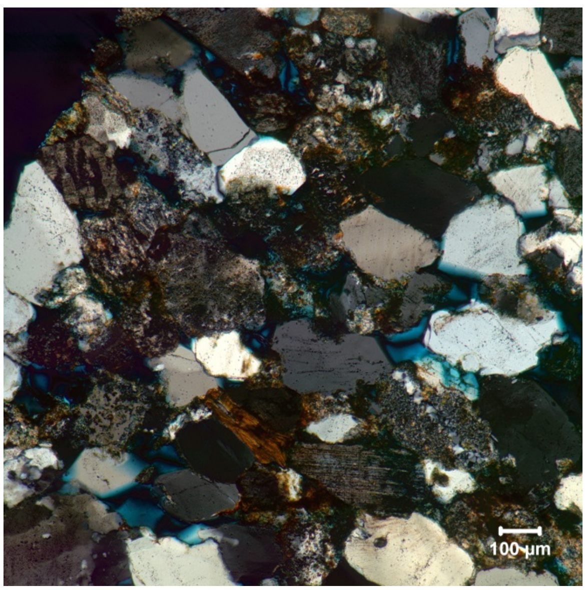
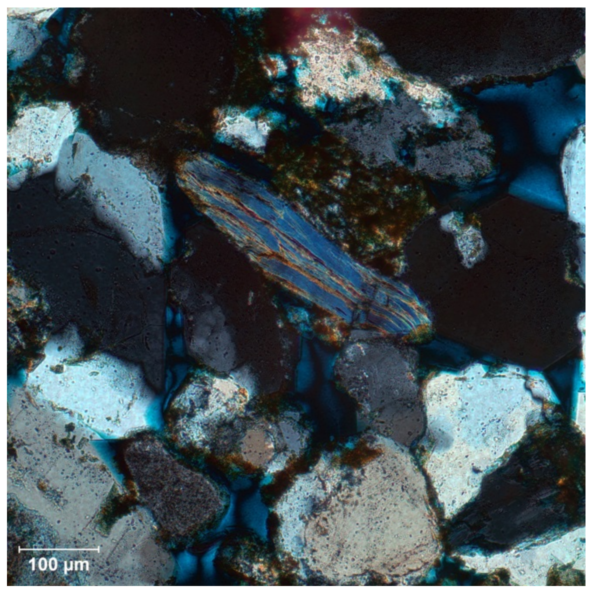


Winterdale Arch 2 (10X, XPL)

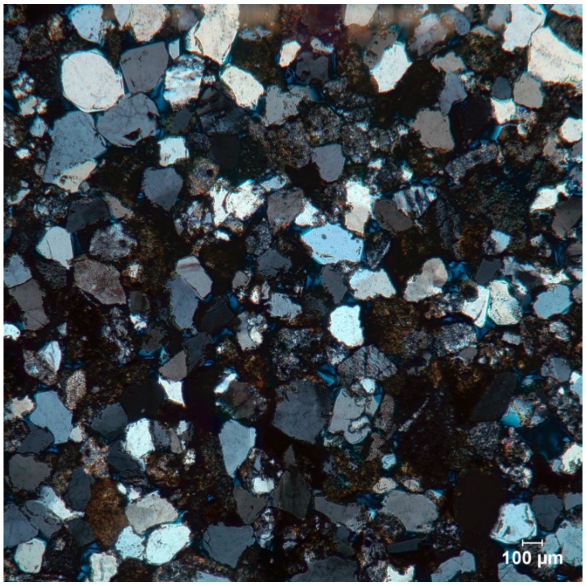


Winterdale Arch 2 (10X, XPL)

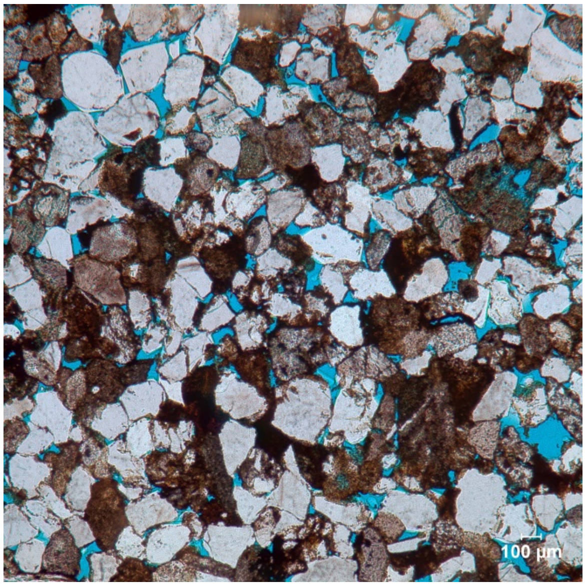


Winterdale Arch 2 (20X, XPL)

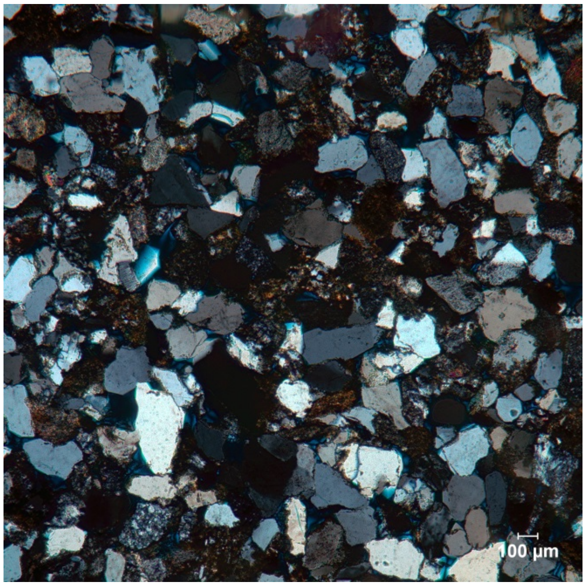
Winterdale Arch 3



Winterdale Arch 3 (5X, XPL)



Winterdale Arch 3 (5X, PPL)



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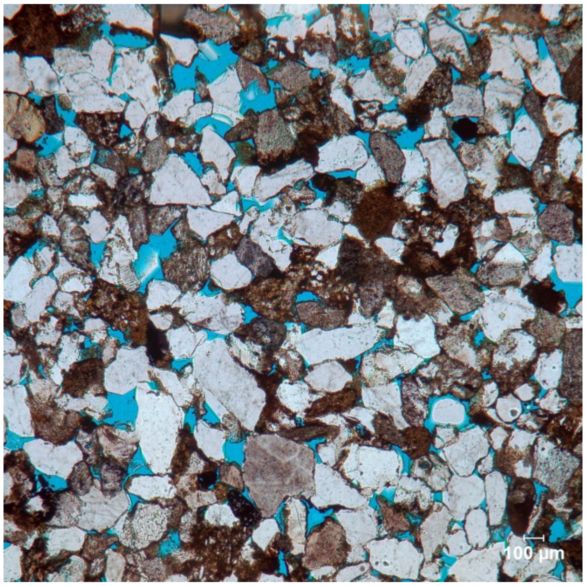

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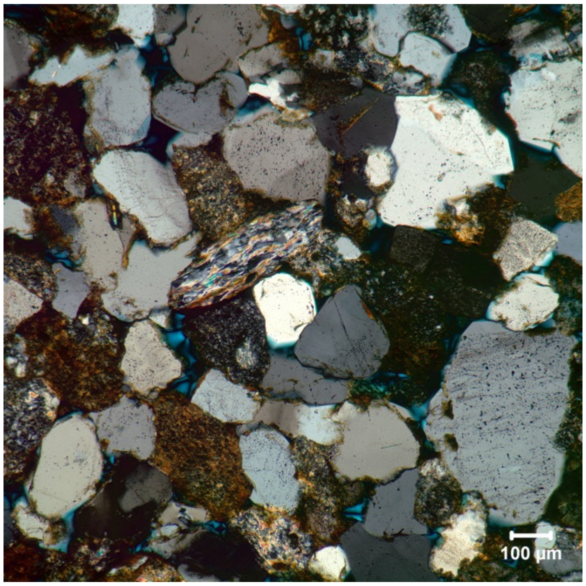
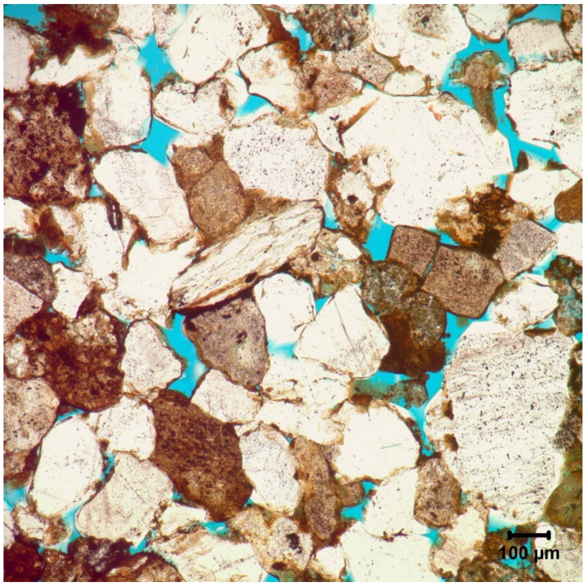
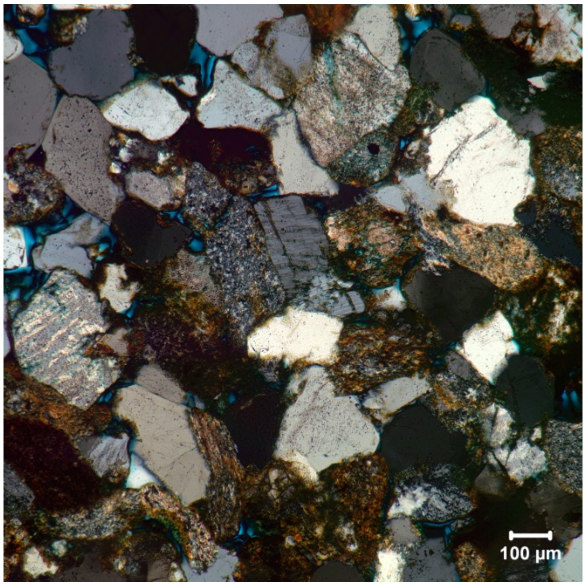


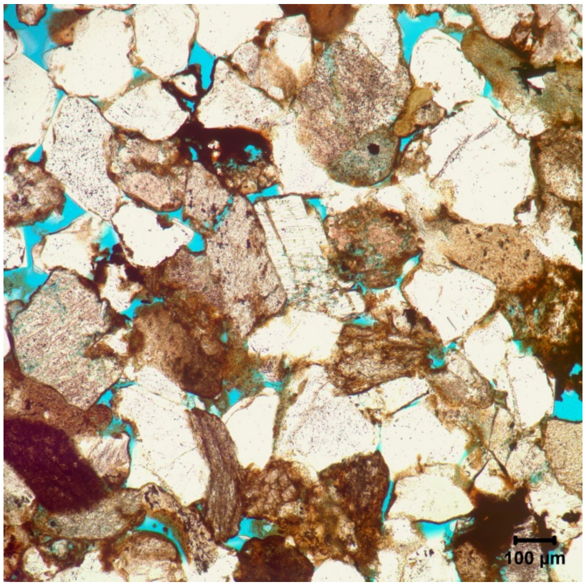
Winterdale Arch 3 (10X, XPL)



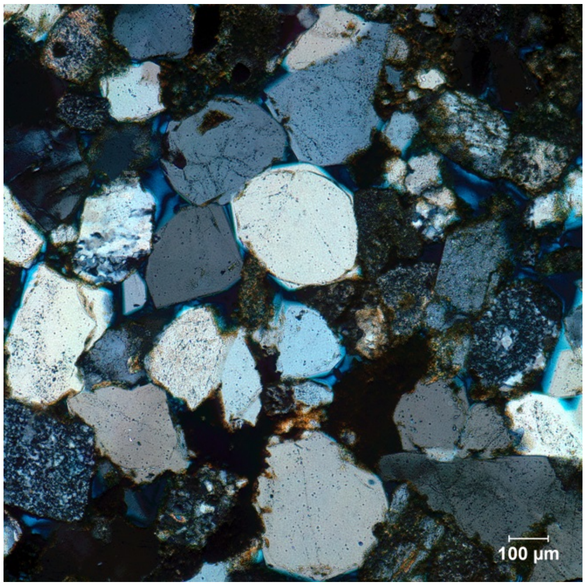
Winterdale Arch 3 (10X, PPL)



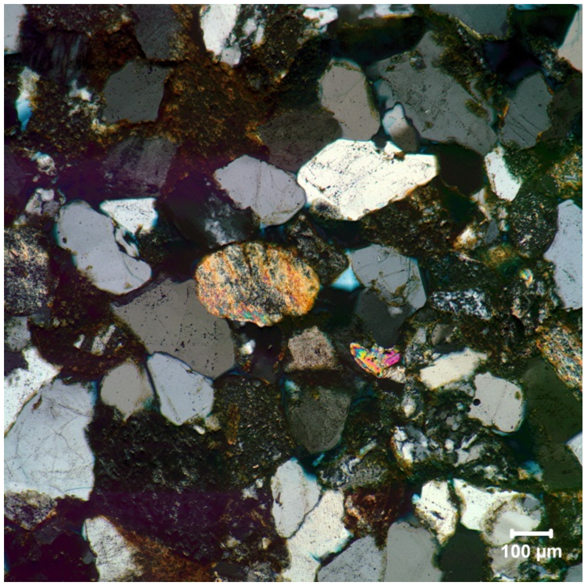
Winterdale Arch 3 (10X, XPL)



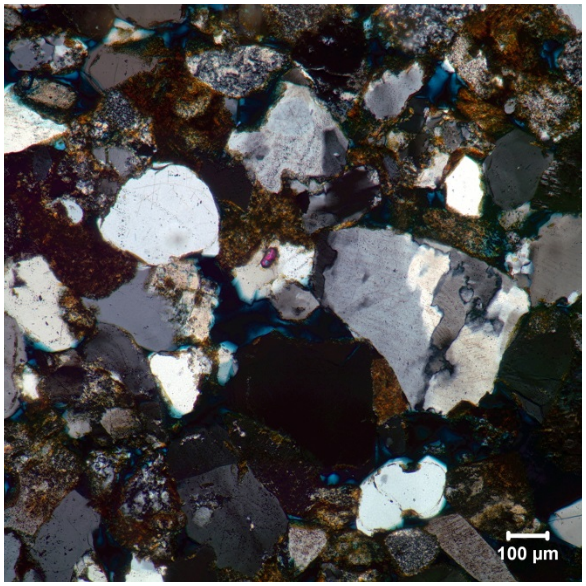
Winterdale Arch 3 (10X, PPL)



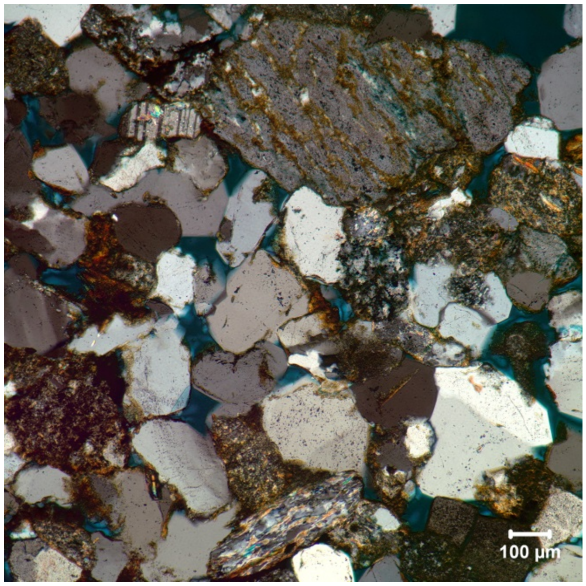
Winterdale Arch 3 (10X, XPL)



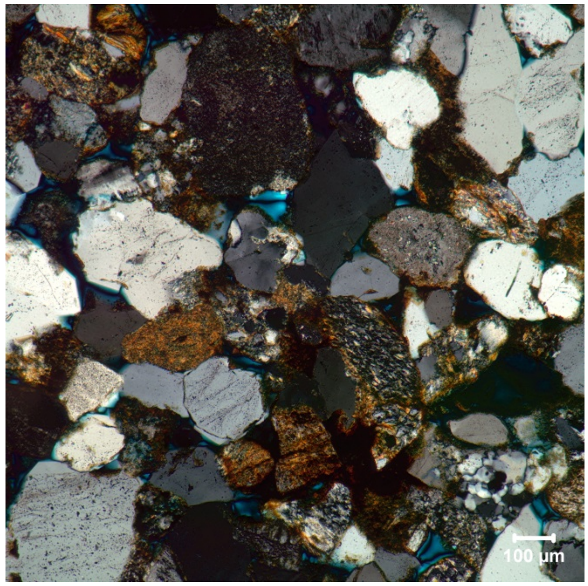
Winterdale Arch 3 (10X, XPL)



Winterdale Arch 3 (10X, XPL)



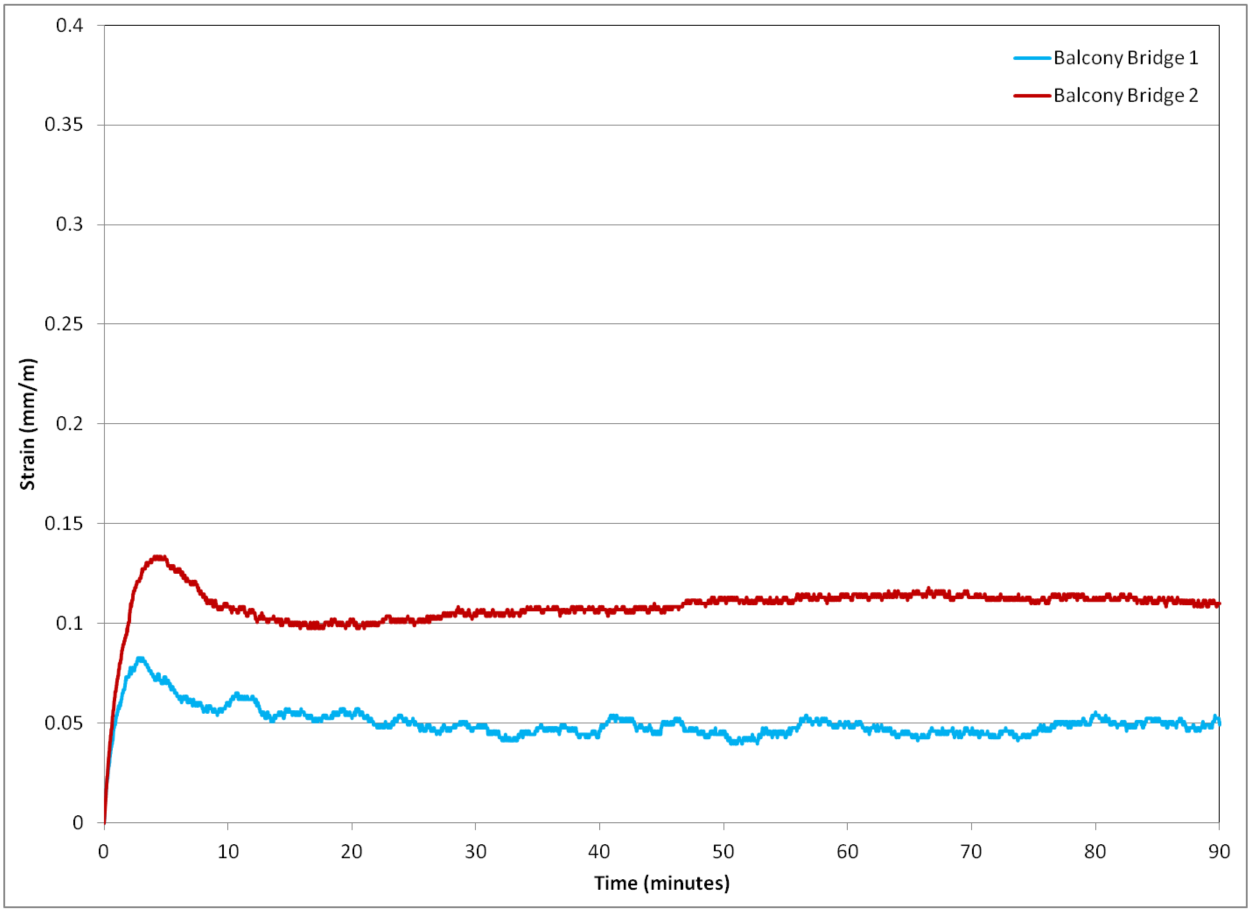
Winterdale Arch 3 (10X, XPL)



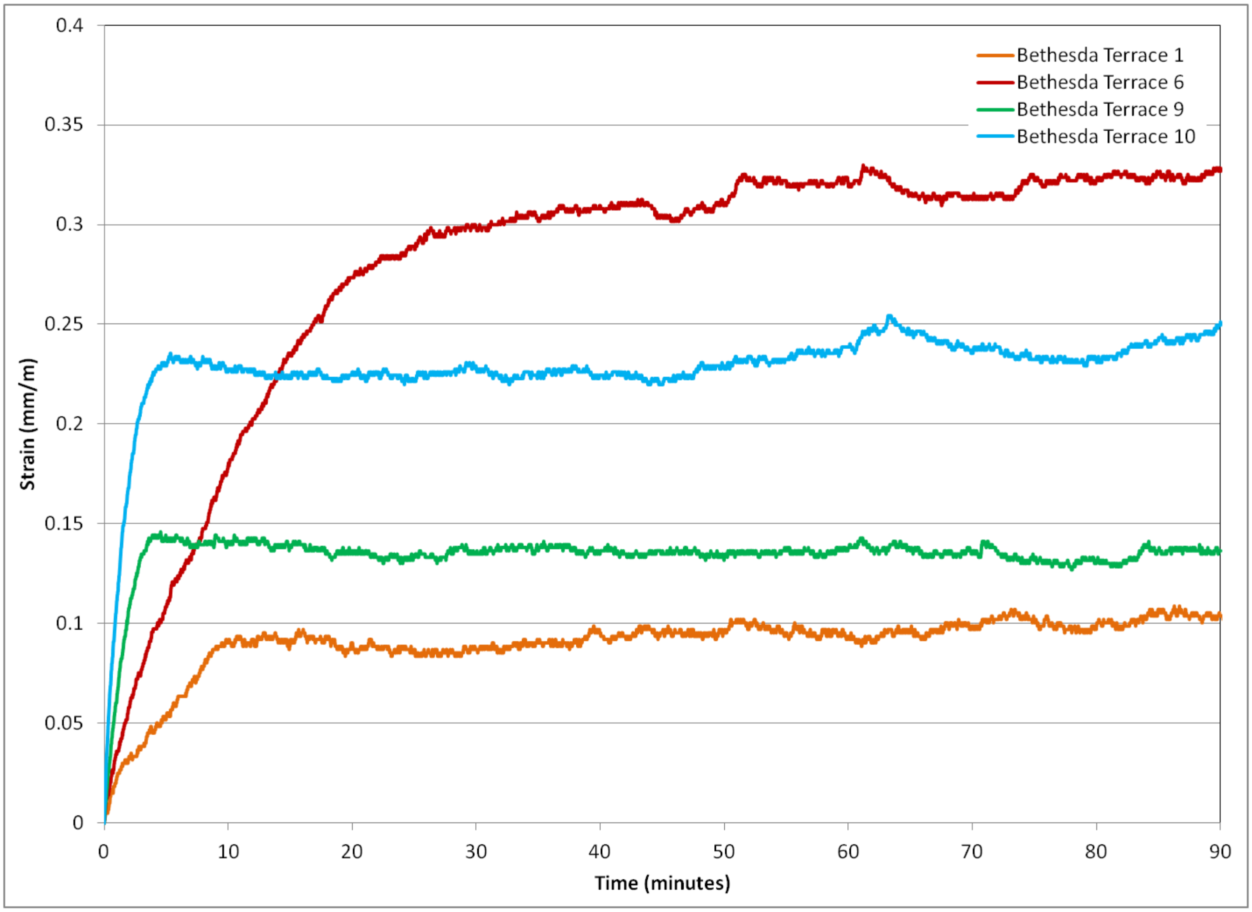
Winterdale Arch 3 (10X, XPL)

APPENDIX F: HYGRIC DILATION GRAPHS

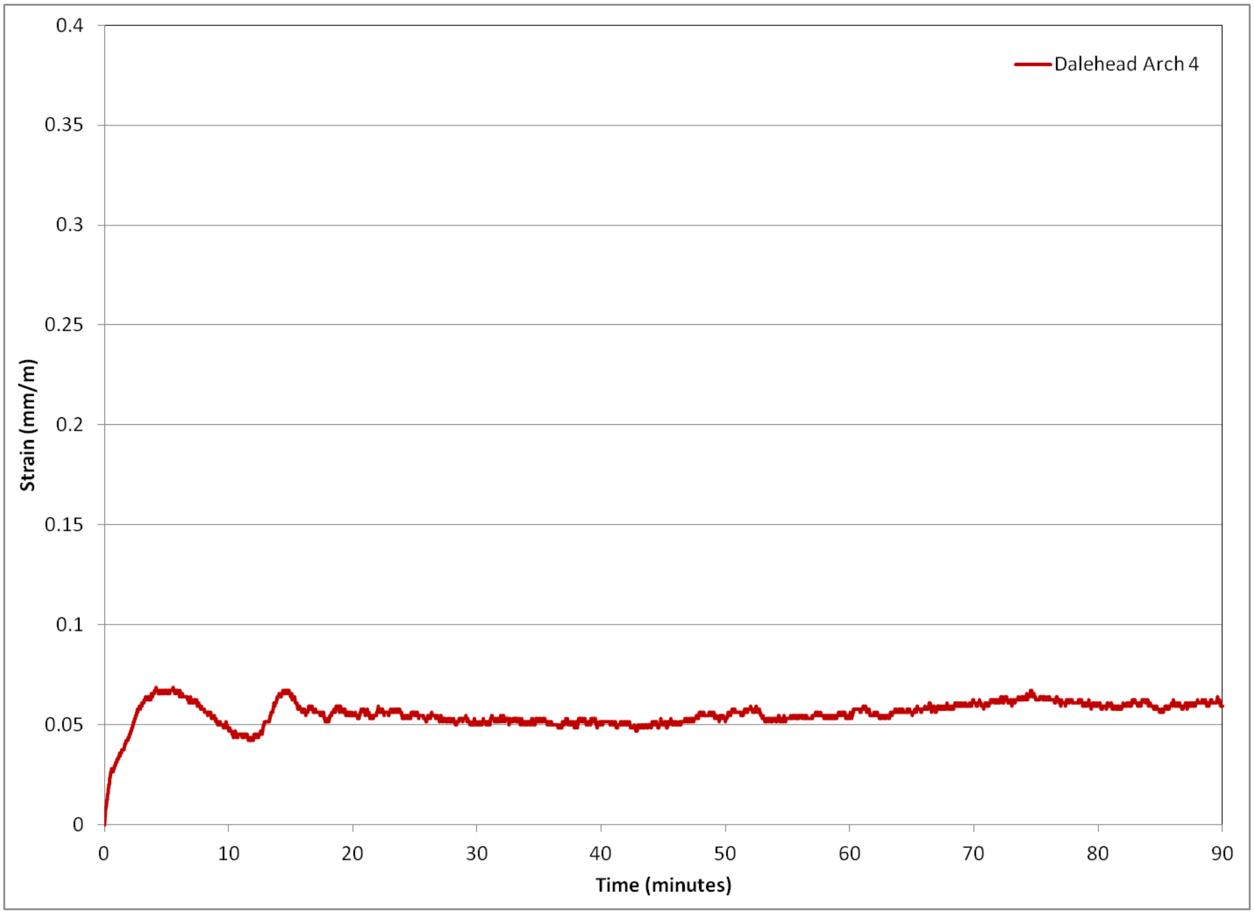
Balcony Bridge

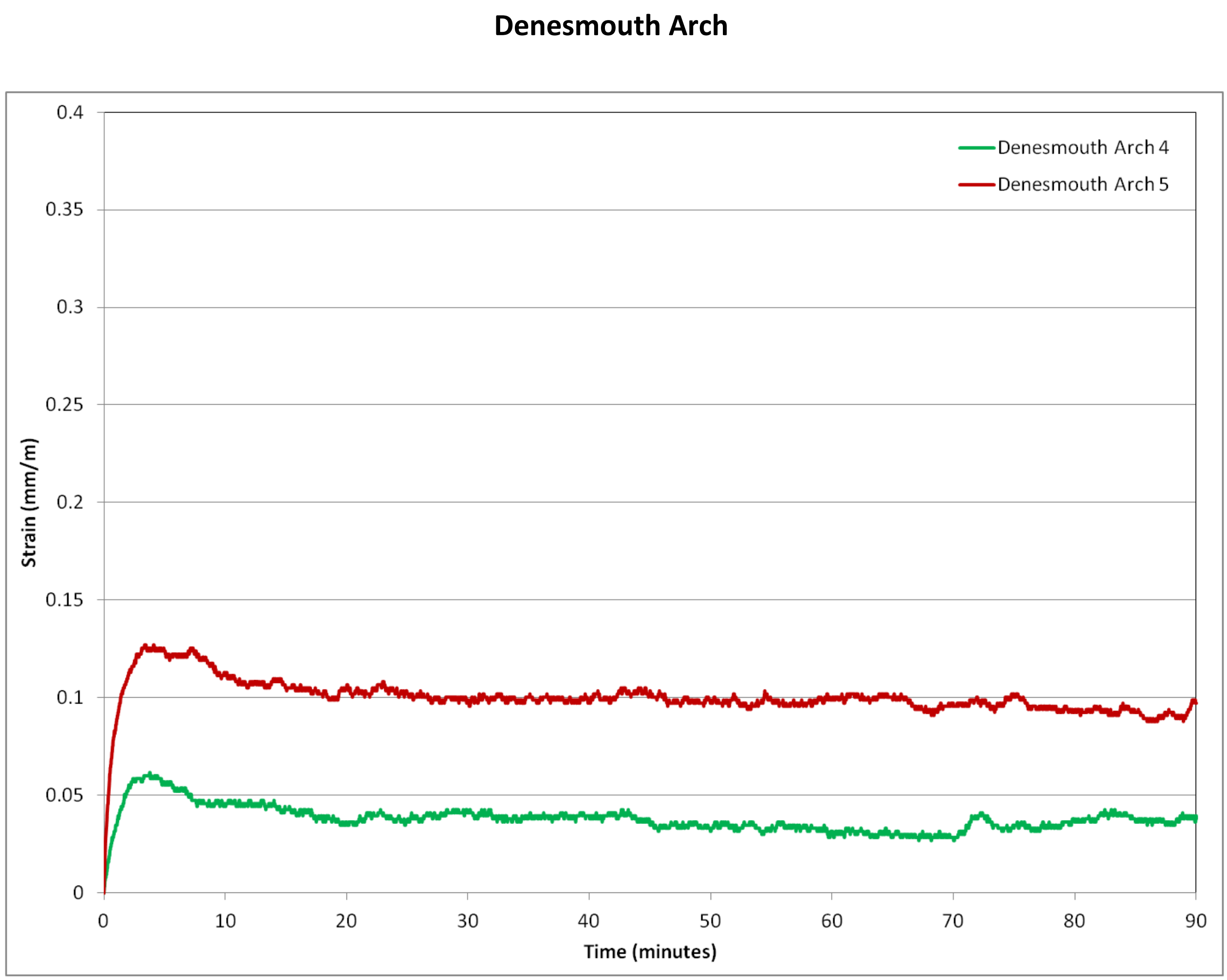


Bethesda Terrace

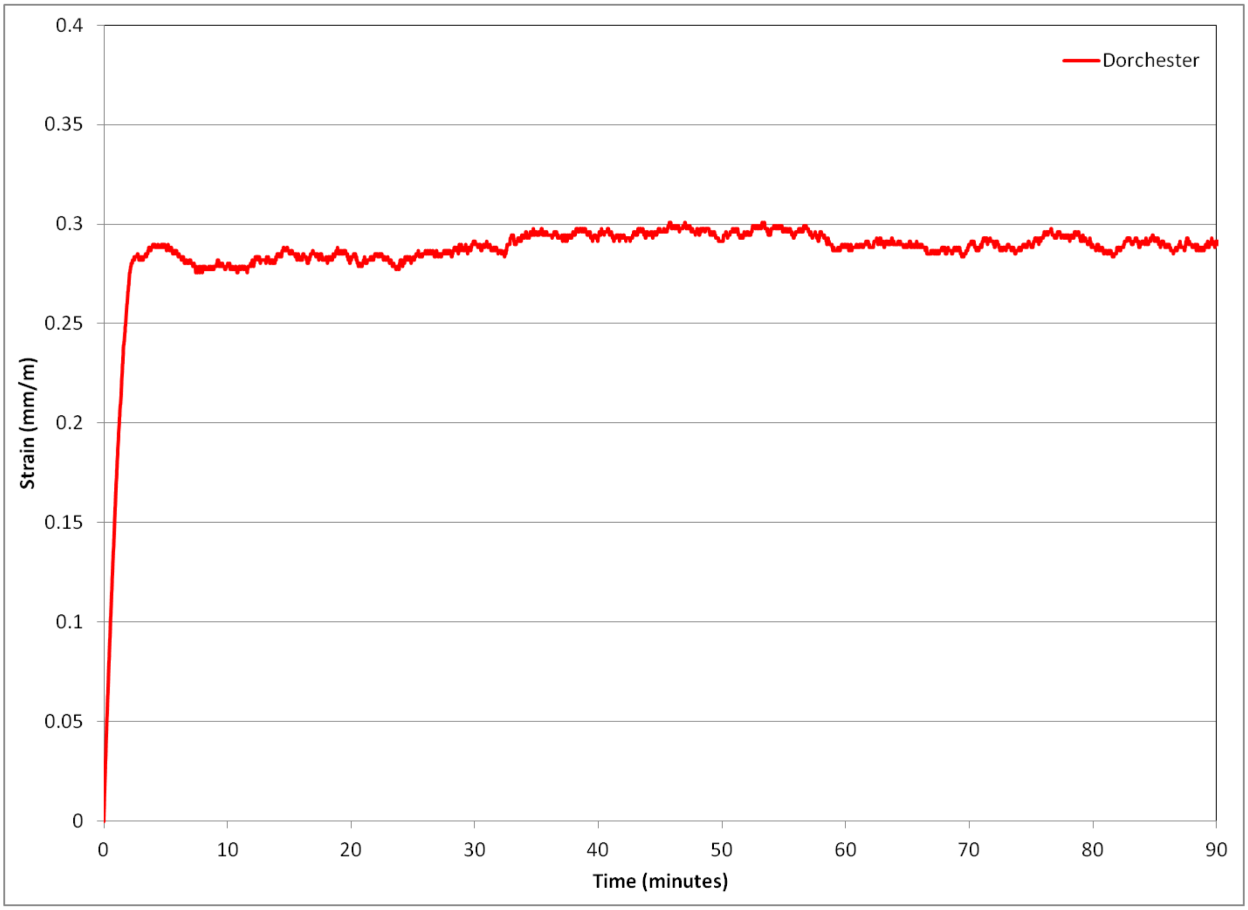


Dalehead Arch

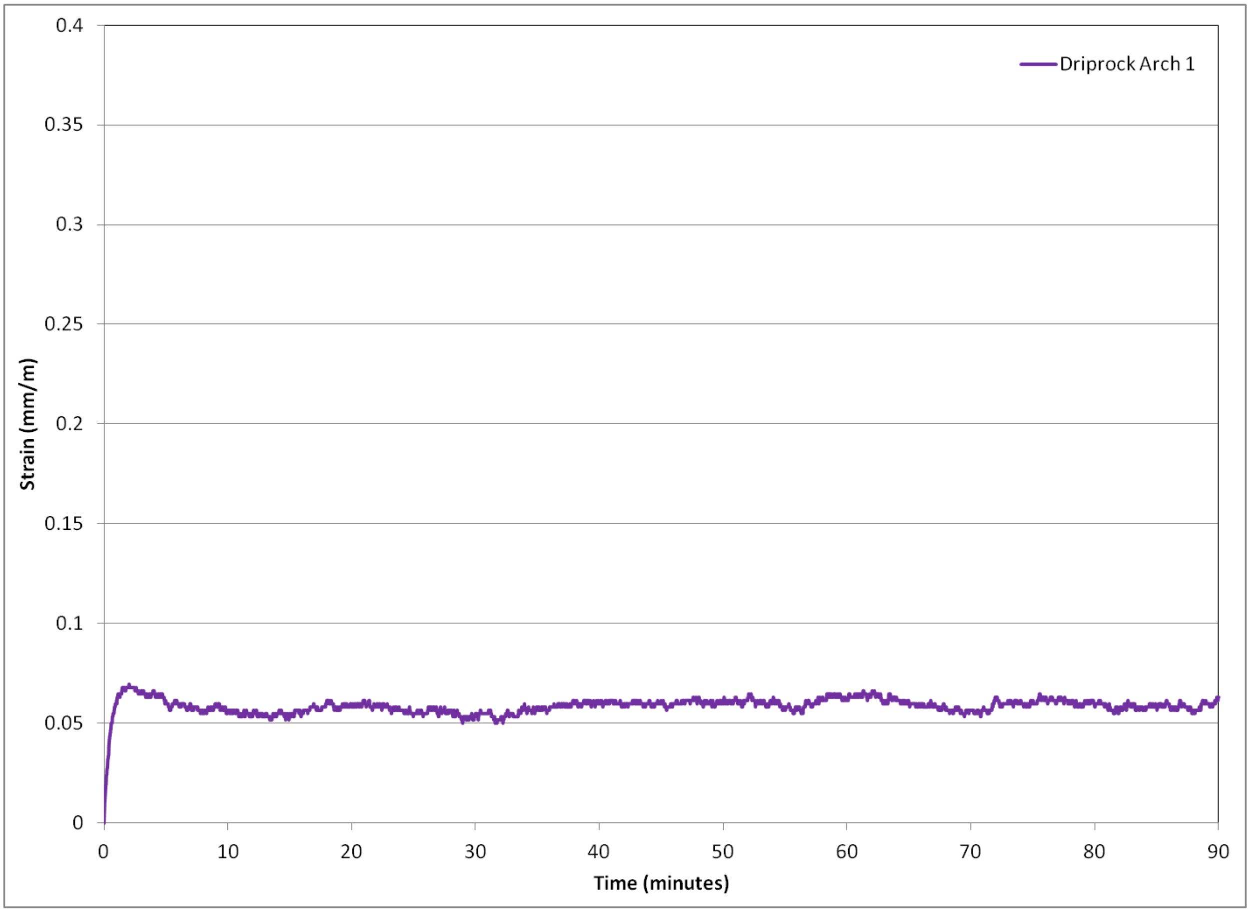



Denesmouth Arch
Denesmouth Arch 4
Denesmouth Arch 5
Strain (mm/m)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
60
70
80
90
Time (minutes)

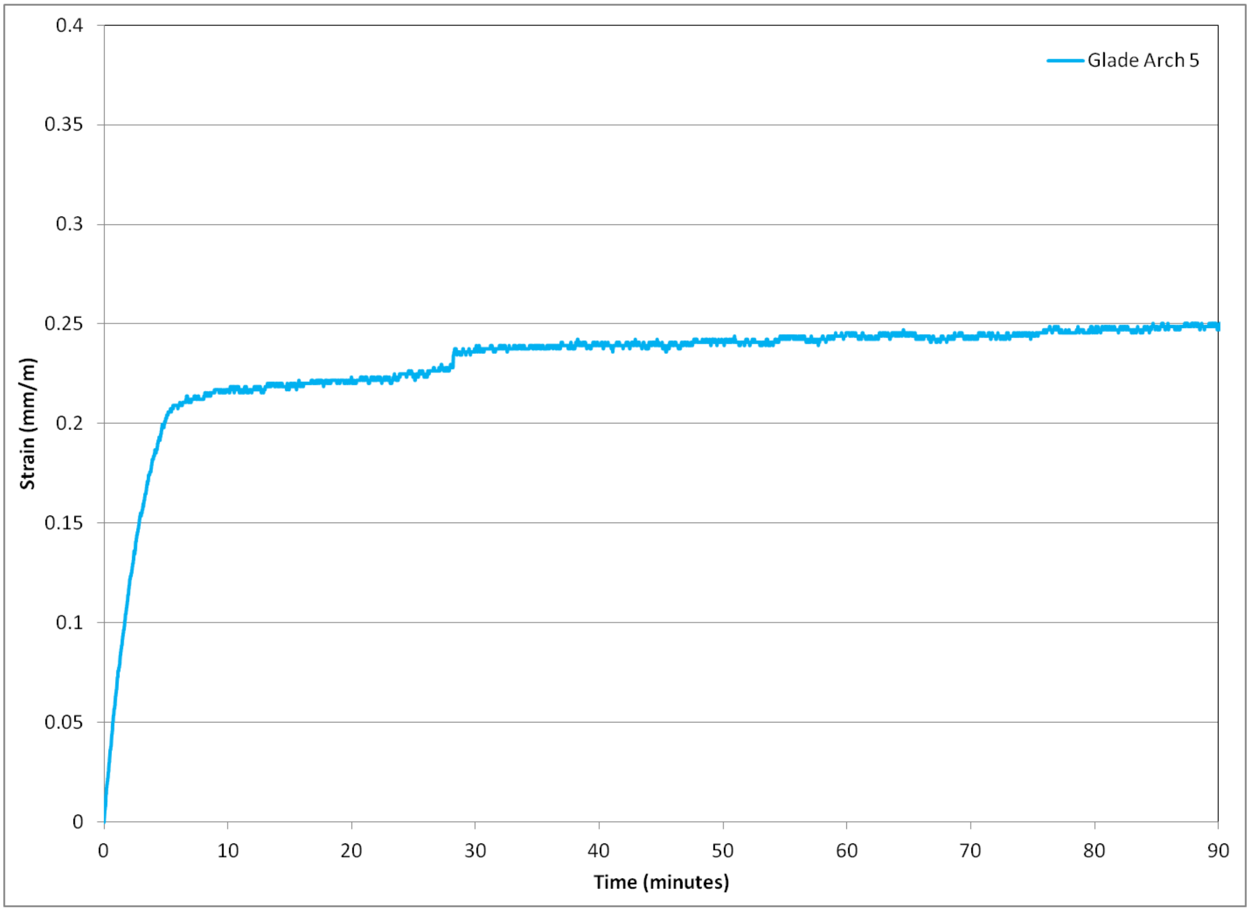
Dorchester

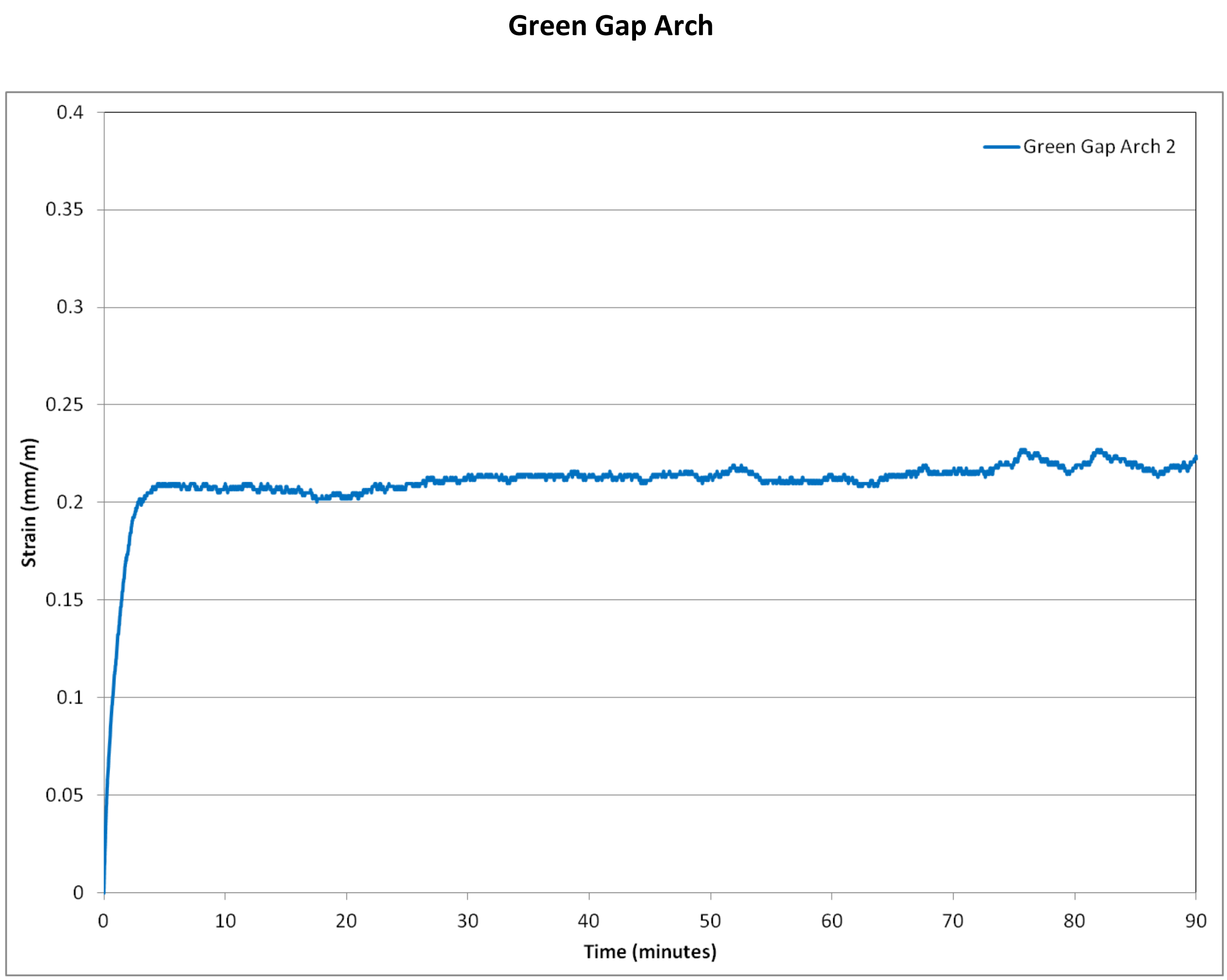

Dorchester
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Strain (mm/m)
0
10
20
30
40
50
60
70
80
90
Time (minutes)

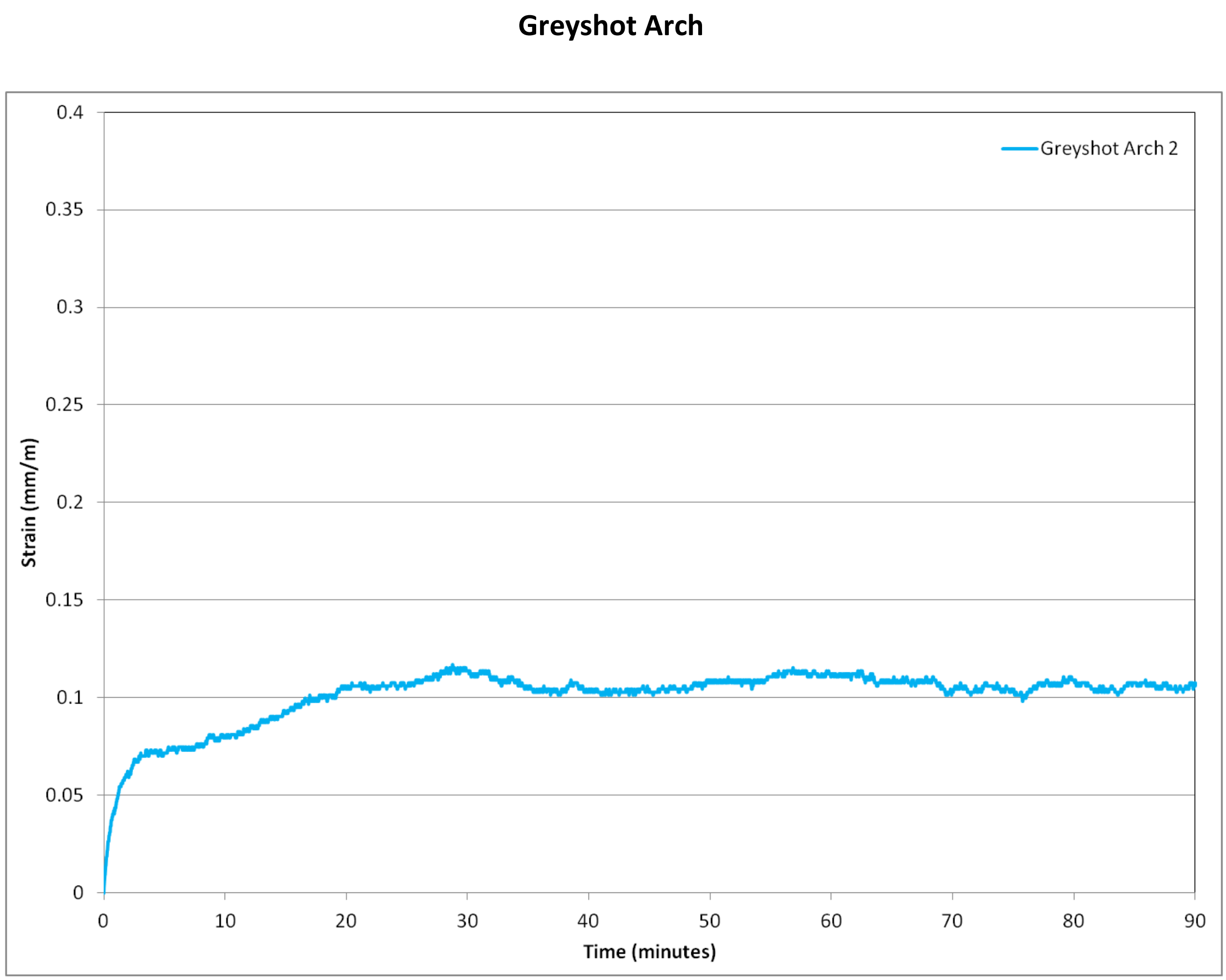
Driprock Arch



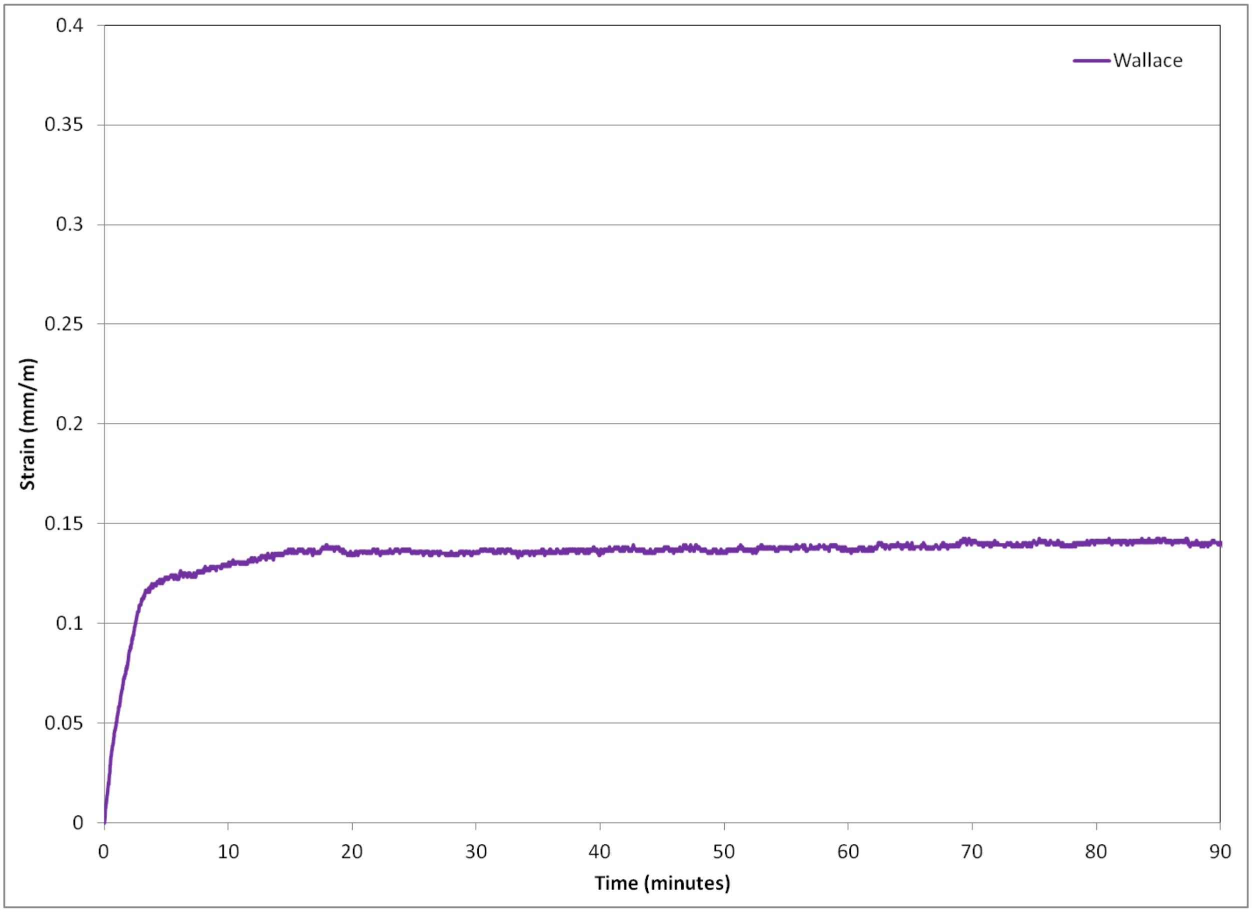
Glade Arch


Glade Arch 5
Strain (mm/m)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
60
70
80
90
Time (minutes)

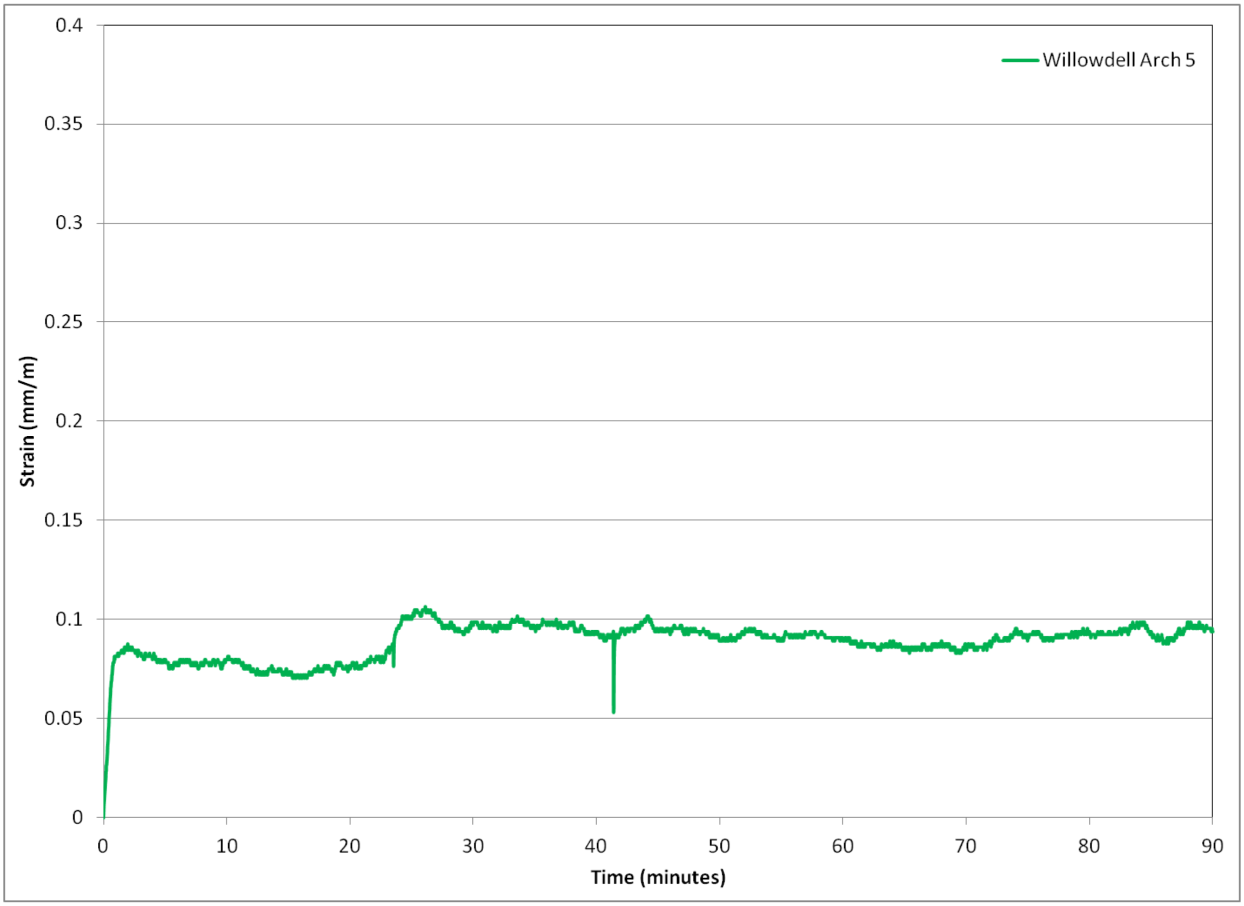

Green Gap Arch
Green Gap Arch 2
Strain (mm/m)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
60
70
80
90
Time (minutes)


Greyshot Arch
Greyshot Arch 2
Strain (mm/m)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
60
70
80
90
Time (minutes)

Wallace


Wallace
Strain (mm/m)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
60
70
80
90
Time (minutes)

Willowdell Arch



Winterdale Arch