XV. JASPER CHARACTERIZATION

Introduction

Archaeologists have sought to understand where prehistoric raw materials were originally procured in geological context. The recovery of distinctive jaspers at the Lums Pond site provided the opportunity to determine if the original geological sources for the stone artifacts could be identified. If this attempt were successful, archaeologists would have a way to infer the distances raw materials were transported.

There were four hierarchically oriented goals of the Lums Pond jasper study:

1) to chemically differentiate the Pennsylvania and Delaware jaspers
2) to differentiate the various jasper quarry areas within Delaware
3) to identify Pennsylvania and Delaware jaspers at the Lums Pond site
4) to provenance Lums Pond jasper artifacts back to source areas.

The experimental design takes on the form of a four-level pyramid whose foundation consists of geological field investigation and map interpretation. As part of the geological mapping, field investigations are made to establish the distribution and interrelationships of the various lithologies present locally, at a scale finer than is typically apparent in published geological maps. Such checks often provide additional data vital to understanding the local expressions of broader regional geologic events, expressions that may be reflected in geochemical variations. Geological samples are also collected at this stage; from these a limited number of slabs and thin sections are later created as references for macroscopic and microscopic petrographic analysis of prehistoric lithic materials.

At the next level of the pyramid, the relevant geological literature is reviewed and data available from previous studies is assembled for later comparison. At this point, the standards to be used for the current study may be defined. At the third level of the pyramid, the samples are subjected to petrographic analysis and various methods of geochemical analyses (X-ray diffraction, clay fractionation, silica crystallinity, SEM/EDX) to establish the textural and chemical characteristics of possible lithic sources for the prehistoric artifacts under investigation. Some of the prehistoric artifacts are subjected to the same analyses for comparative purposes.

At the apex of the pyramid, the data derived from the previous three levels are combined to determine whether any of the lithologies represented by the geological samples is the potential source of the prehistoric lithic material in question. If so, an understanding of the geological context of that lithology allows for prediction of the geographic distribution of potential prehistoric quarry sites for that material. If there is no probable match between the prehistoric lithic material and the geological samples, however, the textural characteristics and geochemistry of the prehistoric artifacts may be used to suggest other possible geological lithologies/settings which may have served as the source of the lithic material.

This chapter is organized into four main sections. The first section discusses the regional geology. Placement of the jaspers in proper geological context is of utmost importance in determining the origin, relationship, and distribution of various rocks. The second section reviews previous archaeological provenance studies on Pennsylvania and Delaware jaspers. The general findings and the advantages and disadvantages of previous chemical studies are addressed. The third section presents the results of the current geochemical analysis. The experimental design, the samples and their regional context, and the results of various analytical studies are discussed. Finally, the last section presents the conclusions drawn from this study.

Regional Geology

Potential Source Lithologies at Iron Hill

The geologic history of the central Appalachians is long and quite complex and has resulted in the formation of various physiographic provinces, each with its distinctive assemblages of rocks (see Drake et al. 1989 for a high detailed synthesis of the regional geology). For the purposes of the present study, however, attention is focused primarily on the igneous and metamorphic rocks of the immediate Iron Hill region.

The Piedmont of northern Delaware and southeastern Pennsylvania contains several small plutons, or intrusive igneous bodies. Two of these, the Arden pluton and the Bringhurst gabbro, are part of the Wilmington Complex. A third pluton, the Iron Hill gabbro, occurs as isolated inliers of the Piedmont in rocks of the Atlantic Coastal Plain. Although most of the exposed plutons are gabbroic, the Arden pluton is intruded by small bodies of felsic rocks. The relationship of the plutons to each other is unknown; neither their petrogenetic relations nor their tectonic environments of formation have been established (Dirska 1990). Based upon the lithologic types and structural and stratigraphic relationships, however, it has been suggested that these plutons may have been tectonically emplaced in their present positions during the mid-late Ordovician Taconic Orogeny (Drake and Morgan 1981).

The Wilmington Complex (WC) is composed of granulite-grade gneisses and plutonic igneous rocks (Ward 1959; Foland and Muessig 1978). It is located in northeastern Delaware and southeastern Pennsylvania, but most exposures occur in Delaware. These rocks represent the highest grade of metamorphism in the Central Appalachian Piedmont. The Wilmington, Delaware Complex is in contact in the north and northwest with deep marine metasediments of the Wissahickon Formation, and on the west by the arc volcanics of the James Run Formation (Higgins 1977). Field relationships imply that the northwestern contact of the WC is a fault contact, but this contact has not actually been observed. To the southeast, the WC is unconformably overlain by sediments of the Atlantic Coastal Plain (Dirska 1990).

The Wilmington Complex (WC) can be divided into two parts. The western portion of the complex is composed of two varieties of gneiss: the most common form is a pyroxene-quartz-plagioclase gneiss, while the other type is an interlayered felsic and mafic gneiss of variable composition (Dirska 1990). Both gneisses have been metamorphosed to the hornblende granulite subfacies of the granulite facies (Srogi 1991). The eastern portion of the WC is the Arden pluton, which is composed of both an orthopyroxene-bearing mafic rock and a felsic plutonic rock. The felsic rocks appear to occur as isolated pods floating within the gabbros. The pods may represent intrusions, or possibly roof pendants (Ward 1959), but their nature cannot be definitively determined as the contacts between the Arden pluton and surrounding gneisses are nowhere exposed. It is also possible that the contact is actually a thrust fault (La Porta n.d.).

The Bringhurst gabbro is located south and west of the Arden pluton, and it also intrudes the gneisses of the Wilmington Complex. Although the Coastal Plain sediments largely cover the southeastern portion of the Bringhurst gabbro, the contact between the Bringhurst gabbro and the WC are occasionally visible on the northwestern side. The mafic composition of the Bringhurst gabbro actually ranges from gabbro to anorthosite.

The Iron Hill gabbro, which includes the lithologies underlying Chestnut Hill, occurs southwest of Newark and extends into Maryland. All contact relations of the Iron Hill gabbro are obscured by Coastal Plain sediments, and outcrops in general are rare. The mafic rock types occurring within the Iron Hill gabbro include pyroxenites and gabbros that range from tholeiitic to calc-alkaline in composition. Both the pyroxenites and gabbros have undergone alteration by the invasion of hydrothermal fluids, producing uralite throughout (Dirska 1990). Regional metamorphism during the Taconic Orogeny has also resulted in the relative abundance of chlorite clay associated with mafic rocks such as the Iron Hill gabbro (Drake et al. 1989).

Iron Hill Area Geochemistry and Implications

The most basic trends in major/minor element distributions within the three plutons are best illustrated on the Harker interelement diagram, which is designed to show chemical variations about a constant plotted along the abscissa (e.g., Si; see Dirska 1990). The Iron Hill, Arden and Bringhurst rocks of the Wilmington Complex are generally similar. The various lithologies from all three plutons show similar values in ranges of Si concentration, but there are discernible differences. The Bringhurst gabbros in general have the lowest Si values, while the Iron Hill gabbros show the greatest variability in Si concentration. Not surprisingly, the highest Si values are associated with the Arden felsic rocks (53%). In terms of the principal feldspar components, Iron Hill rocks have radically different feldspar compositions from those of the other two plutons. Arden and Bringhurst gabbros have similar values for Na_2O and CaO, while the Iron Hill gabbros contain very low Na_2O concentrations and much higher CaO concentrations. The Iron Hill gabbros have negligible K_2O, whereas the K_2O values in the Bringhurst gabbro are intermediate and highest in the Arden complex. For Al_2O_3, the trend is highest in the Bringhurst gabbro, lowest for Iron Hill, and intermediate in the Arden gabbro. All three plutons contain similar concentrations of FeO and MnO. The MgO concentration of the Iron Hill gabbro is quite high in contrast to the other two. The TiO_2 and P_2O_5 trends are highest in the Arden, intermediate in the Bringhurst, and lowest in the Iron Hill. Aside from Si concentrations, the principal difference between the mafic and felsic rocks of the Arden pluton is that mafic rock chemistry usually plots as clusters, whereas felsic rocks show a more linear trend. The felsic rocks of the Arden show considerable scatter in all components associated with alkali feldspar such as Na_2O, K_2O, Rb, Ba and Zr.

In terms of trace element concentrations, both felsic and mafic Arden lithologies have higher concentrations of the incompatible elements Rb, Ba, Zr, and Y. Sr concentrations are lowest in the Iron Hill, and comparable in the other two plutons. Conversely, Ni and Co concentrations are lowest in the Arden rocks, intermediate in the Bringhurst gabbro, and highest in the Iron Hill. The Arden and Bringhurst lithologies show no Fe enrichment trend, while the Iron Hill gabbro illustrates an Fe enrichment trend in relation to decreasing Si values. Ni and Co also increase in the Iron Hill gabbro at the expense of Si.

The chemistry of the Iron Hill gabbros does not present a clear picture of their origin. Our theoretical background and limited field investigations suggest, however, that the Iron Hill gabbro, Bringhurst gabbro and Arden pluton are co-magmatic, genetically related and possibly represent a former mafic layered intrusion. Comparison with Steinmann's Trinity model (Hopson 1981) suggests that the three plutons occurring within the Wilmington Complex may represent the intermediate section of the trinity.

The lowermost dunite and serpentinites of the trinity are not visible at Iron Hill, nor are the upper layer volcanics. Serpentinites do occur, however, at Mount Cuba near Hoope's Reservoir, less than 20 miles north of Iron Hill. The suspicion that the Iron Hill complex may be part of a larger subducted island-arc suite is supported by the comparative statistical study conducted by Higgins and Conant (1990). More recently, Dirska (1990) has suggested that both the calc-alkaline and tholeiitic affinities of Iron Hill chemistries suggest a back-arc basin origin, possibly occurring on the continental side of a former back-arc basin. Dirska's (1990) chemical trends include the presence of Cr, Fe and Mn-bearing spinel, high Rb concentrations coupled with depleted Sr, low K and Si, higher Na and Ca and enriched Co, all elemental characteristics which are in direct agreement with the predicted occurrence in Steinmann's Trinity.

Petrogenetic Models and Bulk Geochemistry

No geological event is unaccompanied by a geochemical fingerprint. The greatest difficulty in interpreting geochemical analyses is determining just how much of the fingerprint is due to large-scale geologic events (i.e., regional processes such as metamorphism); how much is a reflection of a localized response to the large-scale event (e.g., local variations in mineral composition of the country rock); and how much is alteration by some later process (e.g., weathering). In order to establish a geochemical "baseline" for comparison with our test results, several models of petrogenesis (rock formation) may be turned to that indirectly provide an expected bulk rock chemistry that reflects the geologic history of the region. These models are adopted from geochemical (Berner 1972), petrological (Hopson 1981) and economic geology principles which are employed regularly and are governed by the physical laws of thermodynamics.

Steinmann's Trinity

"Steinmann's Trinity" is the term applied to the association of three successive lithological groups: serpentinized ultramafic and mafic rocks (which include olivine peridotites, dunites, pyroxenites, norites, and olivine and hartzburgite-hypersthene-enstatite-bearing gabbros); pillow lavas and basalts; and ochrous sediments, Mn-rich umber shales and bedded cherts (Guilbert and Park 1986). The association of these lithological groups suggests that oceanic crust has been thrust up (or obducted) onto the continental surface during collision events. These obducted terranes are referred to as ophiolites, and usually mark the sutures between continental and oceanic crust. Ophiolite suites have been described to the south of the Iron Hill area within the Baltimore Mafic Complex (Drake and Morgan 1981). The ultramafic and mafic lithologies of Steinmann's Trinity are characterized by the presence of plentiful oxides enriched in variable quantities of Cr, Fe and Mn (Stowe 1994). The gabbros are usually depleted in Sr, enriched in Rb and contain minor concentrates of Ni and Co. During metamorphism, the pillow and columnar basalts are oftentimes metamorphosed into amphibolites. The upper layer of Steinmann's Trinity may also contain sulfide deposits.

Subduction Zone Models for Economic Ore (Ti, Sn) Exploration

The concept of the subduction complex and its distribution of calc-alkaline, volcanic and plutonic rocks is approximately thirty years old (Sillitoe 1970; Snelgrove 1971; Guild 1971). The plate tectonic interpretation of ore mineralization associated with continent-continent or continent-island arc collision belts recognizes four tectonic settings, of which three may be related to the Iron Hill/Chestnut Hill complex and possibly to the Wilmington Complex. These include magmatic arcs, back-arc magmatic belts, outer arc magmatic belts, and foreland fold-thrust belts. Magmatic arcs include extensive Cu-Mo porphyry deposits characterized by low Sr ratios and variable Zn, Pb and S contents. A characteristic of magmatic ore deposits occurring in these environments is extreme chemical alteration of the rock, usually by hydrothermal fluids; thus, plutons originating in these environments are generally extremely weathered. Mineralization in back-arc settings is usually associated with Sn-Ag production or Sn-Ti-Ag production (Beckinsale and Mitchell 1981). The mineralization within the outer-arc settings includes Sn-Cu-As associated with Pb-Zn and F zones. Foreland basin fold-thrust belts or collision belts are associated with granite plutons and Sn-W-REE distributions.

Within subduction zones, the ultrabasic and basic rocks that form under the highest temperature and pressure conditions of the magmatic arcs will be dominated by the presence of Cr-Mn with only minor Fe-Mg. Rocks with intermediate composition, forming at the intermediate temperatures and pressures of the back-arc and outer arc magmatic belts, will be enriched in Fe-Mg and contain only minor Cr-Mn and Ti-Sn. Finally, the lightest composition rocks, the diorites and granodiorites of the foreland fold-thrust belts, will bear higher concentrations of Ti-Sn with only minor Fe-Mg. If the subduction zone model is applicable to the Iron Hill area, then the Iron Hill gabbros should be enriched with Cr-Mn, with minor Fe-Mg and negligible Ti-Sn; and the jaspers that have formed to the west near the Heath Farm and at Elkton, Maryland should be enriched with Fe-Mg, with appreciable quantities of Ti-Sn.

Clay Diagenesis and the Origin of Silica (Laterites and Saprolites)

Laterites and saprolites are paleosols that indicate extreme weathering of host rock to clays. Laterite is a term that has come to have a loose meaning that applies to all highly weathered red soils. More often the term laterite is applied to soils enriched in Fe or Al; for example, bauxite is an Al-rich laterite. By definition, saprolitization is an in-situ chemical decomposition process which permits the leaching of the parent chemistry of the host rock and the retention of both the immobile chemistry as well as the host rock's original texture. Laterites, on the other hand, consist of transported material and therefore do not retain any relict structure (Patterson 1967).

The types of clay present in laterites and saprolites, and some metal cation concentrations, are influenced by the composition of the original host rock. Most illite forms from the decomposition of sedimentary rocks that already contained illite as a cementing agent. Illites may be very Si-rich and retain radiometric ages of their ancient source rocks. Vermiculite forms from the partial weathering of muscovite and biotite mica, and are typically enriched in Mg and Fe and depleted in Si. Kaolinite and montmorillonite have compositions and structures that differ radically from the compositions of their source rocks; they form via the weathering of plagioclase feldspar and volcanic glass. Chlorite is also enriched in Mg and Fe and depleted in Si. While the predominance of chlorite over kaolinite suggests weak chemical decomposition, it is also possible for chlorite to form from mixed-layer smectites, illites and kaolinites as a result of thermal metamorphism. Many researchers (e.g., Burst 1959; Weaver 1967) have shown that burial metamorphism and the transition from smectite to vermiculite to illite to chlorite occurs in deeply-bedded sediments. Owing to their extended and complicated geologic histories, which often include long periods of metamorphism, older Phanerozoic and Precambrian rocks are usually enriched in illite and chlorite only.

The clays within laterites and saprolites oftentimes transport silica; some clays, such as kaolinite, montmorillonite and illite, can bear appreciable quantities of silica in their lattice structure. Where the clays exist at the interface between marine and continental meteoric waters, the increase in pH values to approximately 8.0 permits the rapid dissolution and reprecipitation of silica. Chert diagenesis can occur rather quickly under these conditions, bypassing two or three metastable phases and leaving behind no early diagenetic precursors - just illite.

Archaeological Studies of Jaspers

A number of chemical studies have focused on the study of the Pennsylvania/ Delaware jaspers (Blackman 1974; Miller 1982, 1987; Hatch and Miller 1985; Stevenson et al. 1990, 1992; Hatch 1993). These investigations have utilized various analytical techniques in an attempt to identify elemental fingerprints that could differentiate prehistoric lithic sources in both Pennsylvania and Delaware. While the studies succeed in pointing out potentially useful chemical differences, major problems have arisen, principally due to the authors' lack of understanding of the role of the geologic history in the origin of variability in bulk rock chemistry and the geographic distribution of rocks with similar chemistry. The following review is intended to outline some of the salient points of these studies and offer suggestions for placing future jasper studies in a firmer geological context.

Blackman's (1974) pioneering effort to differentiate Pennsylvania and Delaware jaspers indicated that both atomic absorption and flame emission spectrophotometry could be useful in isolating chert types originating in diverse geological terranes. Both methods were employed to test for seven minor elements (Mg, Cr, Fe, Cu, Ni, Co and Zn) and eight trace elements (Na, Li, K, Ca, Sr, Rb, Ba and Mn). The precision determined from the two methods varied in their accuracy by ± 3-8%. Blackman found that the range of concentrations of nine of the fifteen elements studied (Na, Li, Mg, Ca, Sr, Ba, Mn, Cu, and Zn) overlapped in the Pennsylvania and Delaware jasper samples, and therefore were not useful discriminators. The six remaining elements - K, Cr, Ni, Co, Fe, and Rb - illustrated non-overlapping concentration ranges, and showed promise as discriminating markers for the two source regions. Cr, Ni, Co, Fe, and Rb occurred in higher concentrations in the geological samples gathered near Iron Hill, Delaware than those samples collected from the Reading Prong of Pennsylvania, while the K content was slightly more concentrated in the Pennsylvania samples. The study suggested that the Iron Hill jaspers can be differentiated from Pennsylvania jasper sources based upon the high concentrations of Cr, Ni and Co present in the Iron Hill samples. These results are the first to have shown that the Iron Hill, Delaware jaspers had an average chemistry that was very different from the chemistry of any of the jaspers originating in the Reading Prong of Pennsylvania. In addition, the work suggested that the wide-ranging chemical variability of the Pennsylvania jaspers themselves would hinder future provenance studies. Blackman's choice of major/minor elements and method of pairing elements reflects an intimate knowledge of the chemistry involved, and his sampling design reveals that he was in touch with local experts on the regional geology (e.g., Wilkins 1974; Thomas 1963; and Melson 1969) who were well aware of the spatial distributions of poorly documented jasper locations.

Over the past decade, various members of the Penn State group (Miller 1982, 1987; Hatch and Miller 1985; Hatch 1993; Stevenson et al. 1990, 1992) have structured a large-scale, regional research design to address, among other questions, the ability to provenance jasper artifacts to specific quarries. Their research design includes the large-scale investigation of jasper-dominant archaeological collections held in repository; the creation of a tremendous inventory of amateurs' collections; and cooperation with the local geological surveys. A multidisciplinary approach was conducted that included employment of the X-ray fluorescence and neutron activation apparatus located within the Materials Science Research facility at the university. In conjunction with all of this, the group relocated and accurately mapped jasper quarries which were discovered and mapped by Mercer in the late 1800's (Mercer 1894). Precise maps and the rediscovery of the Leinbach's Mills quarry are among the significant findings. Apparently, this particular location eluded even Anthony and Roberts (1988), and has only been rediscovered in 1993 (Hatch 1993). From this groundwork stems a series of chemical studies which have made great impact upon the literature, and have furthered our understanding of the difficulties in addressing jasper distributions.

Stevenson et al. (1990, 1992) analyzed jasper samples from three quarry locations (Vera Cruz and Durham, Pennsylvania and Iron Hill, Delaware) and two prehistoric sites. They employed X-ray fluorescence to create chemical profiles for thirteen elements: Si, K, Ca, Mn, Fe, Co, Cu, Nb, Ni, Zn, Cr, Ti, and Al. Not surprisingly, Si is the most abundant element in all the jasper samples. A subtle trend does exist in the Si profile, however; this trend indicates that the Vera Cruz quarry contains the highest stable Si content, while the Durham quarry has a slightly lower stable Si content, and Iron Hill's stable Si content is noticeably diminished by comparison. Other trends that are discernible (Stevenson et al. 1990) suggest that K and Ca are most abundant at Durham, diminished somewhat at Vera Cruz, and diminished significantly in the Iron Hill samples. Also abundant at Durham and Vera Cruz but absent at Iron Hill are Co, Cu, and Nb. Conversely, Cr, Mn, Fe and Ni occur abundantly within all Iron Hill samples, while Ni, Cr, and Al are starkly absent from the two Pennsylvania sources. In a deviation from the general trends, Ti is absent at Iron Hill and Vera Cruz but extremely abundant at the Durham quarry. The ranges of Zn concentration are overlap somewhat at all three quarry areas. Based upon the results of these studies, it would appear that Co, Cu, Nb, Cr, Mn, Fe and Ni would be most useful in distinguishing the Pennsylvania sources from Iron Hill, and that Ti is useful in distinguishing between Vera Cruz and Durham.

Hatch and Miller (1985) present the partial results of Miller's (1982) Penn State Master's thesis. This study diverges from the use of X-ray fluorescence and employs the neutron activation technique. Approximately 140 samples were run, which included roughly 20 samples from each of the following quarries: Macungie, Vera Cruz, Durham, Lyons, and Houserville (all in Pennsylvania); Iron Hill, Delaware; and Flint Run, Virginia. Chemical elements run in the studies include Cu, As, Mn, K, Sm, La, Sc, and Fe; the results of the analysis suggested that these eight elements are consistent within specific quarries, but highly variable between quarries, making them potentially useful as markers. When the results of the chemical analysis were combined with multivariate statistical analysis, the combination of analytical procedures appeared to yield a 100% success rate in distinguishing between the Pennsylvania, Delaware and Virginia quarry sources. Among the individual Pennsylvania quarries, however, the success rate varied between 58-88%; this drop in accuracy is thought to be due to both the chemical variability within a quarry source and the relative similarity of all the quarry sources within the Reading Prong. Stevenson et al. (1992) had previously suggested that the chemical variability and less-than-successful statistical results might be caused by mineralogical differences in host rock sources; Hatch and Miller (1985) suggest that the further quantification of additional chemical elements, longer and shorter irradiation times, would further improve the accuracy in distinguishing individual sources of Pennsylvania jasper.

Hatch (1993) presents the synthesis of a decade of research into the prehistoric jasper quarries of Bucks, Lehigh and Berks counties, Pennsylvania. Approximately 100 "geological" and 80 artifact samples from locations as distant as Maine and southern Virginia were analyzed. Hatch employed X-ray fluorescence rather than the neutron activation technique that had previously yielded 100% confidence levels (Hatch and Miller 1985). The fourteen elements chosen for this study include Na, Al, Si, K, Ca, Ti, Mn, Fe, Cu, Zn, Rb, Sr, Zr, and Nb. The results of the artifact analysis suggested that the experimental error for X-ray fluorescence varies from 1% for elements such as K to as much as 17% for the rare earth Nb, and 30% for Sr. The elements in oxide form encountered during the analysis of the geological samples are given as Si, Al, P_2O_5 (phosphate), Fe_2O_3, Ba, Ca, Co, Cr, Cu, K, Mg, Mn, Nb, Ni, Pb, Rb, Sr, Ti, Y, Zn, and Zr. The results of the chemical analysis were again subjected to multivariate statistical analysis. In this study, a discriminant analysis is used to create parameters or functions that are then employed to assign unknown samples to a specific source; essentially, all samples are force-fit to a source in a "best fit" format. From his statistical analyses, Hatch (1993) ultimately concluded that 27% of the Pennsylvania artifacts were derived from local (i.e., Reading Prong) sources, 55% from eastern Mid-Atlantic sources, 9% from western Mid-Atlantic sources, and 9% from southern sites. Owing to the relatively low degree of confidence (often only approximately 70%) with which he was able to assign artifacts to a given source, Hatch concludes that there must be other as yet unknown quarry sources of jasper in the eastern United States.

The Penn State group's efforts, while pioneering, do suffer from scientific problems. Their sampling designs often lack precise context, and include artifact samples from private collections, avocational societies, and survey offices; and "geological" samples collected from areas in and around quarries, rather than from the outcrop itself, leaves open the possibility of misidentification of the sample source. In addition, the choices of elements measured in their studies, particularly in Hatch and Miller (1985), show some misunderstanding of the chemistry - some elements (e.g., Fe, K and Cu) were chosen for analysis, while other elements that would have added meaning to those results (e.g., Cr, Mg, and Zn) were not. The most problematic parts of Hatch and Miller (1985), and Hatch (1993) in particular, are the statistical methods used to analyze the raw chemical data. The studies' use of physiographic provinces to define quarry clusters ignores the fact that lithologic types are only one of several factors that influence physiography; thus quarries clustered in different lithologies within a single physiographic province may have radically different chemistries, while distant quarries may have similar chemistries owing to the continuity of geological formations across physiographic boundaries. In addition, the use of discriminant analysis, which "forces" artifacts into a defined source area, involves a certain amount of circular reasoning, so the assignation of artifacts to particular quarry regions based on such analysis should be regarded as suspect.

However, the raw data provided by the X-ray fluorescence analysis (Stevenson et al. 1990, 1992; Hatch 1993) can still be interpreted in a useful manner once a probable lithologic source has been identified and placed in its appropriate geologic context. For example, the enrichment of K and Ca and the presence of Cu and Zn in the Vera Cruz jaspers (Stevenson et al. 1990) suggests that they formed as the result of the weathering of predominantly cratonic, continental rocks that are light-colored and have light chemistries with low insoluble content and high illite clay content. The Durham jaspers, which are part of Hatch's (1993) Reading Prong group, are enriched not only in K and Ca but also in Fe, Cu, Mn, Co and Ti, which suggests that the Durham jaspers were created as the result of the weathering of mixed-layered mafic and felsic volcanics. At the other end of the spectrum, the chemistries of the Iron Hill jaspers (Stevenson et al. 1990) reveal diminished quantities of Si, Ca and K and substantial quantities of Mn, Fe, Ni, and Cr, all indicators that the Delaware jaspers are derived almost entirely from ultramafic and mafic plutonic rocks. In addition, the Fe concentrations of the Delaware jasper is suggestive of a limonite-goethite ore.

Regional Jasper Sources and Lums Pond Artifacts

A prior section reviewed the geological-geochemical models that have been established. The following section discusses all procedures and methods used in this study. This section presents the results of X-ray diffraction (XRD), clay fractionation, silica crystallinity, SEM and EDX analyses performed on various samples including Iron Hill and Chestnut Hill gabbros and jaspers, Pennsylvania jaspers and archaeological samples recovered from the Lums Pond excavation. The results of the analyses are presented in Tables 120-123, as well as in the conclusions at the end of each subsection.

Selection of Samples and Definition of Standards

Geological samples from three distinct lithologies were chosen for chemical analysis in addition to the Lums Pond artifacts. The Delaware samples were collected during field inspections and visits to quarries; samples from various Pennsylvania quarries were available in type collections made prior to the Lums Pond study. The first lithologic type is a gabbro from Iron Hill; while the gabbro itself was unlikely to have been used as a lithic raw material, it represents apparent mineralogy from which the Delaware jaspers are possibly derived. The gabbro samples were collected at Interstate 95 (sample I-95) and at Iron Hill east (IHE), Iron Hill west (IHW), Iron Hill park (IHP), and Iron Hill west flank (IHWF). The second lithologic type sampled is a local jasper (hereafter referred to as "Delaware jasper"). Samples of Delaware jasper were collected from Iron Hill (IH), Iron Hill east (IHE), Iron Hill park (IHP), Iron Hill west flank (IHWF), Chestnut Hill northwest flank (CHNW), and the Amtrak site (ATB and ATS). The third lithologic type is jasper from five well-known quarries in the Reading Prong of eastern Pennsylvania (hereafter called "Pennsylvania jaspers"). Each Pennsylvania jasper sample analyzed is actually a composite of five samples from each quarry, thus yielding a general mineralogy for each quarry location. The 30 Pennsylvania jasper samples were taken from Frankenfield (CH-1), Macungie (CH-2), Vera Cruz (CH-3), and Lyons (CH-4). Two additional samples were taken from the Long Swamp quarry (CH-5 and CH-6). Sample CH-6 was chosen specifically for its apparent outward resemblance to the Delaware jaspers; this sample was later found to be anomalously high in goethite (Figure 132).

For each of the lithologies examined, the modal mineralogies (i.e., proportions of major minerals present) were defined as weight percents and placed in table form (Table 120). From these analyses clay fractionation and silica crystallinity studies were constructed, employing the same samples as well as a few additional ones

In order to create a geochemical standard for our samples, one geological sample of jasper from a Reading Prong location (CH-3) and one sample from a Delaware quarry (ATS) were chosen. These samples were run through all levels of analysis, and are treated as average "types" bearing a mineralogy representative of their district of origin. As determined by the XRD analysis, the modal mineralogy of the Pennsylvania jasper (CH-3) is more than 95% silica as quartz, less than 1% hematite as stain, approximately

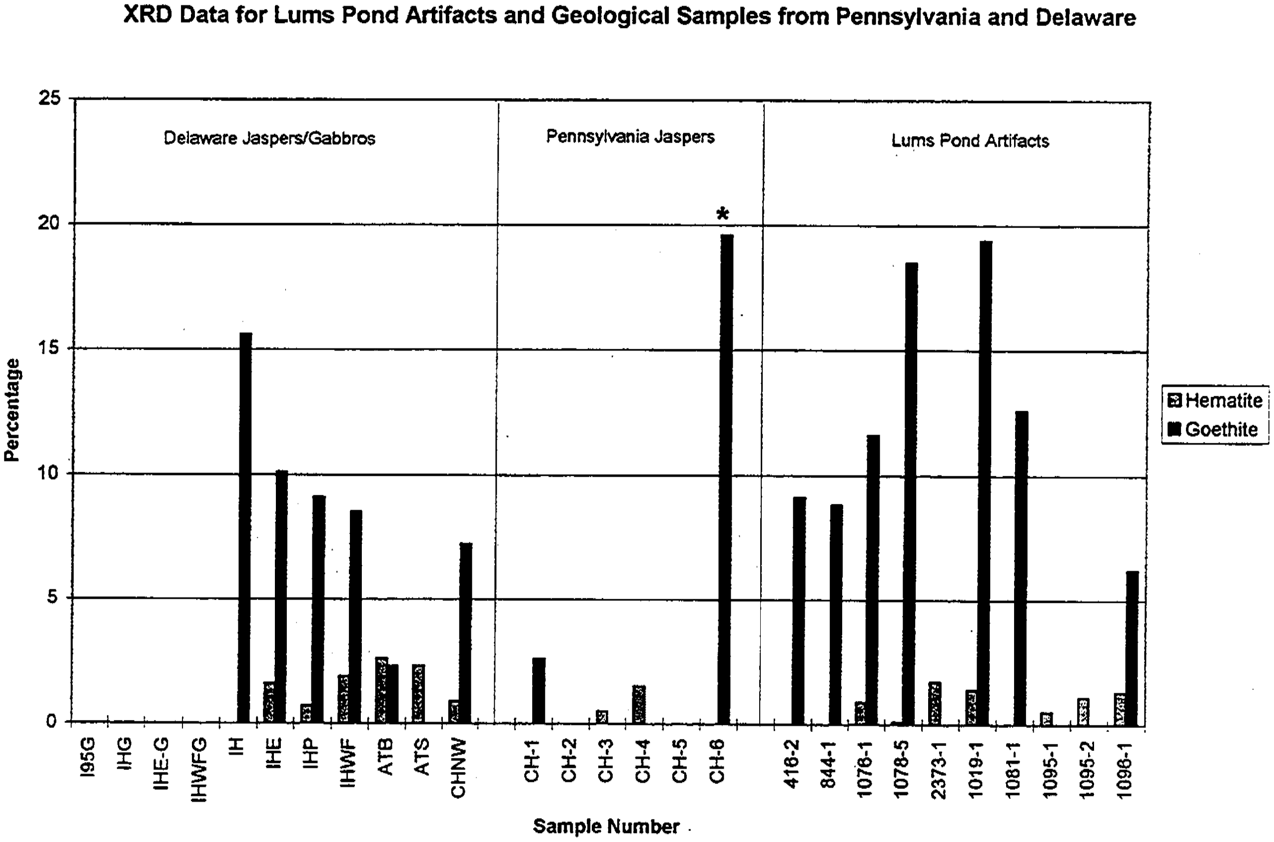

Figure 132. XRD Data for Lums Pond Artifacts and Geological Samples from Pennsylvania and Delaware

1-2% illite clay, detrital K-feldspar or apatite, and only trace amounts of insoluble oxides. The clay fractionation studies yielded only illite clay for CH-3, with occasional detrital K-feldspar. The silica crystallinity studies displayed no bifurcation in the silica peaks, but instead showed strong, sharp definition of stable quartz. The SEM characteristics indicate high Si-Al pairs, moderate Na-Ca, moderate K-Mg, and at best trace amounts of Mn and Cr. Fe^{2+} and Fe^{3+} are present in moderate amounts, while Sn and Ti are virtually absent. The Pennsylvania jaspers are occasionally enriched in Zn and Cu.

Sample #	Quartz	K Feldspar	Plagioclase	Pyroxene	Hornblende	Magnetite	Apatite	Siderite	Hematite	Goethite	Illite	Chlorite	Total	Magnetism
Iron Hill gabbros														
IHG	0	0	60.0	24.6	15.0	0.1	0	0	0	0	0	0.3	100	2
I95G	1.4	0	55.7	29.1	10.4	3.5	0	0	0	0	0	0	100	2
IHE-G	1.3	0	31.0	37.9	29.2	0.7	0	0	0	0	0	0	100	1
IHWFG	0.5	0	8.8	0	88.3	0	0	0	0	0	0	2.4	100	0
Delaware jaspers														
ATB	82.9	0	0	0	2.3	4.3	0	1.0	2.6	2.3	0	4.6	100	2
IH	84.4	0	0	0	0	0	0	0	0	15.6	0	0	100	0
IHE	87.4	0	0.9	0	0	0	0	0	1.6	10.1	0	0	100	1
IHWF	88.9	0	0.5	0	0	0	0	0	1.9	8.5	0	0.2	100	1
IHP	89.7	0	0	0	0.5	0	0	0	0.7	9.1	0	0	100	1
CHNW	91.5	0	0	0	0	0	0	0	0.9	7.2	0	0.4	100	1
ATS	95.3	0	0	0	0	1.2	0	0	2.3	0	0	1.2	100	2
Pennsylvania jaspers														
CH-1	96.6	0	0	0	0	0	0	0	0	2.6	0.8	0	100	0
CH-2	98.7	0	0	0	0	0	1.3	0	0	0	0	0	100	0
CH-3	99.5	0	0	0	0	0	0	0	0.5	0	0	0	100	0
CH-4	98.5	0	0	0	0	0	0	0	1.5	0	0	0	100	0
CH-5	96.1	0	0	0	0	0	3.9	0	0	0	0	0	100	0
CH-6	73.7	5.7	0	0	0	0	0	0	0	19.6	1.0	0	100	0
Lums Pond artifacts														
416-2	90.9	0	0	0	0	0	0	0	0	9.1	0	0	100	0
844-1	91.2	0	0	0	0	0	0	0	0	8.8	0	0	100	0
1076-1	87.0	0	0.5	0	0	0	0	0	0.9	11.6	0	0	100	1
1078-5	81.3	0	0	0	0	0	0	0	0.1	18.5	0	0	100	0
2373-1	98.1	0	0	0	0	0	0	0	1.7	0	0	0.2	100	0
1019-1	79.2	0	0	0	0	0	0	0	1.4	19.4	0	0	100	0
1081-1	87.4	0	0	0	0	0	0	0	0	12.6	0	0	100	1
1095-1	99.5	0	0	0	0	0	0	0	0.5	0	0	0	100	0
1095-2	77.8	0	3.9	0	0	0	0	0	1.1	0	0.8	16.4	100	0
1096-1	92.6	0	0	0	0	0	0	0	1.3	6.2	0	0	100	0

Table 120. XRD Data for Modal Mineralogy (in weight %)

The Delaware sample (ATS) was treated in the same fashion. The modal mineralogy shows that the sample is somewhat depleted in quartz (average of 87%), but enriched in goethite and hematite (both iron oxides; see Figure 132). The detrital minerals include plagioclase, pyroxene, talc, and a variety of amphibole minerals. The clay fractionation studies suggest that chlorite is the dominant clay in almost every sample, with illite present in only trace amounts. Silica crystallinity studies suggest that occasionally unstable phases of relict early diagenetic quartz may be present in a few of the samples. The SEM characteristics of the sample include high Si content combined with low K, Ca and Na, although the Ca peaks may be deceiving. Mg derived from the amphiboles is present in moderate amounts, and all samples are saturated with Fe^{2+} and Fe^{3+}. Ti and Sn are present in trace to moderate amounts. The sample displays significant magnetism, not surprising since magnetite is present everywhere, ranging from 20,000-40,000ppm; it contains moderate to large quantities of Cr and Mn in varying proportions.

Non-chemical standard descriptions of the Delaware and Pennsylvania jaspers were also defined. Petrographic analysis of two thin sections of the two jasper types shows that Pennsylvania jaspers are composed of finely laminated quartz with hematite cement, while the Delaware jaspers are composed chiefly of fairly translucent to opaque stable quartz with abundant corroded igneous mineral grains such as plagioclase, amphibole, pyroxene, and chlorite in association with euhedral to subhedral grains of opaque oxides such as magnetite and chromite. Goethite, hematite, and occasionally siderite occur as a stain or cement surrounding the mineral grains. Analysis of approximately 50 SEM images at low to moderate magnification (100-1000x) also reveals distinct microtextural characteristics for the Pennsylvania and Delaware jaspers. The Pennsylvania jaspers are rather glassy and show few, if any, grain boundaries, while the Delaware jaspers are scaly (perhaps a remnant of the original saprolitic structure) and exhibit high concentrations of goethite and clays, as well as outlines of detrital grains.

A representative chemistry for the prehistoric artifacts was constructed from the analysis of one piece (artifact no. 1479-1) from Area 1 of the Lums Pond site. The modal mineralogy of the artifact yielded approximately 88% quartz, detrital amphibole, and abundant goethite (up to 12%). Hematite was also abundant; chlorite was the only clay present. The clay fractionation studies yielded predominantly chlorite clay, goethite, hematite, and diminished quartz (approximately 65%). The silica crystallinity studies suggest that unstable silica is still present. The SEM results show high silica values coupled with low Na, K, Ca, Mg and Al. Neither Sn nor Ti were present in the sample, but the samples did contain great quantities of Fe^{2+} and Fe^{3+} (as would be expected for a sample containing large amounts of goethite). Mn and Cr are present in moderate amounts. The sample in general is highly magnetic.

Geochemical Analyses

X-ray diffraction (XRD) represents the foundation of upper level (i.e., atomic level) analyses described below. Prior to any major/minor elemental study, XRD is often performed on all samples in order to fully understand the basic mineralogical make-up of the geological materials and artifacts under investigation. After the XRD modal mineralogies have been determined, both clay fractionation and silica crystallinity studies provide additional distinguishing characteristics that can be used to help define the original mineralogical composition and, broadly, the age of the mineralization. The data derived from these analytical methods is then combined with the geologic field data and petrogenetic models to determine the geographic distribution of the probable lithic sources for the prehistoric artifacts.

X-ray Diffraction

A total of 27 samples were subjected to XRD analysis: there were five geological samples of Iron Hill-Chestnut Hill gabbro, six geological samples each of Pennsylvania and Delaware jasper, and ten archaeological samples from material found at the Lums Pond site. The results of the modal mineralogy analyses of the gabbros, Delaware jaspers, Pennsylvania jaspers, and Lums Pond artifacts are reported here (see Table 120) .

Procedure: The sample was ground to a powder (the powder was passed through a 300 micron sieve) using a corundum mortar and pestle. A hand magnet was passed over the sample to see if it contained any magnetic phases. The entire sample was then ground to a fine powder in alcohol in an agate micronizing mill. After the slurry dried, the resulting powder was packed into a cavity-type sample holder for analysis. The XRD pattern was collected using a Siemens automated powder diffractometer equipped with a copper source and a solid-state detector. The sample was scanned from 2-70 degrees 2-theta at a rate of 1.0 degree per minute using a sample spinner to reduce preferred orientation effects. Identification of the crystalline components was done using graphical software and the JCPDS database of minerals and inorganic compounds. Quantitative analysis was performed by measuring integrated peak areas derived from profile-fitting techniques, and by applying empirical reference intensity ratio (RIR) factors to the peak areas. Results were normalized to 100% and represent relative crystalline phase amounts exclusive of organic materials and other X-ray amorphous components.

Results: The five Iron Hill-Chestnut Hill gabbros tested were samples IHG, I-95G, IHE-G, IHWFG, and ATB. Samples IHG, I-95G and IHE-G are hypersthene gabbros containing varying amounts of plagioclase, hypersthene and amphibole as antigorite, talc or serpentine. This group also contain minor amounts of quartz, magnetite, and chlorite as clay. Sample IHWFG consists largely of amphibole as antigorite, talc and serpentine, with minor plagioclase and quartz; chlorite is abundant as clay in this particular sample. Sample ATB is dominated by quartz and contains minor amounts of magnetite, hematite, goethite, amphibole, siderite and chlorite. The presence of higher percentages of quartz suggests that this is not a suitable sample for study as it is also extremely weathered. Samples that exhibited magnetism with a hand magnet were IHG, I-95G, IHE-G, and ATB. XRD analysis detected magnetite in all four of the samples that showed magnetism. The lack of magnetite and excessive amphibole content in sample IHWFG suggests that this sample is a heavily weathered fragment. The relatively high percentage of quartz in sample ATB is also suggestive of heavy weathering of the sample.

The seven Delaware jaspers tested were samples IH, IHE, IHWF, IHP, CHNW, ATS, and ATB. These seven samples are similar to each other in that all are dominated by quartz (approximately 88% Si) and have varying amounts of goethite and hematite. Samples IHE and IHWF also contain plagioclase; IHP contains hornblende. The only clay mineral present is chlorite. Five of the samples (IHE, IHWF, IHP, CHNW, ATS, ATB) exhibited extreme magnetism with a hand magnet; however, XRD was only able to detect magnetite in ATS and ATB. IH did not show any magnetism with a hand magnet. It is estimated that the Delaware jaspers analyzed here contain upwards of 20,000-50,000 ppm insoluble oxides.

The six Pennsylvania jaspers tested were samples CH-1, CH-2, CH-3, CH-4, CH-5, and CH-6. These six samples are similar to each other in that all are dominated by very high percentages of quartz (average 97% Si), and have low but measurable amounts of goethite and hematite. Samples CH-2 and CH-5 contain apatite, and CH-6 contains K-feldspar; none of the samples contains amphibole, plagioclase or magnetite. Illite is present only in samples CH-1 and CH-6. None of these six jaspers exhibited any magnetism with a hand magnet.

The ten archaeological samples from the recovered Lums Pond flakes and tools include samples 416-2, 844-1, 1076-1, 1078-5, 2373-1, 1019-1, 1081-1, 1095-1, 1095-2, and 1096-1. These ten samples exhibit Si ranges varying from 77.8% (1095-2) to 99.5% (1095-1). Samples 416-2 , 844-1, 1076-1, 1078-5, 1019-1, 1081-1 and 1096-1 all exhibit appreciable quantities of goethite. Sample 1076-1, 1078-5, 2373-1, 1019-1, 1095-1, 1095-2 and 1096-1 all contain low but measurable amounts of hematite. Samples 1076-1 and 1095-2 contain plagioclase. None of the samples contained any K-feldspar, siderite, apatite, amphibole or magnetite. Clay minerals, where present, include illite and chlorite. Sample 1095-2 is different from any of the other jaspers in that it contains both illite and chlorite. It is also different in appearance - it is a black jasper, whereas the other jaspers have a red to orange color. Two samples (1076-1, 1081-1) exhibited magnetism with a hand magnet; however, XRD did not detect magnetite in either of these samples. The remaining eight samples did not show any magnetism with a hand magnet.

Conclusions: The results of the XRD modal mineralogy suggest that, of the Lums Pond artifacts, only sample 1095-1 may possibly originate from one of the Pennsylvania Reading Prong quarries; the presence of 99.5% Si and only 0.5% hematite occurring as a stain is characteristic of a Pennsylvania source (see Figure 132). It may only be coincidence, but the geological sample CH-3 (from the Vera Cruz quarry) has a modal mineralogy similar to 1095-1.

All the other Lums Pond samples appear to correlate with the Delaware jaspers, as suggested by the presence of plagioclase, elevated quantities of goethite, chlorite, hematite and magnetism (Figures 132 and 133), coupled with diminished Si concentrations. Certainly samples 1076-1 and 1081-1, by their low average quartz content and the presence of magnetism, probably originate from the Iron Hill region. Concentrations of goethite such as that occurring in samples 416-2, 844-1, 1076-1, 1078-5, 1019-1, 1081-1 and 1096-1 are probably all artifacts which originate in the vicinity of Iron Hill. Sample 2373-1 has elevated quantities of quartz and an appreciable amount of hematite and detrital chlorite, and sample 1095-2 contains detrital plagioclase, hematite, illite clay and chlorite; these two samples may originate from the vicinity of the Amtrak site (ATS). As mentioned later in the clay fractionation section, the association of minor amounts of illite with large concentrations of chlorite may aid in discriminating the Iron Hill site (IH) and the Amtrak site (ATS) from the other Delaware cherts.

Clay Fractionation

A total of 22 samples were tested via clay fractionation analysis: four samples of Iron Hill gabbro, seven samples of Delaware jasper, four samples of Pennsylvania jasper, and seven Lums Pond artifacts. The following accounts the results of X-ray diffraction (XRD) clay fractionation analyses performed on the Iron Hill and Chestnut Hill gabbros and jaspers, Pennsylvania jaspers and archaeological samples excavated from the Lums Pond site (see Table 121).

Procedure: Each sample was ground to a powder using a steel mortar and pestle. The powder was then dispersed in a dilute sodium phosphate solution using an ultrasonic probe and centrifugally size-fractionated into >1 micron and <1 micron equivalent spherical diameter fractions. The <1 micron suspension was then decanted and vacuum-deposited onto a silver metal membrane filter to produce an oriented mount. Clay mounts were then attached to glass slides and run in a Siemens X-ray diffractometer. The XRD pattern was collected using a Siemens automated powder diffractometer equipped with a copper source and a solid-state detector. The sample was scanned from 2-50 degrees 2-theta at a rate of 1.5 degrees per minute. Identification of the crystalline components was done using graphical software and the JCPDS database of minerals and inorganic compounds. Quantitative analysis was performed by measuring integrated peak areas derived from profile-fitting techniques, and by applying empirical reference intensity ratio (RIR) factors to the peak areas. Results were normalized to 100% and represent relative crystalline phase amounts exclusive of organic materials and other X-ray amorphous components.

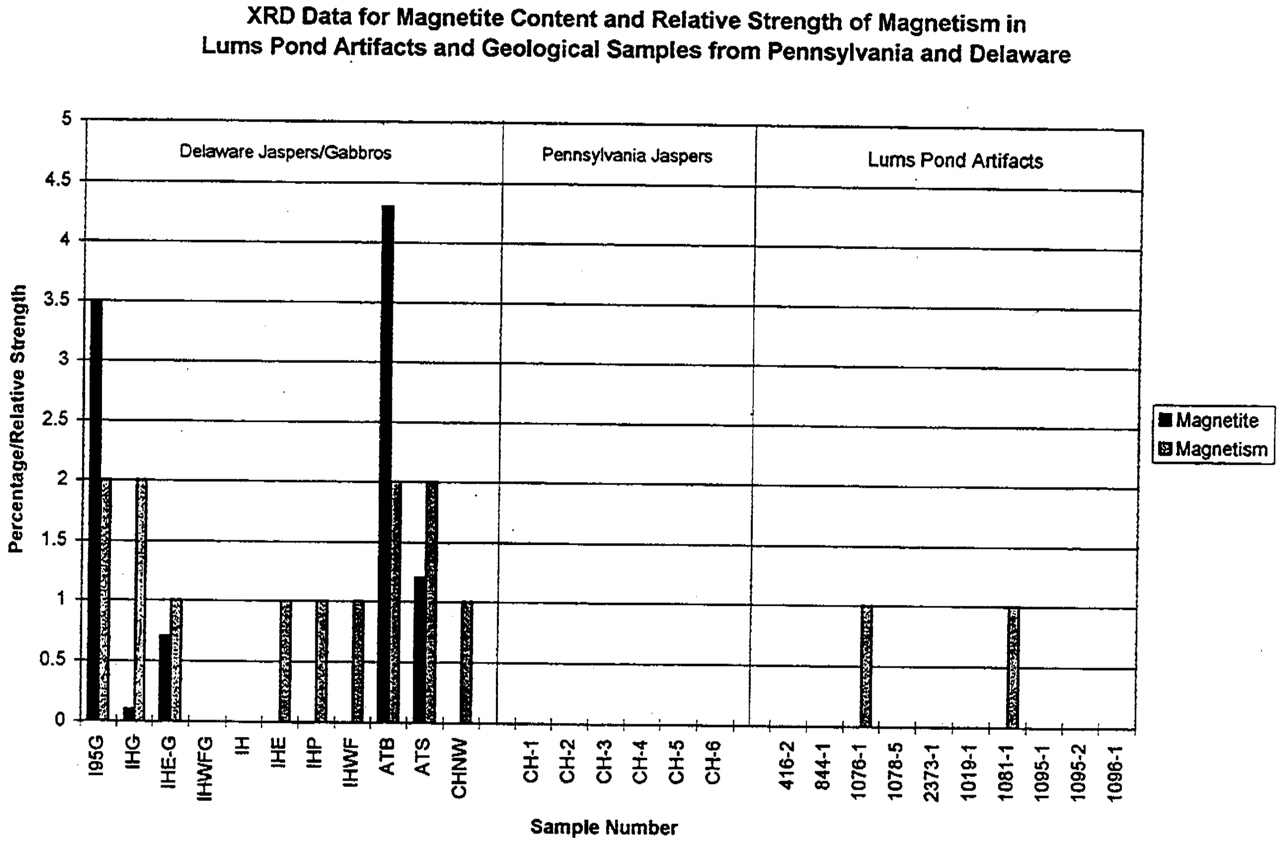

Figure 133. XRD Data for Magnetite Content and Relative Strength of Magnetism in Lums Pond Artifacts and Geological Samples from Pennsylvania and Delaware

Results: The four geologic samples of Iron Hill/Chestnut Hill gabbro tested were samples IHG, I-95G, IHE-G, and IHWFG. All four samples contain chlorite, and two of these (IHG and IHE-G) also contain talc. All of the samples are depleted in quartz but are enriched in plagioclase, pyroxene, and amphibole. The high concentrations of amphibole result from retrograde metamorphism of the gabbro, and are present as the mineral phases talc, antigorite, serpentine, and uralite. The clay group present includes smectite, chlorite, and talc, but all samples contain chlorite. The iron oxides are rarely present, suggesting that these samples are fresh and largely unweathered. None of the samples contain K-feldspar, apatite, or magnetite.

Sample #	Quartz	K Feldspar	Plagioclase	Pyroxene	Amphibole	Magnetite	Apatite	Siderite	Hematite	Goethite	Smectite	Illite	Chlorite	Talc	Total
Iron Hill gabbros															
IHG	2.1	0	23.5	9.5	50.7	0	0	0	0	0	9.3	0	2.4	2.5	100
195G	1.1	0	63.7	5.7	26.4	0	0	0	0	0	0	0	3.1	0	100
IHE-G	1.2	0	6.3	2.3	68.2	0	0	0	0	.0	18.9	0	1.3	1.8	100
IHWFG	0.2	0	6.0	0	83.3	0	0	0	0	2.2	0	0	8.4	0	100
Delaware jaspers															
IH	46.6	0	0	0	0	0	0	0	0	47.7	0	1.7	4.0	0	100
IHE	55.1	0	0	0	0	0	0	0	0	44.9	0	0	0	0	100
IHP	48.7	0	0	0	0	0	0	0	0	51.3	0	0	0	0	100
IHWF	76.9	0	0	0	0	0	0	0	0	19.7	0	0	3.3	0	100
CHNW	29.5	0	0	0	0	0	0	0	0	65.1	0	0	2.6	2.8	100
ATB	53.6	0	0	0	2.4	4.8	0	0.8	4.0	8.6	0	0	25.9	0	100
ATS	61.3	0	0	0	0	1.2	0	0	0.9	20.4	0	0	16.2	0	100
Pennsylvania jaspers															
CH-2	98.4	0	0	0	0	0	0.6	0	0	0	0	0.9	0	0	100
CH-3	99.4	0	0	0	0	0	0	0	0.6	0	0	0	0	0	100
CH-4	92.2	0	0	0	0	0	0	0	0.6	0	0	0	0	0	100
CH-6	73.9	9.2	0	0	0	0	0	0	0	15.0	0	1.8	0	0	100
Lums Pond artifacts															
844-1	89.2	0	0	0	0	0	0	0	0	10.8	0	0	0	0	100
1096-1	81.0	0	0	0	0	0	0	0	0	19.0	0	0	0	0	100
589-2	96.4	0	0	0	0	0	0	0	0	3.6	0	0	0	0	100
656-1	79.8	0	0	0	0	0	0	0	0	20.2	0	0	0	0	100
676-2	81.6	0	0	0	0	0	0	0	0	1.4	0	17.0	0	0	100
815-3	92.1	0	0	0	0	0	0	0	0	5.0	0	2.8	0	0	100
2562-1	64.4	0	0	0	21.8	0	0	0	0	9.4	0	0	4.5	0	100

Table 121. Clay Fractionation Data

The seven samples of Delaware jasper include samples IH, IHE, IHP, IHWF, CHNW, ATB, and ATS. The Delaware jaspers are also depleted in quartz, averaging approximately 50% Si as quartz, while all samples are enriched in goethite. Amphibole, magnetite, siderite, and hematite are present in samples ATS and ATB, which are the jaspers collected at the Amtrak site. Illite clay is present in only the Iron Hill sample (IH), while chlorite is present in all samples except IHE and IHP. Talc is abundant in the Chestnut Hill northwest site (CHNW). None of the samples contains smectite clays, K-feldspar, plagioclase, apatite, or detrital pyroxene.

The four samples of Pennsylvania jasper tested were samples CH-2, CH-3, CH-4, and CH-6. All these samples are generally saturated with stable quartz. Iron oxides occur basically as cements, and only CH-6 (the geological sample derived from the Long Swamp quarry) contained appreciable quantities of goethite. Sample CH-5 is also derived from the Long Swamp quarry, but it is a siliceous piece whose mineralogy resembles the

Delaware jaspers. While chlorite, talc and smectite clays are totally absent from the Pennsylvania jaspers, illite is present in CH-2 (Macungie) and CH-6 (Long Swamp quarry). Detrital K-feldspar and apatite are also present in these two samples.

The eight Lums Pond artifacts tested include samples 844-1, 1096-1, 589-2, 656-1, 676-2, 815-3, and 2562-1. These samples are somewhat enriched in quartz (averaging less than 87% Si) and all samples include abundant goethite. Samples 676-2 and 815-3 contain abundant illite, while chlorite is present in sample 2562-1; the remaining four had no appreciable clay content. Detrital amphibole is present in sample 2562-1, while no other detrital components were detected in this analysis.

Conclusions: In general, clay fractionation studies suggest that samples such as 2562-1, which are depleted in quartz, enriched in goethite, and contain chlorite and detrital amphibole, best describe artifacts from the greater Delaware area. Samples 844-1, 1096-1, and 656-1 may possibly originate in the greater Delaware area, based largely upon their high concentration of goethite. Samples 589-2 and 815-3, although enriched in silica, contain variable concentrations of Cr, Mn, Ti and Sn, which suggests a Delaware source. Sample 676-2 may originate from one of the Reading Prong quarries owing to its high illite content.

Silica Crystallinity

Silica crystallinity research has not been generally applied to provenance studies, but may provide a fruitful avenue for future research. The theory is based upon an understanding of the crystal structure of quartz, its atomic level weaknesses or glide planes, and its various polymorphs, which are present in various percentages in solid phase (Borg and Smith 1969). Silica transfers to solid quartz through a number of phase transformations that are not only predictable, but are assigned rate functions. Based upon geologic field evidence and geochronological studies, the Precambrian to Cambrian-age cherts of the Reading Prong should possess only stable phases of silica appearing as alpha and beta quartz. The Delaware cherts, however, may have formed much later during the Cretaceous period (Dirska 1990); therefore, the Delaware jaspers may yet contain relict early diagenetic (i.e., metastable) phases of silica. These phases would appear as subtle peaks in the diffraction data, peaks which are rarely studied yet well understood.

Procedure: A total of 15 samples were analyzed through the silica crystallinity method; these include six Pennsylvania jaspers, seven Delaware jaspers, and two Lums Pond artifacts. Using the data generated from both the XRD and clay fractionation studies, a graph is created showing the characteristic wavelengths of the silica polymorphs present (both metastable and stable phases) as a function of the angle of x-ray diffraction through the sample. The peak resolutions of the samples are then compared to standard graphs described in Borg and Smith (1969); any deviations from the standard graphs signify the presence of metastable phases of silica.

Results: The six Pennsylvania jaspers examined included samples CH-1, CH-2, CH-3, CH-4, CH-5, and CH-6. All samples clearly illustrate strong quartz peaks at 21 and 27 degrees, and more subtle quartz peaks at 37, 39, 41, 43, 46, 50, 55, 60, 65, and 70 degrees of rotation of the sample. There were no deviations in the crystallinity patterns for these samples. The entire range of degree angles, especially that occurring at 27 degrees, indicates the presence of stable quartz, just as would be expected for an ancient Precambrian chert. Those peaks present at 21, 27, 39, 41, 50, 60, and 68 degrees are the strongest peaks, and are all related to the presence of stable beta quartz.

Next, the Delaware jaspers were examined in the same fashion. As suspected, two populations of silica peaks were present. Samples IH, ATS, CHNW, IHE, IHP, and IHWF all contain the silica peaks mentioned above that are associated with stable quartz. These and additional samples of IH, IHE, IHWF, IHP, CHNW, ATS and ATB were then subjected to the clay fractionation process and analyzed in the XRD as an aid in sharpening the various silica peaks. As a result of the additional processing, distinct bifurcation can be seen within certain peaks, especially those occurring at 21 and 39 degrees (Figure 134). The bifurcation in the peaks indicates the presence of the metastable or relict unstable phases of silica, as predicted for a relatively young chert.

Conclusions: Bifurcated peaks at 21 degrees were found at artifacts 2562-1 and 656-1; it is likely, then, that these artifacts were fashioned from Delaware jasper. The success in discriminating between the Pennsylvania and Delaware jaspers suggest that silica crystallinity can be employed in the future as a provenance tool for discriminating between cherts of varying ages from differing geological terranes.

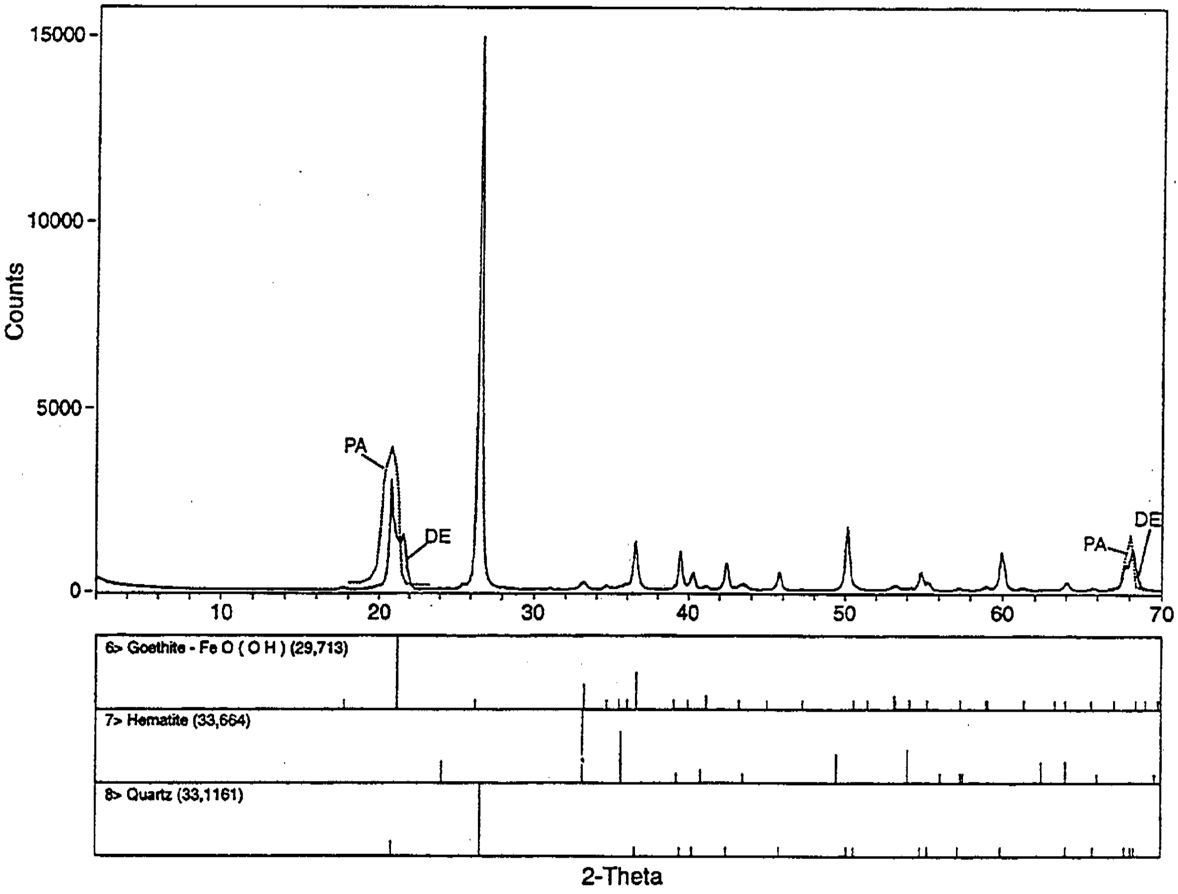

Figure 134. X-ray Diffraction Chart Depicting Mineral Peaks for Goethite, Hematite and Quartz (silica)

SEM and EDX Analysis

Procedure: A total of 50 samples were examined under the SEM and EDX; these include 22 samples of Iron Hill gabbro, 12 samples of Delaware jasper, four samples of Pennsylvania jasper, and 12 Lums Pond artifacts. The samples chosen for SEM and EDX analysis included fresh chips of Iron Hill and Chestnut Hill gabbros, Pennsylvania and Delaware jaspers, and artifacts recovered from the Lums Pond excavation. The sample fragments were broken with a porcelain mortar and pestle; 1-gram samples were then carbon-coated and mounted onto a stainless steel stub with silver (Ag) paint. The mounted samples are then placed in the SEM's sample chamber, where an electron beam can interact with the sample in a high vacuum. The three dimensional topographic image (SEM micrograph) is created by collecting secondary electrons generated from a primary electron beam; the characteristic x-rays emitted by each sample are utilized to generate the EDX spectrum. Once the peaks in the EDX spectrum are matched to their respective elements, the peak heights are converted to power functions that reflect the element's concentration in a semi-quantitative fashion (i.e., 0 = negligible, 1 = trace, 2 = low, 3 = moderate, 4 = high; see Table 122).

Results: The 22 Iron Hill gabbro samples tested originate from several locations: these include Route I-95 (I95-G0 through I95-G5), Iron Hill west flank (UIH(WF)-1, UIH-G2 through UIH-G6), Iron Hill Park (IHP-G1 through IHP-G4), Iron Hill East (IH(E)-G1) and Iron Hill (IH-G2 through IH-G6). As was noted earlier, the chemistries of the gabbros represent apparent mineralogy from which the Delaware jaspers are possibly derived.

In general, the Iron Hill gabbros show strong peaks for the Si-Al, Ca-Na and Mg-K element pairs. The Si:Al ratios are high because nearly all the minerals present in a gabbroic composition are silicate minerals; overall, however, the samples are depleted in quartz (as would be expected for a mafic rock). The high Ca:Na ratio is characteristic of high-Ca plagioclase, and the high Mg:K ratio typifies the presence of a hydrous mineral phase such as the amphibole minerals talc, antigorite and uralite. The K content is negligible to trace to moderate (0-2), which is expected for mafic rocks, but the Al content is anomalously high; the petrographic examination of the gabbros suggests that Al is abundant within the pyroxene-hypersthene in the Iron Hill region. The Fe^{+2} and Fe^{+3} ratios are extremely high due to the presence of abundant pyroxenes, amphiboles and magnetic oxides. The trace element Rb appeared in abundance in all Iron Hill samples analyzed. The clustering of Sn in trace to low amounts (1-2) only within the Iron Hill Park samples is intriguing, and suggests that the subduction zone petrogenetic model (Stowe 1994) may be applicable to the region. Unfortunately, none of the gabbro samples yielded discernible Ti quantities. The oxide component is predominantly Cr-Mn (Figure 135) with minor Fe-Mg.

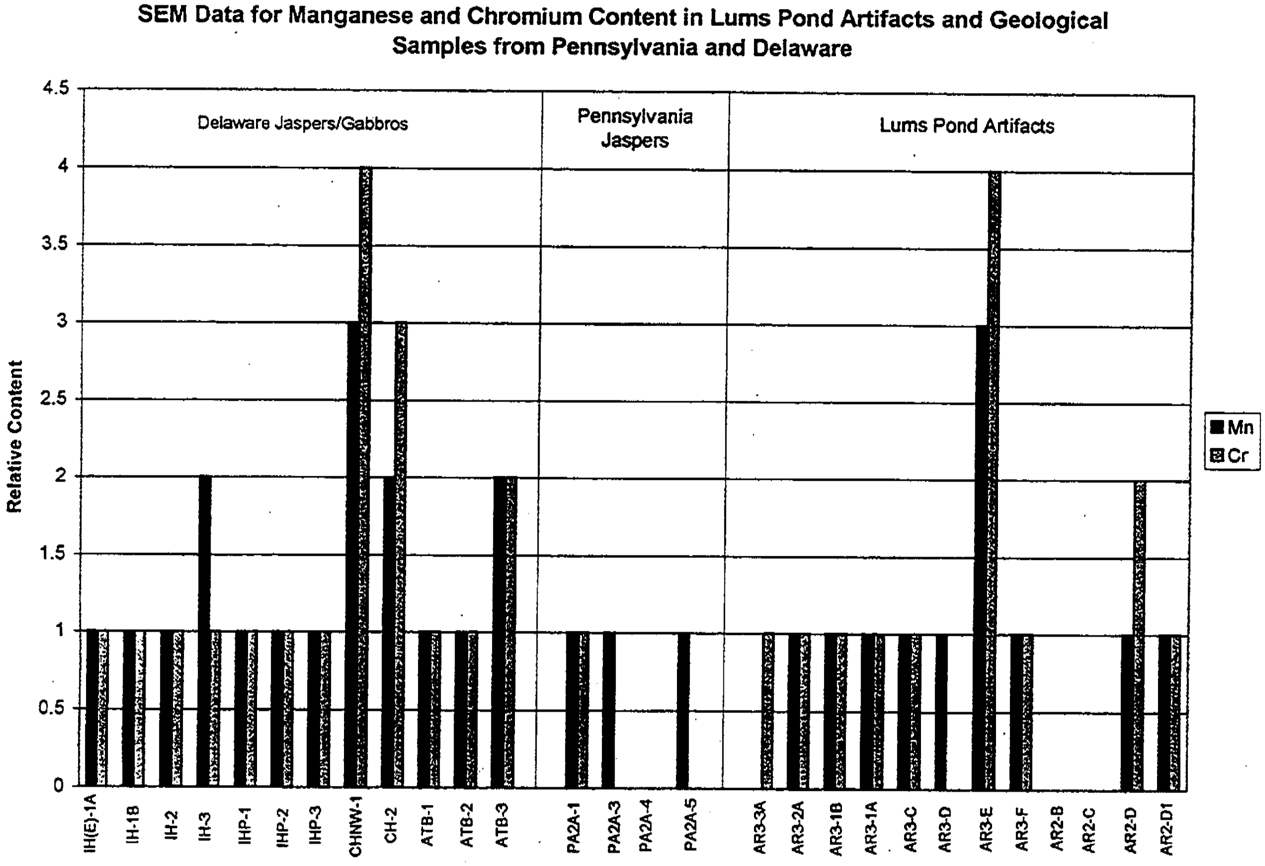

Figure 135. SEM Data for Manganese and Chromium Content in Lums Pond Artifacts and Geological Samples from Pennsylvania and Delaware

Table 122. SEM/EDX Data

Sample #	Na	K	Ca	Mg	Si	Al	Ti	Sn	Mn	Cr	Fe+2	Fe+3	Cl	Zn	Cu	Pb	S
Iron Hill gabbros																	
I95-G0	2	1	4	3	4	4	0	0	1	1	4	2	–	–	–	–	–
I95-G1	2	1	4	3	4	4	0	0	1	1	4	3	–	–	–	–	–
I95-G2	2	1	4	3	4	4	0	0	1	1	3	2	–	–	–	–	–
I95-G3	2	1	4	2	4	4	0	0	1	2	4	1	–	–	–	–	–
I95-G4	2	1	4	3	4	4	0	0	1	1	3	2	–	–	–	–	–
I95-G5	2	1	4	3	4	4	0	0	1	1	3	2	–	–	–	–	–
UIH(WF)-1	2	1	4	3	4	3	0	0	0	0	4	3	–	–	–	–	–
UIH-G2	2	1	4	3	4	3	0	0	1	1	4	2	–	–	–	–	–
UIH-G3	2	1	4	3	4	3	0	0	0	0	3	2	–	–	–	–	–
UIH-G4	3	1	4	3	4	3	0	0	1	1	4	3	–	–	–	–	–
UIH-G5	2	1	4	3	4	3	0	0	0	0	4	3	–	–	–	–	–
UIH-G6	2	1	4	3	4	3	0	0	1	0	4	3	–	–	–	–	–
IHP-G1	1	1	4	3	4	3	0	1	2	2	4	3	–	–	–	–	–
IHP-G2	1	0	4	3	4	4	0	2	2	2	4	2	–	–	–	–	–
IHP-G3	2	2	3	2	4	4	0	2	2	2	4	2	–	–	–	–	–
IHP-G4	2	1	4	3	4	4	0	1	1	0	4	2	–	–	–	–	–
IH(E)-G1	2	1	3	3	4	2	0	0	2	1	4	3	–	–	–	–	–
IH-G2	2	0	3	3	4	2	0	0	2	1	4	3	–	–	–	–	–
IH-G3	2	1	4	3	4	2	0	0	2	2	4	3	–	–	–	–	–
IH-G4	2	1	4	3	4	2	0	0	2	2	4	3	–	–	–	–	–
IH-G5	2	2	4	3	4	4	0	0	2	4	4	3	–	–	–	–	–
IH-G6	2	1	4	3	4	2	0	0	3	3	4	3	–	–	–	–	–
Delaware jaspers																	
IH(E)-1A	1	1	1	1	4	1	0	0	1	1	3	2	0	0	0	0	0
IH-1B	1	1	1	1	4	1	0	0	1	1	3	2	0	0	0	0	0
IH-2	1	1	1	1	4	1	0	0	1	1	3	2	0	0	0	0	0
IH-3	1	1	1	1	4	1	0	1	2	1	4	2	0	0	0	0	0
IHP-1	1	1	1	1	4	1	0	0	1	1	4	2	0	0	0	0	0
IHP-2	0	1	1	1	4	1	0	0	1	1	4	2	0	0	0	0	0
IHP-3	1	1	1	1	4	1	0	0	1	1	4	2	0	0	0	0	0
CHNW-1	2	1	2	2	4	2	0	0	3	4	4	2	0	0	0	0	0
CHNW-2	1	1	1	2	4	1	0	0	2	3	3	2	0	0	0	0	0

Table 122. SEM/EDX Data (continued)

ATB-1	1	1	1	2	4	2	0	0	1	1	3	1	0	0	0	0	0
ATB-2	1	1	1	3	4	2	0	0	1	1	3	1	0	0	0	0	0
ATB-3	1	1	1	3	4	2	0	0	2	2	4	2	0	0	0	0	0
Pennsylvania jaspers																	
PA2A-1	3	1	3	2	3	3	0	0	1	1	3	3	0	4	2	0	0
PA2A-3	3	1	2	1	3	4	0	0	1	1	3	1	0	4	3	0	0
PA2A-4	2	2	2	2	4	4	0	0	0	0	3	2	0	0	2	0	0
PA2A-5	1	3	2	2	4	2	0	0	1	0	3	1	0	0	0	0	0
Iron Hill artifacts																	
AR3-3A(A1) (art. # 1094-3)	1	1	1	2	4	2	1	1	0	1	4	2	0	0	0	0	0
AR3-2A(A1) (art. # 1094-3)	1	3	2	1	4	3	3	1	1	1	3	2	3	0	0	0	0
AR3-1B(A1) (art. # 1078-1)	1	1	1	2	4	2	0	0	1	1	4	2	0	0	0	0	0
AR3-1A(A1) (art. # 1053-4)	1	3	2	2	4	3	3	0	1	1	4	2	0	0	0	0	0
AR3-C (art. # 815-3)	1	3	2	2	4	3	3	1	1	1	3	2	1	0	0	0	0
AR3-D (art. # 676-2)	1	2	1	1	4	2	0	0	1	0	4	2	0	0	0	0	0
AR3-E (art. # 589-2)	1	2	1	3	4	2	1	0	3	4	4	3	0	0	0	0	0
AR3-F (art. # 589-2)	1	2	1	1	4	2	1	0	1	1	4	3	0	0	0	0	0
AR2-B (art. # 2562-2)	1	1	1	2	4	2	0	0	0	0	3	2	0	0	0	0	0
AR2-C (art. # 2562-2)	1	2	2	1	4	3	0	0	0	0	2	2	2	0	0	3	3
AR2-D (art. # 2350-6)	1	2	1	2	4	2	2	1	1	2	4	2	0	0	0	0	0
AR2-D1 (art. # 2350-6)	1	2	3	2	4	2	1	1	1	1	4	2	0	0	0	0	2

The Delaware jasper samples examined include pieces collected at Iron Hill East (IH(E)-1A), Iron Hill (IH-1B, IH-2 and IH-3), Iron Hill Park (IHP-1 through IHP-3) and Chestnut Hill northwest (CHNW-1 and CHNW-2). Also included in the analysis were three samples from the Amtrak site along the Maryland border (ATB-1 through ATB-3). Not surprisingly, all the samples were enriched in Si, but the Si concentration is lower than would be expected in other cherts; this is due largely to the Si deficiency in the jasper's gabbroic precursor. The Delaware jaspers all have depleted Na:Ca and K:Mg ratios (those from the Amtrak site, to a lesser degree than Iron Hill); this depletion is also a result of the mineralogy of the gabbroic precursor. Even the Al content is depleted, as well as the Fe^{+3} content. Within the oxide range, Sn appears in trace amounts in one Iron Hill sample (IH-3), while Ti is negligible in all samples. The Fe^{+2} content is enriched in each sample, indicating the presence of hematite, limonite and goethite occurring in almost minable concentrations. The presence of the element pair Mn-Cr is another indicator that the jasper formed directly as a result of the chemical weathering of a gabbro, or possibly a nearby serpentinite. In summary, the Iron Hill cherts are composed of appreciable quantities of hematite, goethite and limonite iron oxides and detrital fragments of amphibole, pyroxene and K-feldspar, with minor to accessory magnetic oxides.

The Pennsylvania jaspers include samples collected from the Frankenfield (CH-1), Vera Cruz (CH-3), Lyons (CH-4) and Long Swamp (CH-5) prehistoric quarries of the Reading Prong. The chemical trends within the Pennsylvania series are fairly different than those elucidated from the Delaware jaspers. The Pennsylvania series is generally enriched in Si, Al, Zn and Cu, with moderate concentrations of Na:Ca and K:Mg. These element concentrations suggest that the jasper is formed largely from the chemical weathering of intermediate to light composition continental rocks. The enriched Al concentrations additionally indicate the presence of desilicated kaolinite and illite clay. The Fe^{+2} and Fe^{+3} ratios are slightly lower in the Pennsylvania jaspers, and in no sample are hematite, goethite or limonite abundant. The elemental pair Ti-Sn is absent, and Mn-Cr occurs only as a trace (Figure 136). Oxides occur only in trace amounts, if present at all. The absence of oxides indicates that the Si in clay form is far traveled. In contrast to the Delaware jaspers, then, the Pennsylvania jaspers are composed predominantly of stable quartz, with Fe oxides occurring only as minor stains or cementing agents.

The nine Lums Pond artifacts tested include samples found in three different areas of the excavated site. Samples from area 1 include two artifacts labeled 1094-3, and artifacts 1078-1 and 1053-4; samples from area 2 include two artifacts numbered 2562-2 and artifacts 2350-6 and 2535-3; and samples from area 3 include two artifacts numbered 589-2 and artifacts 815-3 and 676-2.

The Na:Ca ratio is consistently low in all samples except 2535-3, and the K:Mg ratios are fairly low overall; these concentrations are consistent with Delaware rather than Pennsylvania jaspers. The Fe^{+3} and Fe^{+2} counts are moderate to high for all samples. High Ti:Sn ratios are also present in artifacts 1094-3, 815-3, 2350-6 and 2535-3, while Ti is present alone in artifacts 589-2 (both) and 1053-4. Only artifact 2562-2 (both samples) does not contain the Cr-Mn oxide pair; all other artifacts examined contain trace to high levels of Cr-Mn (Figure 136).

Conclusions: Of the archaeological samples examined under the SEM, most can likely be provenanced to the vicinity of Iron Hill. Artifact numbers 1094-3, 589-2 (both), 1078-1, 676-2 and 2535-3 all contain the varying proportions of Cr-Mn characteristic of Iron Hill jasper. Artifacts 1094-3, 1053-4, 815-3 and 2350-6 contain elevated Ti concentrations not found at Iron Hill, but which may occur in the Delaware jaspers of the Heath Farm to the west, as predicted by the petrogenetic model for subduction zone mineralization (Stowe 1994). (cf. Stevenson et al. [1990] and Hatch [1993], where Ti signatures were thought to be indicative of the Durham quarry in the Reading Prong or the Flint Run quarry of Virginia, respectively).

Of the entire series of samples analyzed, only sample 2562-2 (both) from Area 2 of the Lums Pond excavation may provenance to a Pennsylvania jasper source. The absence of the Sn-Ti and Cr-Mn element pairs in this sample suggest a source outside the Delaware region. The elevated Al and associated Cl, Pb, S, Zn and Cu concentrations suggest element transport by meteoric waters, which has likely happened within the Pennsylvania jaspers. The slightly elevated Al signature can be further attributed to the presence of illite clay, which is present in the Pennsylvania jaspers but not those from Delaware.

Conclusions

For this study, the following questions were tackled: 1) Can the Pennsylvania and Delaware jaspers be differentiated chemically? 2) Is it possible to differentiate the various jasper quarry areas within Delaware? 3) Is it possible to identify Pennsylvania and Delaware jaspers at the Lums Pond site? 4) Can any of the Lums Pond artifacts be provenanced back to their source areas?

In answer to question 1, it was realized that, although hand samples show many similar and overlapping characteristics, on the petrographic level discernible differences between the Pennsylvania and Delaware jasper districts could be seen. Chemically, the Pennsylvania jaspers tend to have slightly greater percentages of Si occurring as stable chert. Both the geological samples and archaeological artifacts thought to have originated in Pennsylvania contain well over 90% Si by volume. The Pennsylvania jaspers contain hematite and goethite in only trace quantities, typically as a stain, whereas the Delaware jaspers contain on average less than 90% Si and elevated quantities of hematite and goethite. The Pennsylvania jaspers are dominated by the presence of illite clay, while the Delaware series contains largely metamorphic chlorite and only minor quantities of illite. The remarkably high concentrations of magnetic oxides clearly distinguishes the Delaware jaspers from jaspers found in the Reading Prong of Pennsylvania. The elemental pairs Mn-Cr and Ti-Sn are characteristic of the Delaware jaspers. Ti is also present at the Durham quarry in Pennsylvania and within the Flint Run complex of Virginia, but neither of these locations contains Mn-Cr.

The answer to question two is also yes. To approach this problem, a total of 30 gabbro samples were collected from outcrops and ravines within the Iron Hill/Chestnut Hill area predicated upon the theory that the jaspers of saprolitic origin would reflect the parent mineralogical chemistry of the underlying gabbro. A total of 33 samples of Delaware jasper were also analyzed through the various chemical methods described above. All of the Delaware jasper and gabbro samples contain magnetic grains that occur as magnetite octehedra with various proportions of Cr, Mn, Ti, Sn, and Fe. The analytical results from the gabbros suggest that the highest concentrations of Sn, Mn and Cr exist in the vicinity of Iron Hill (IH) and Iron Hill park (IHP). All of the Delaware jasper samples examined include both Mn and Cr, but only the Iron Hill samples contain minor amounts of Sn. The presence of Ti in a number of artifacts examined from the Lums Pond site suggests a slightly western source for those artifacts. According to our geological models, the Ti-rich jaspers may occur in the vicinity of the Heath Farm near the Maryland border. The results of our chemical studies suggest that the Mn and Cr-rich jaspers are most abundant in the vicinity of Iron Hill and Chestnut Hill. While chlorite is present in most Delaware jasper samples, chlorite is found in association with minor illite at the Iron Hill location.

Because the Pennsylvania and Delaware jaspers could be differentiated chemically, the Pennsylvania and Delaware jaspers could be distinguished within the Lums Pond artifacts. Nearly all of the artifacts examined originated from quarry locations in the Iron Hill/Chestnut Hill area, as they contain the characteristic chlorite, oxide minerals, slightly lower Si concentrations, and elevated quantities of goethite and hematite. The Ti signatures present in samples 1053-4, 1094-3, 2350-6, 2535-3, and 589-2 all represent possible candidates for a Heath Farm source as suggested by the geological models. Alternately, the Sn content of samples 1094-3 and 2350-6 may indicate their

	Analytical	Technique				Quarries		
Sample #	XRD	Clay fractionation	Silica crystallinity	SEM	Distinguishing features	Penn.	Delaware	Remarks
Area 1								
1019-1	X				goethite-rich		X	
1053-4				X	Ti-Mn-Cr-rich		X	CH/Heath
1076-1	X				plagioclase present, goethite-rich		X	
1078-1				X	Mn-Cr-rich		X	CH
1078-5	X				goethite-rich		X	
1081-1	X				silica-poor, magnetic, goethite-rich		X	
1094-3				XX	Ti-Sn-Mn-Cr-rich		X	IH, IHP, CH/Heath
1095-1	X				silica-rich, hematite-deficient	X		
1095-2	X				plagioclase/goethite, illite/chlorite present		X	IH/ATS
1096-1	X	X			goethite-rich		X	
1479-1	X	X	X	X	Mn-Cr-rich		X	CH
Area 2								
2350-6				X	Ti-Sn-Mn-Cr-rich		X	IH, IHP, Heath
2373-1	X				hematite/chlorite present		X	
2535-3				X	Cr-Mn-Ti-rich		X	CH/Heath
2562-1		X	X		goethite/chlorite/amphibole-rich		X	ATS
2562-2				XX	absence of Cr, Mn, Ti, Sn	X		
Area 3								
416-2	X				goethite-rich		X	
589-2		X		XX	Cr, Mn, Ti present		X	CH/Heath
656-1		X	X		goethite-rich		X	
676-2		X		X	Mn present, hematite-poor, silica-rich	X		
815-3		X		X	Cr, Mn, Ti, Sn present		X	IH, IHP, Heath
844-1	X	X			goethite-rich		X	

Key to abbreviations in Remarks: CH = Chestnut Hill, IH = Iron Hill, IHP = Iron Hill Park, ATS = Amtrak site, Heath = Heath Farm

Table 123. Summary of Lums Pond Artifacts with Analytical Techniques and Probable Quarry Sources

origin in Iron Hill or Iron Hill Park. However, several samples may have originated from outside the Delaware study area. XRD analysis of sample 1095-1 from Area 1 at Lums Pond consisted of 99.5% quartz and only minor hematite stain (0.5%), and may represent a Pennsylvania source. SEM/EDX analysis of sample 2562-2 contained none of the oxides Cr, Mn, Ti or Sn characteristic of Delaware sources, and with its high Si content is also likely to represent a Pennsylvania source. Sample 676-2 from area 3 contains elevated quantities of illite clay, and although the sample contains trace quantities of Mn, the illite concentration suggests a source outside Delaware. Other samples which at first appeared to have originated outside Delaware include samples 815-3 and 589-2. Clay fractionation and SEM/EDX analysis of 815-3 yielded 2.8% illite and 92.1% Si, similar to Reading Prong jaspers, but the presence of Ti, Sn, Mn and Cr point to a Delaware source, possibly even the Heath Farm. Sample 589-2 was analyzed in the same fashion; this sample also contained elevated quantities of Si (96.4%), but the variable concentrations of Ti, Mn, and Cr point toward a source on the northwestern side of Chestnut Hill, or possibly to the Heath Farm.

Finally, the last question remains, can any of the Lums Pond artifacts be provenanced to specific quarry areas in the Delaware region? The answer is yes, with reservations (see Table 123 and Figure 136). Sample 1095-2, with its coupling of illite and metamorphic chlorite clays, may originate from Iron Hill, according to the clay fractionation data. Sample 589-2, as mentioned above, may originate from Chestnut Hill, and sample 815-3 may, by our geological models, originate in the vicinity of the Heath Farm. Other artifacts which may provenance to Chestnut Hill include samples 2350-6 and 2535-3 from Area 2 and samples 1094-3 and 1078-1 from Area 1. Sample 2562-1 contains 21.8% detrital amphibole, 9.4% goethite and 4.5% chlorite; the bulk mineralogy of this sample conforms best to the Amtrak site (ATS) on the Maryland border.

The combination of the three analytical methods employed in this study have permitted us to answer the four questions posed with varying but relatively strong degrees of confidence. Importantly, the coupling of chemical analytical techniques with a geological framework has allowed us to create a meaningful data set that will aid in future provenance studies in the Delaware region. The geologic framework also acts as a predictive tool for further research into the geographic distribution of prehistoric quarries.

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Glossary

allochthonous - Term applied to geologic units that originated at a distance from their present position and were subsequently transported.

amphibolite - Medium-grained, dark colored metamorphic rock composed of hornblende and plagioclase with minor biotite, quartz, sphene and epidote; formed by moderate pressure/medium to high temperature (amphibolite facies) metamorphism of mafic igneous rocks such as basalts.

anorthosite - Plutonic rock composed almost entirely of plagioclase feldspar (>90%).

autochthonous - Term applied to geologic units that were formed or produced in their present position.

bimodal composition - In reference to igneous bodies, the term refers to the simultaneous presence of both mafic and felsic rocks.

calc-alkaline - Name given to a suite of rocks comprising the volcanic association basalt-andesite-dacite-rhyolite or the plutonic association gabbro-diorite-granodiorite-granite when the amount of silica present ranges between 56 and 61 wt %; these rocks typically develop on the continental side of plate subduction zones.

charnockite - Light-colored, medium to coarse-grained igneous rock with quartz and microcline feldspar as major constituents and lesser amounts of oligoclase feldspar, hypersthene, biotite and magnetite.

chromatite - A chromite-rich mafic igneous rock.

cratonic - Term referring to stable continental crust.

cumulate - Term applied to intrusive igneous rocks whose crystals accumulate by gravity settling from a melt. Early-formed minerals are called "cumulus" minerals and show a regular variation in composition with their height in the intrusion.

dike - Cross-cutting, tabular-shaped igneous intrusion that is typically vertical or near-vertical in orientation.

dunite - Coarse-grained igneous rock consisting mainly of olivine.

ensialic - Descriptive term for continental rocks high in silica and aluminum.

facies - Sum total of features that reflect the specific environmental conditions under which a given rock was formed. For sedimentary rocks, these features include mineral composition, sedimentary structures and bedding characteristics; for metamorphic rocks, facies is determined by characteristic mineral assemblages produced as a result of both metamorphic conditions and the starting rock composition.

felsic - An igneous rock with more than 60% silica by weight, with about 10% occurring as free quartz, and low quantities of iron and magnesium-bearing minerals.

granoblastic - A textural term referring to a mosaic of equidimensional anhedral grains in metamorphic rocks.

granulite - Coarse-grained, equigranular metamorphic rock consisting of quartz, feldspar, pyroxene and garnet in varying proportions, depending on the starting composition of the rock; produced by high temperature/high pressure (granulite facies) metamorphism near the base of the continental crust.

greenschist - Low-grade metamorphic rock containing abundant chlorite with albite, actinolite, epidote and quartz, and possessing a distinct cleavage; produced by moderate temperature/moderate pressure (greenschist facies) metamorphism of a mafic igneous rock, and usually associated with continent-continent or ocean-continent collision zones.

mafic - An igneous rock with a relatively high concentration of iron, magnesium and calcium, with 45-53% silica.

melange - A mappable body of rock containing broken rock fragments, of all sizes and many origins, in a sheared matrix; tectonic melanges are believed to form in subduction zones at shallow depth.

meteoric waters - Water that occurs in, or is derived from, atmospheric water (e.g., rainfall).

monzonorite - A variety of norite which also contains orthoclase feldspar.

norite - A coarse-grained mafic igneous rock containing plagioclase feldspar, orthopyroxene (e.g., hypersthene), clinopyroxene (e.g., augite), and accessory ilmenite; often found as layers in large mafic intrusions.

obduction - The lateral, sub-horizontal displacement of crust (usually oceanic crust) onto a continental margin at a convergent plate margin.

opaque mineral - A mineral which appears black in a microscope thin section viewed in plane-polarized light. Metal oxides are frequently, but not always, opaque.

ophiolite - Sequence of rock types consisting of deep-sea sediments lying above basaltic pillow lavas, dikes, gabbro, and ultramafic peridotite; some ophiolitic complexes are the remains of main oceanic crust, others of back-arc basins.

pegmatite - Very coarse-grained igneous rock, usually granitic in composition, which contains individual crystals at least 2.5 cm long; crystallization usually takes place at a late stage, when the magma is enriched in volatiles and trace elements.

pelitic - Term applied to an aluminum-rich metamorphic rock formed by the metamorphism of clay-rich sedimentary rocks such as shales and mudstones.

peridotite - A coarse-grained ultramafic igneous rock consisting of magnesium-rich olivine and lesser amounts of other iron and magnesium-rich minerals (e.g., orthopyroxene, clinopyroxene, chromite); can be found within large, layered ultramafic intrusions, in ophiolite complexes, and as xenoliths brought up in certain basalts.

retrograde metamorphism - A type of metamorphism in which minerals of a lower grade are formed at the expense of minerals characteristic of a higher grade, a readjustment necessitated by a change in physical conditions, e.g., lowering of temperature.

saprolitization - Process by which igneous or metamorphic rocks are chemically weathered in place to form a soft, earthy, clay-rich and thoroughly decomposed rock, especially in humid environments. Saprolites are characterized by the preservation of structures that were present in the unweathered rock.

serpentinite - Altered rock formed by low temperature and water interaction with an ultramafic rock; in the process of serpentinization, olivine and orthopyroxene are altered to such minerals as antigorite and chrysotile (asbestos).

spilitization - Low-grade metamorphic process by which mid-ocean-ridge basalts are altered to albite, chlorite, actinolite, sphene, and calcite, with or without some additional minerals. Alteration occurs when sodium and water are added to the rock system via the interaction of sea water with cooling basalt dikes and lava flows.

tholeiitic - Term applied to a fine-grained basalt consisting of calcium plagioclase, subcalcic augite and pigeonite with fine quartz-feldspar overgrowths. Tholeiitic basalt is extremely abundant and is the main extrusive component of the ocean floor.

tonalite - A coarse-grained igneous rock composed of sodium plagioclase, quartz, hornblende and/or biotite, with accessory apatite, zircon and iron oxide.

ultramafic - An igneous rock that consists almost entirely of iron and magnesium-bearing minerals, with no free quartz and less than 45% silica.

uralitization - The alteration of primary igneous pyroxene to a fibrous mass of amphibole during late-stage hydrothermal activity or low-grade metamorphism of igneous rock.