The Prehistoric Bedrock Quarries Occurring within the Chert Bearing Carbonates of the Cambrian-Ordovician Kittatinny Supergroup, Wallkill River Valley, Northwestern New Jersey-Southeastern New York, U.S.A.

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Abstract Geologic and archaeologic field work in the Cambrian-Ordovician chert bearing carbonates of the Wallkill Valley (New York and New Jersey) has located greater than 800 prehistoric bedrock quarries. Detailed examination of quarry landscapes, as well as excavated quarry tailings, has elucidated an organization to quarry development controlled by tectonics, structural geology and stratigraphy of the raw material. Geological control impacts quarry development, types of quarry tools used, and manufacture of quarry products. A predictive model for prehistoric bedrock quarry development was proposed, which in turn allowed for a chain of operation that began at the quarry face and ended with the quarry product. The chain of operation fills in a void left by previous quarry studies that were unable to visualize the steps from extraction to workshop activity, and as such led to the dismissal of quarry tailings and artifacts due to mischaracterizations stemming from misunderstanding of geological controls on extraction.

Keywords: ore, microlithon, domain, boudinage, First Tectonic Cycle Quarry Model.

Introduction

The interplay of geologic factors such as tectonics, structure, stratigraphy and diagenesis are the fundamental criteria for development of prehistoric bedrock quarries. The degree to which raw material is extracted, the resulting architecture of the quarry, the chain of operation, and types of manufactured quarry products are established within the parameters set by the regional geological framework (LaPorta 1994, 1996b, 2005, 2009). Therefore, the placement of prehistoric quarries into proper archaeological contexts necessitates an understanding of the geological framework at several scales stated above (LaPorta 2005). The type location for this method of prehistoric-quarry investigation is the Appalachians of New Jersey and New York, specifically the Cambrian-Ordovician, chert-bearing, carbonate rocks of the First Tectonic Cycle (LaPorta *et al.* 2007), Great Valley of the Appalachian fold-thrust belt. Applications of the First Tectonic Cycle Models to regions outside of the type locality would necessarily require considerable modification in order to fit the geological criteria unique to those regions.

Bridging the Terminology Gap with Geological Constraints of Raw Materials

The First Tectonic Cycle is represented by multiple episodes of tectonism in the Wallkill Valley. The rock is stressed, strained, and fractured, tilting the beds from 4–70 degrees from the horizontal (LaPorta 2009). The fractures result from multiple tectonic events and provide a macroscopic and microscopic effect on the cherts (LaPorta 2009). The rocks contain visible fractures in the form of joints (fracture in a rock with no visible displacement of the parts) and cleavage (splitting of rock crystals on a preferred plane of weakness). The fractures are caused by brittle shear (Scholz, 2002), where a crack is idealized as a mathematically flat and narrow fracture in a linear elastic medium. Lamoraal Ulbo DeSitter (1956) defined microlithons as narrow slices of rock enclosed between cleavage planes, which he analogized as compressed bricks that form a staircase. The microlithon represents the largest measurable homogenous volume of chert which can be successfully refined into a functional stone tool, without serious risk if failure. Conversely, the microlithon represents the smallest measurable microstructural element visible in outcrop, and confirmed in the laboratory by traditional microscopic methods (i.e., the light transmitting petrographic microscope with attached universal stage; LaPorta 2005, 2009).

Archaeologists have mislabeled, and subsequently discounted, artifacts and the associated classes of quarry tailings as 'slabby', 'block', 'shatter', and 'chunk' (Binford and Quimby 1963; Crabtree 1972; Amick 1982; Munford 1982; Church 1994). This practice of de-evaluation was most prevalent when prehistorically worked chert contained angular and flat surfaces that did not exhibit taxonomic flake scars. Observations of brittle-shear fractures in prehistoric chert quarries, and their presence in artifacts, led Philip LaPorta (1994, 1996b, 2005, 2009) to propose a model for the organization of prehistoric quarries and subsequent processing of the fractured chert; placing four phases of raw-material comminution before initiation of workshop activity. LaPorta (2005) documented in southern India the task subdivision organized by extant quarry workers at long established hand-operated bedded limestone quarries. Here, workers accentuated bedding planes and master joints of the Shahabad Limestone employing dolerite hammerstones, which were extracted from the nearby Deccan Plateau basalts, and rolled to the quarries, all orchestrated with ritual life, song and prayer.

As such, LaPorta (1994, 1996a, 1996b, 2005, 2009) treated the chert as an ore, a naturally occurring complex of minerals from which any fraction of value can be extracted and used (Pryor 1965). LaPorta also employed the principles of economic geology, the study of earth materials that humans have adapted for their use (Tarr 1930; Chatterjee 1993), as the paradigm for investigating prehistoric extraction/processing of chert. In essence, chert as an ore serves in part to fuel lithic based economies. Actually, Walter Tarr (1930) notes that chert, along with quartz and quartzite, were the first earth material utilized by early humans. Kaulir Chatterjee (1993) stated that in the Lower Paleolithic Period, 'economic value started being added to the naturally occurring minerals with the help of labor and intelligence' and considered it the birth of mineral economics.

There is a long history of mining and rock processing literature, from the Renaissance to the 20th Century – replete with a mining terminology and a description of the various stages and methods in quarrying, mining, and rock processing (Agricola 1950 [1556]; Richards 1903; Simons 1924; von Bernewitz 1931; Richards and Locke 1940; Pryor 1965). The same ideas of familiarity, ingenuity, intelligence, and systematics noted in the works of historic mining texts can be seen in the prehistoric workings of the Wallkill Valley chert quarries. Prehistoric peoples, spurred by the same need for survival as historic and modern quarry workers and miners, developed a folk geology or ethnogeology, in order to record and archive their empirically based geological expertise (LaPorta 2009). Perhaps this was accomplished with the purpose of archiving their history of geological observations, in essence a folk-geology predictive model, designed for conservation and survival (James Moore, personal communication to Philip LaPorta).

Because the cherts of the Wallkill Valley are multiply deformed, the quandary of the prehistoric stone tool maker is to locate a microlithon oriented between as many as three sets of oblique or acutely intersecting planes; not to mention the added effects of diagenesis and pressure solution. Therefore, the quarries in the Wallkill Valley are the most elaborate, possess the greatest number of organized task subdivisions, have the most elongate chains of operation, and exhibit the most elaborate quarry tool and instrument inventory (LaPorta 1994, 1996b, 2005, 2009).

Tectonic-Stratigraphy of the Wallkill Valley

Within the Wallkill Valley, the Cambrian-Ordovician chert bearing carbonates (Fig. 1) can be grouped into three stratigraphic packages; each of which was initiated at a position of sea-level low stand, followed by a period of sea-level rise, and terminated by sea-level draw down. Each of the three packages is initiated with a lagoonal or estuarine facies, transgresses upwards to open-water epeiric conditions, and is finally reduced to sabkha shorelines. The most laterally persistent cherts tend to be in the shoreline facies; but the greatest volume of chert is housed within the chert-replaced evaporitic units. In between are a plethera of biohermal, mound and reef facies which are partially to completely replaced by chert. The package boundaries are punctuated by chert-lined regional unconformities. The cherts associated with organic accumulations are the most areally restricted.

Lithostratigaphic Package 1

The Leithsville Formation reveals four varieties of chert within the upper Wallkill Member. Midway in the Wallkill Member is a concentration of chert-replaced, domal-aglal stromatolites (LaPorta 2009). The upper Wallkill Member is indexed by three stratigraphically close spaced cherts representing shoreline features in a sabkha environment. The cherts occur in three interrelated sedimentary facies; an enterolithic gypsum, a cryptalgal laminated dolomite, and a thick, storm deposited pisoidal unit (LaPorta 2009). The cherts within the Wallkill Member are strand-line deposits and

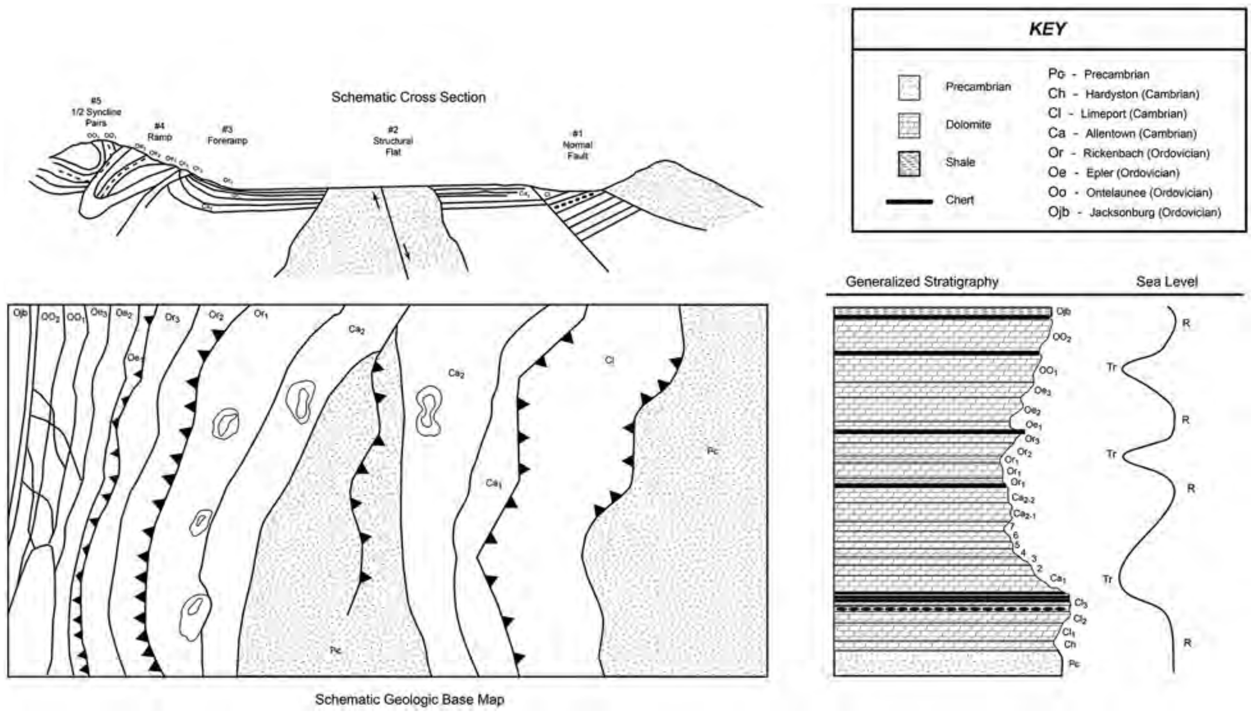

Fig 1. Generalized geologic base map, cross section, and stratigraphic column for the Wallkill Valley, New Jersey-New York. Drawn: Philip C. LaPorta.

can be traced intermittently along stratigraphic strike for tens to hundreds of kilometers (LaPorta 2009).

The overlying Limeport Formation bears six formation members containing mixed dolomites and limestones representing open-marine epeiric conditions (LaPorta 2009). Chert occurs in both oolitic units and stromatolite mounds. The spatial distribution of the cherts is the result of Middle Cambrian reef/mound ecology; as such the cherts are areally restricted (LaPorta 2009).

The overlying Upper Allentown Formation is deposited in response to a regional sea-level rise (LaPorta 2009). The cherts completely replace limestones that are areally restricted. Chert is most common though in regressive evaporates, and as unconformity linings occurring in the upper part of the section (LaPorta 2009).

Lithostratigraphic Package 2

Rapid sea-level rise represented by the deposition of the Stonehenge Formation is responsible for a myriad of chert replaced, spindly, algal stromatolite colonies that are very areally restricted, occurring sporadically along stratigraphic strike (LaPorta 2009).

The Rickenbach Formation consists of evaporitic flats, with small algal mounds and cross bedded, trough filling, quartz-sand units (LaPorta 2009). The uppermost chert replaced cryptalgal laminates in the Rickenbach's Hope Member represent lower supratidal facies and are similar to the upper portion of the Wallkill Member of the Leithsville Formation. In many respects, the Wallkill and Hope members represent the successive establishments of passive-margin sabkha sequences and their associated strandline cherts (LaPorta 2009). These thin bedded, closely spaced, cherts can be traced along stratigraphic strike from northeastern Pennsylvania into southeastern New York, and represent a continuous shoreline facies. They have been interpreted as a series of closely spaced, chert replaced, algal stromatolites or possibly the static position of a former paleoaquifer (LaPorta 2009).

The cherts are thickest in the overlying Crooked Swamp Member of the Rickenbach Formation, which contains chert-replaced evaporites and silcretized doloarenites (LaPorta 2009). The uppermost Crooked Swamp Member provides considerable chert for prehistoric needs, housed predominantly in chert-replaced patch reefs, oolites, chert-lined unconformities, and thickly bedded evaporites. The cherts are areally restricted and strongly tectonized (LaPorta 2009).

Lithostratigraphic Package 3

The Epler Formation cherts are extremely varied. The brackish water Branchville Member contains isolated chert-replaced algal mats and colonies (LaPorta 2009).

The Big Springs Member exhibits silcretized quartz-sands, magadi-type cherts, chert-replaced ooid and algal colonies, chert-lined unconformities, and paleo-karst infillings. The chert is areally restricted due to facies changes associated with the interplay of tectonics and sea-level rise (LaPorta 2009).

Gradual, but prolonged, sea-level fall gives rise to the overlying Beaver Run Member of the Ontelaunee Formation, which includes a series of voluminous, chert-replaced, shallow-subtidal, stromatactis mounds. The Beaver Run Member, in places, reveals approximately 80 distinctive, closely spaced, chert-replaced evaporates (LaPorta 2009).

The gradual drawdown of sea level results in the deposition of the overlying Harmonyvale Member of the Ontelaunee Formation. The Harmonyvale exhibits expansive chert accumulations in the form of repeated successions of chert-replaced evaporites and wholesale chert-replaced limestone beds (LaPorta 2009). The chert beds are continuous for hundreds of meters along stratigraphic strike and the co-occurrence of Beaver Run and overlying Harmonyvale cherts comprise the greatest volume of minable chert in the Wallkill Valley. Structural deformation of the region attenuated the interbedded cherts of the Ontelaunee Formation; deforming the more brittle chert into a succession of rigid en'echelon boudinage structures (LaPorta 2009).

Structural Geology of the Wallkill Valley

Geological mapping of the Wallkill River Valley (Fig. 1) elucidated three domains of structural deformation impacting the Cambrian-Ordovician carbonates; namely the normal fault, thrust ramp, and fold-thrust sections (LaPorta 2009).

Normal Fault Domain

The first structural domain in the Wallkill Valley involves normal faulting and fault-block rotation of chert bearing units ranging from 4–50 degrees of dip (LaPorta 2009). The stratigraphic unit that shows the most extensive aerial exposure in the normal fault section is Lithostratigraphic Package 1. The shallower dips, and restricted distribution of rocks due to normal faulting, limit accessibility of cherts for prehistoric mining (LaPorta 2009). However, where the Leithsville Formation is exposed within the normal fault section, it is extensively quarried, as these are continuous strand-line deposits.

Thrust Ramp Domain

The second structural domain involves a thrust ramp in which a fault moves and rotates the stratigraphy into a steeply dipping (50–90 degrees) panel of rocks tilted to the northwest (LaPorta 2009). Lithostratigraphic packages 2 and 3 are exposed along strike within the ramp. The attitude of the beds permits access from both underneath and above the chert bearing units through the accentuation of master joints (LaPorta 2005).

Prehistoric quarries in Lithostratigraphic Package 2 are smaller and discontinuous in the ramp, as stratigraphic factors work against structural considerations to limit lateral continuity. Collectively, the package two cherts provide a tremendous tonnage of ore for prehistoric stone-tool production over a prolonged period of time; however, singularly, the quarries are relatively small (LaPorta 2009). Quarries in Lithotectonic Package 3, however, are larger and better developed. This is in part due to boudinage development within the Ontelaunee Formation. The rheological contrast between ductile dolomite and more ridged interbedded cherts works in conjunction with stratigraphic factors to generate ideal field conditions for raw-material extraction.

The along-strike continuity of the stratigraphy, continuous sequences of boudinage cherts, as well as the structural orientation of the ramp, allowed easy access to raw materials and supported prehistoric mining endeavors. This is particularly true within the Crooked Swamp Member of the Rickenbach Formation, and the Beaver Run and Harmonyvale members of the Ontelaunee Formation, which represent the evaporitic sequences and near shorelines along the crest of Lithostratigraphic Packages 2 and 3.

Fold and Thrust Domain

The third structural domain involves folds truncated by southeast and northwest dipping thrust-faults (LaPorta 2009). The entire Cambrian-Ordovician succession is exposed in this domain; however, the folded nature of the rocks and truncation by thrust faulting severely limits along-strike distribution. Additionally, rocks located in the hinges of folds will change orientation due to folding, as opposed to faulting, leading to complications that impact quarry prospecting and raw-material discovery by native populations. The rocks in the folded section dip in multiple directions; either northwest or southeast, depending on where in the fold they occur. Dip angles range from 20–50 degrees, with a few outlier measurements existing in the 60–70 degree dip range (LaPorta 2009).

The structural nuances occurring within the third lithostratigraphic package serve to challenge the ingenuity of prehistoric quarry workers. Many of the quarries in the third domain fail due to the pinch-out of beds, fading of sedimentary facies along strike, radical changes in dip angle, etc. (LaPorta 2009). For these

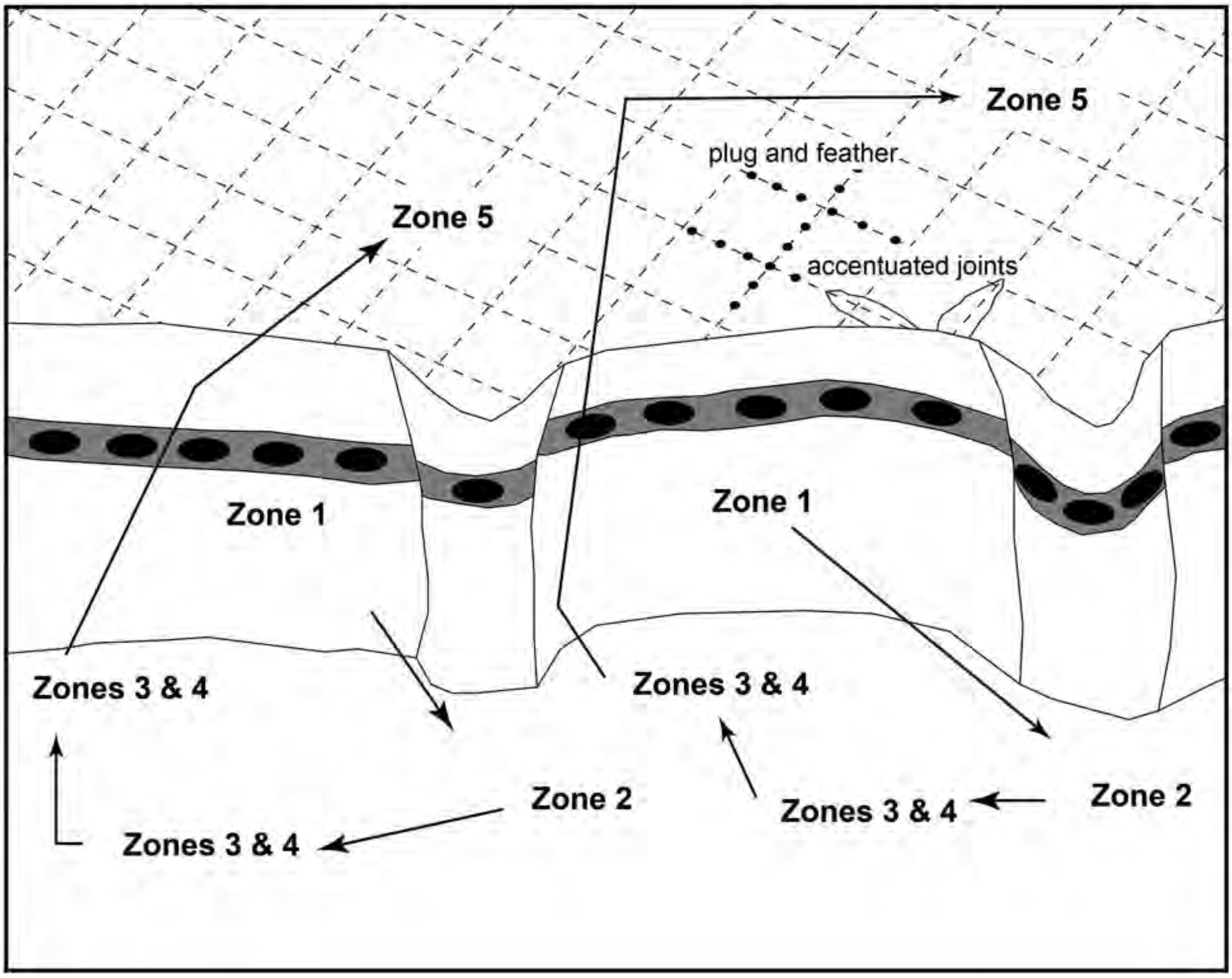

Fig 2. LaPorta Prehistoric Quarry Model (LaPorta 2004, 2009), revised, from the Wallkill River Valley, New Jersey-New York. Drawn: Philip C. LaPorta.

reasons, these are among the most interesting quarries to study, as they contain more elements of prehistoric behavior than the simpler quarries in the Normal Fault Domain.

In essence, quarries become more complex from the first, through the second, into the third lithostratigraphic package. However, when structure is superimposed upon stratigraphy, the quarries that are most elaborately developed are executed within the Wallkill Member in the Normal Fault Domain and the Crooked Swamp, Beaver Run and Harmonyvale members occurring within the Fold-Thrust Domain.

The First Tectonic Cycle Quarry Model

Field mapping and archaeological excavations of prehistoric bedrock quarries in the Wallkill Valley permitted the development of the First Tectonic Cycle Quarry Model (Fig. 2; LaPorta 2005, 2009). Master joints are accentuated and loosened due to plug-and-feather methods, the direct impact of hammers, and the application of heat. Repeated removal of joint-bounded ore blocks results in the development of a declivity, referred to as the Zone of Extraction (Zone 1; LaPorta 2005, 2009; Fig. 2 and 3a). The deepest declivities correlate with quarries that possess the best developed lower stable platform (LaPorta 2005, 2009). Boudinage in rocks of Lithostratigraphic Package 3 are also conducive to the development of deep declivities within Zone 1 because they provide easy access to large homogenous pods of chert.

The joint bounded ore block is physically passed downwards along the stable platform to a location where the dolomite gangue can be separated or 'cobbed 'away from the chert-bearing units in a location that is safe and does not impede active mining (LaPorta 2005, 2009). This locale is referred to as the Zone of Ore Milling (Zone 2; LaPorta 2005, 2009; see Fig. 2).

The chert fragments and remaining dolomite are then transported laterally to an area where the dolomite (gangue) is separated from the chert. This elongate chain of comminution of the ore is referred to as the Zone of Beneficiation (Zone 3; see Fig. 2; LaPorta 2005, 2009). Zone 3 is poorly understood because it is frequently buried underneath large debris from Zone 1. The products of beneficiation include dressed ore, microlithon packages and microlithons.

The Ore Processing Station (Zone 4; LaPorta 2005, 2009) is the location where the various grades of chert are again sorted for imperfections (Fig. 2). The chert, as refined ore, is then passed upwards to yet another stable platform, occurring above the Zone of Extraction (Zone 1), where finished tools are manufactured, and is referred to as Zone 5, the Zone of Ore Refinement (see Fig. 2; LaPorta 2005, 2009).

Quarries are often associated with quarry-support sites which may occur up to a kilometer from the site (LaPorta 2005, 2009). These sites typically exhibit the remains of quarry tools and instruments, as well as finished and recycled products emanating from the quarry.

Room for variation does exist within the Tectonic Cycle 1 Quarry Model, depending on the characteristics for quarry development outlined in LaPorta (2005); namely

1. the concentration of raw material-bearing units,
2. dip of the raw material-bearing rocks into the subsurface,
3. thickness of the surrounding rocks,
4. thickness of the ore within a bed,
5. presence of well-defined bedding planes,
6. presence and orientation of joint surfaces,
7. presence of a stable platform below the zone of extraction, and
8. availability of glacial till, which includes boulders of high-rank metamorphic rocks (preferably meta-quartzites), or other minable raw materials as a source for

These are the considerations that must be modified when applying the quarry model outside of Tectonic Cycle 1.

Evidence for the First Tectonic Cycle Quarry Model

The First Tectonic Cycle Quarry Model relies upon numerous data sources: specifically, geological (outcrop) and archaeological mapping; measuring of stratigraphic, and petrofabric characteristics of the rock; morphological features on bedrock quarry faces due to the extraction process; morphological and petrological analysis of quarry tools and instruments; petrofabric analysis of chert quarry tailings; and reconstruction of quarry-task subdivisions and resultant chains of operation. Geological and archaeological mapping involves observing chert within bedrock outcrops. The presence of prehistoric activity is usually discovered by observing overturned strata, fractured chert-bearing blocks of dolomite, and disrupted block boudinage of chert strewn over the base of outcrops. Evidence for the intensive use of outcrop in extraction activities is indexed by the discovery of anomalous quantities of broken, fractured, and severely battered meta-conglomerate boulders, scattered throughout the vicinity of the outcrop. Intimately associated with the outcrop area are distinctive, beehive shaped mounds of preferentially sorted, glacially derived boulders that are inferred as storehouses of potential tools and instruments for use during the developmental period of the quarry. Structural and petrofabric measurements of the ore, and surrounding country rock, elucidate how steeply beds are dipping and if they are also intersected by steeply inclined joints that have been pryed open. Such data is important because it determines the level of accessibility to miners given the use (limits) of quarry tools at their disposal.

Close inspection of outcrops reveals a typical sinusoidal outline to the chert beds, associated with a castellated and crushed or pulverized upper surface resulting from repeated impacts directed against the chert bed (Fig. 3a). The castellated surfaces are inferred as representing the limit of quartzite hammerstone technology at the quarry. The circumference of the castellation fits the circumference of the impactors and impact wedges lying about the surface (Fig. 3d). Analysis of overburden excavated from backfill piles occurring in front of Zone 1 suggests that after the limits of quartzite technology have been reached, the quarry technician employs a large hammer (impactor) to remove the exhausted quarry face. The impactor (up to 36kg) is focused on the intersecting joint surfaces occurring directly behind the active wall of the quarry. Repeated impacts will eventually release the joint bounded ore block and expose a new face of the chert bed. The exhausted quarry face has ensconced upon it the castellations recorded during earlier extraction episodes. Wall architecture represents one of the most common diagnostic artifactual remains to be examined within the scree occurring along the base of the quarry face.

Quarry Instruments and Tools

The instrument and tool kit directly associated with rock extraction, as excavated from prehistoric chert quarries, is most elaborate when occurring in the First Tectonic Cycle (LaPorta 2005, 2009). The petrology of the objects, their morphological and petrofabric characteristics, as well as the excavated contexts are critical evidence towards deciphering the task subdivision and resulting chain of operation. The following descriptions apply

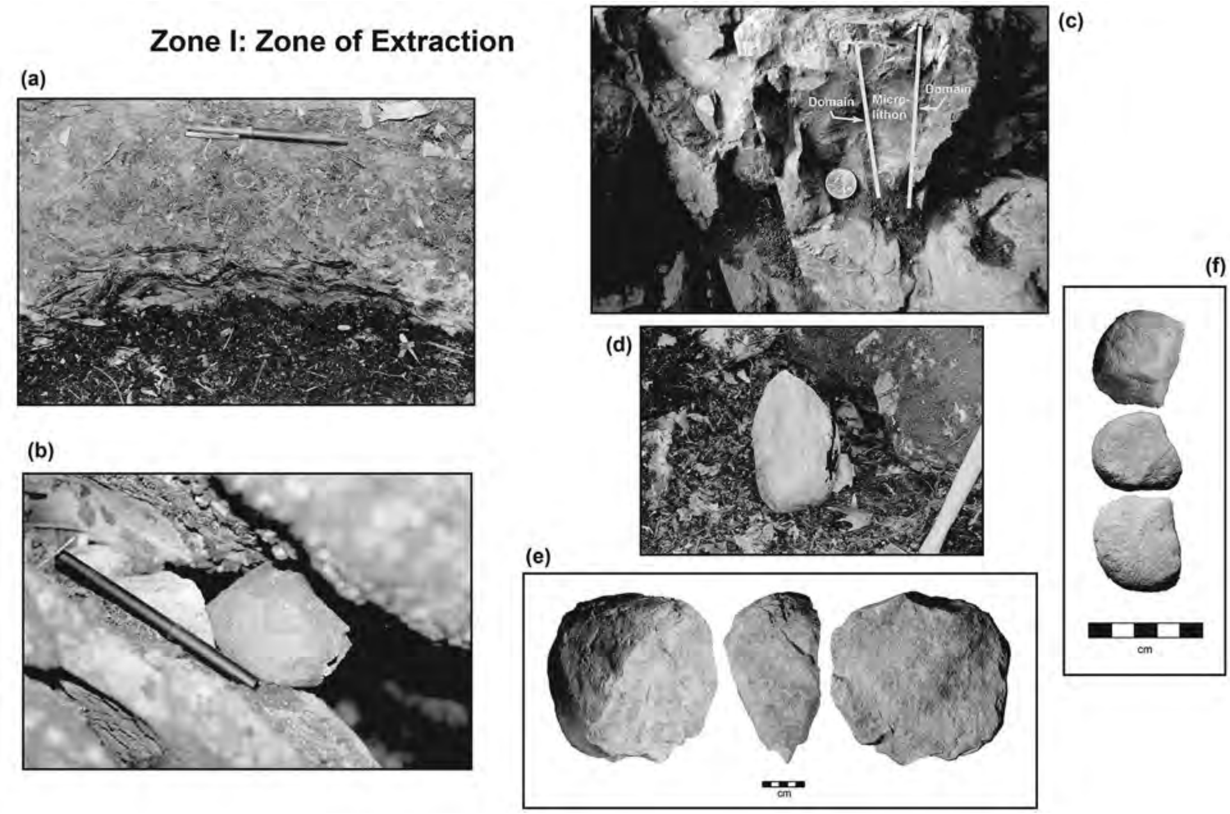

Fig 3. Zones of extraction (a-c), and associated instruments (d-f). Examples included are: (a) cuspate and castellated surface; (b) small instrument lodged in an accentuated joint, zone of extraction (Zone 1); (c) step and conchoidal scars on an excavated quarried outcrop; (d) impact object (with multiple flake scars); (e) impact wedge; and (f) focal chisel. Scales: the pen (a-b) is 14cm; the US quarter (c) is 2.5cm; and the rock hammer (d) is ca. 35cm. Graphic design: Philip C. LaPorta and Scott A. Minchak.

to the full complement of objects excavated from the entire spectrum of chert quarries cropping out within the lithostratigraphic packages and structural domains of the Wallkill Valley.

Zone of Ore Extraction

Fashioned predominantly from Silurian metaconglomerate, impactors represent the largest class of instruments excavated at Wallkill Valley quarries (Fig. 3d and Table 1). Their location at Zone 1, large size, and durable raw material support the inference that they are the primary tool for crushing block boudinage and joint-bounded ore blocks from the quarry face. They can also be used, or recycled, in the production of other tools and instruments after their breakage. Small ortho-/metaquartzite cobbles/pebbles are found wedged into the intersections of joint surfaces at Zone 1, and as such they are thought to be focal hammers or chisels (Fig. 3b). Prehistoric miners might take advantage of seasonal freeze-thaw processes to assist in the accentuation of joint surfaces. The force of the impactor can be focused upon focal hammers/chisels (Tab. 1) in order to channel the compressive stress of the impactor to a confined point between two joint surfaces, thus assisting in forcing the separation of contiguous ore blocks. Many of the focal chisels rupture on impact, as evidenced by broken chisels occurring in all states of use, re-use, and abandonment littering the quarry floor (Fig. 3f). Eventually impactors rupture at a point where bedding planes and joint surfaces within the instrument intersect. The rupture along joint surfaces will determine if the broken sleeve of the object will become a spatula-shaped wedge, or possibly a lap anvil (Tab. 1). Larger, flat surfaced, oblate remnants may become non-portable anvils which are usually found in Zone 5, above the Zone 1 declivity. Recycled fragments of sleeves are ready made as struts or chocks (Tab. 1), which serve to lever the bed outwards. Impactors which do not rupture during usage are found as highly granulated, slightly smaller, impact wedges which can further accentuate unyielding joint surfaces. The wedges may have as many as three cusps, which appear to be maintenanced. Excavated in context with wedges are small, thin, oval to rounded, metaquartzite hammers; the diameter of which corresponds with the surface area of the wedge cusps described above. These smaller hammers may be retooling instruments (Tab. 1) employed in the maintenance of quarry tools. Elongate quartzite hammers found in Zone 1 may also function

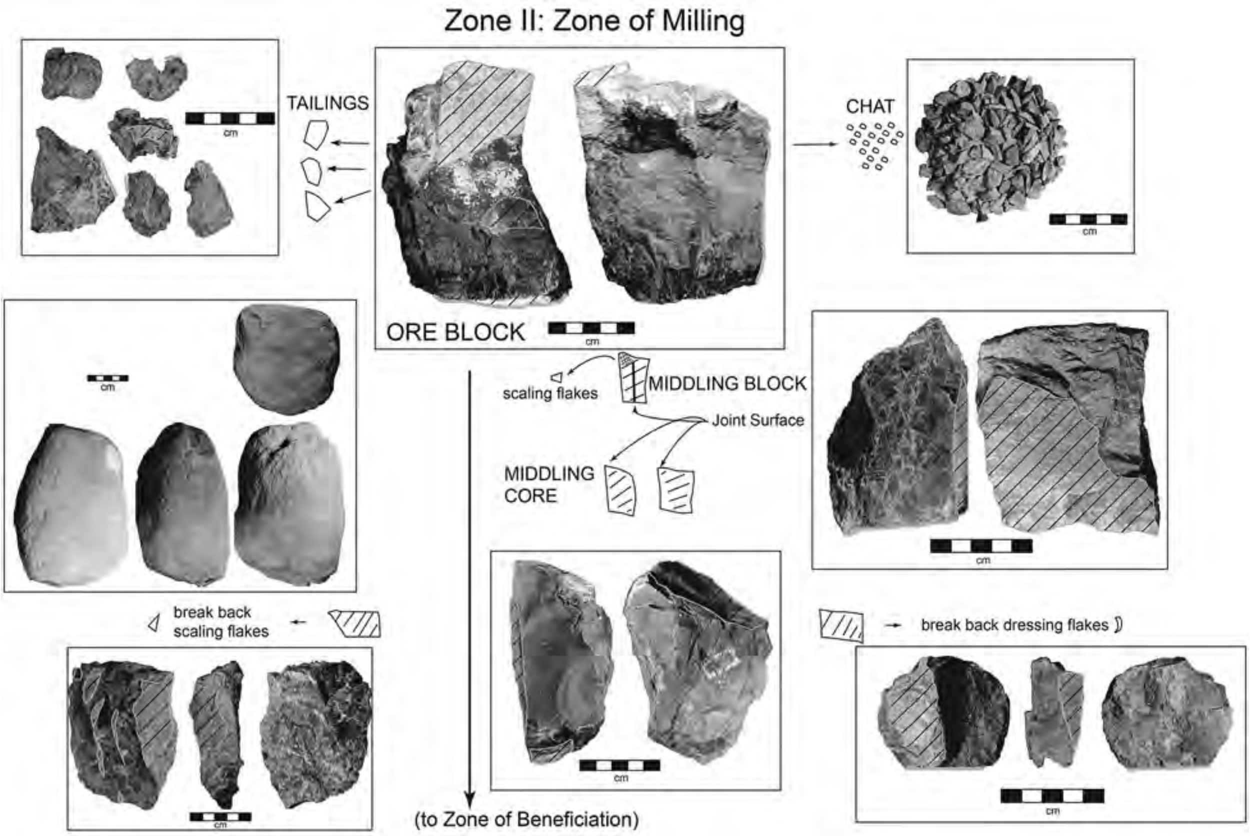

Fig 4. The following are artifacts classified as Zone II (Zone of Milling) artifacts from the LaPorta Prehistoric Quarry Model. Note: the hatching represent domains. Graphic design: Philip C. LaPorta and Scott A. Minchak.

as scaling bars (Tab. 1) used to remove jagged edges from the quarry face.

Zone of Ore Milling

Zone 2 is replete with ore crushing tools fashioned from clay-rich, arkosic sandstone and orthoquartzite (Fig. 4h). These petrological groupings are unique because they serve to apply a flat, enduring impact to the ore block. This is due to the elevated clay content of the arkose, combined with the general elongate rectangular shape of the objects. Distally battered and proximally pounded flat, the elongate rectangular ore milling instrument is designed to apply the full weight of the object to a more focused area of the ore block. The focal chisels (Tab. 1) are fashioned from ortho-/metaquartzite. This process serves to remove, or 'cobb', the dolomite away from the chert without penetrating the chert with microfractures. Re-tooling hammers (Tab. 1) composed of ortho-/metaquartzite serve to blunt the proximal edges of the elongate rectangular instruments.

Zone of Beneficiation

Beneficiation is less well understood than extraction, in part because Zone 3 occurs below Zone 1, therefore both quarry instruments and mine tailings are backfilled over Zone 3 during periods of stable platform maintenance. The excavated objects and associated tailings suggests that the chert is further dressed in order to remove all lower grades of ore and remaining dolomite gangue (Fig. 5). The ore is dressed as chert whose parameters are defined by large, well-spaced domains and whose interiors are generally free of noticeable fractures (Fig. 5a and 5b). The rough edges of the chert are removed. There is evidence for testing the homogeneity of the dressed ore in the form of small, more portable anvils. The instrument kit includes ortho-/metaquartzite ore dressing hammers (Tab. 1) which are small enough to be hand held and show considerable curation and re-tooling (Fig. 5f). Many of these objects are recycled from the ruptured impactors and may represent thin sleeves, or outer cortex of boulders. In general, a wide variety of petrological classes is evident, including instruments fashioned from meta-argillite, ortho-/metaquartzite, metaconglomerate, granite, granite gneiss, and ultrabasic rocks. The instruments, beneficiation hammers (Tab. 1), are generally rounded and show evidence of having been flaked and ground through re-tooling. Some objects appear circular or wheel shaped; some even possessing flattened or battered upper edges.

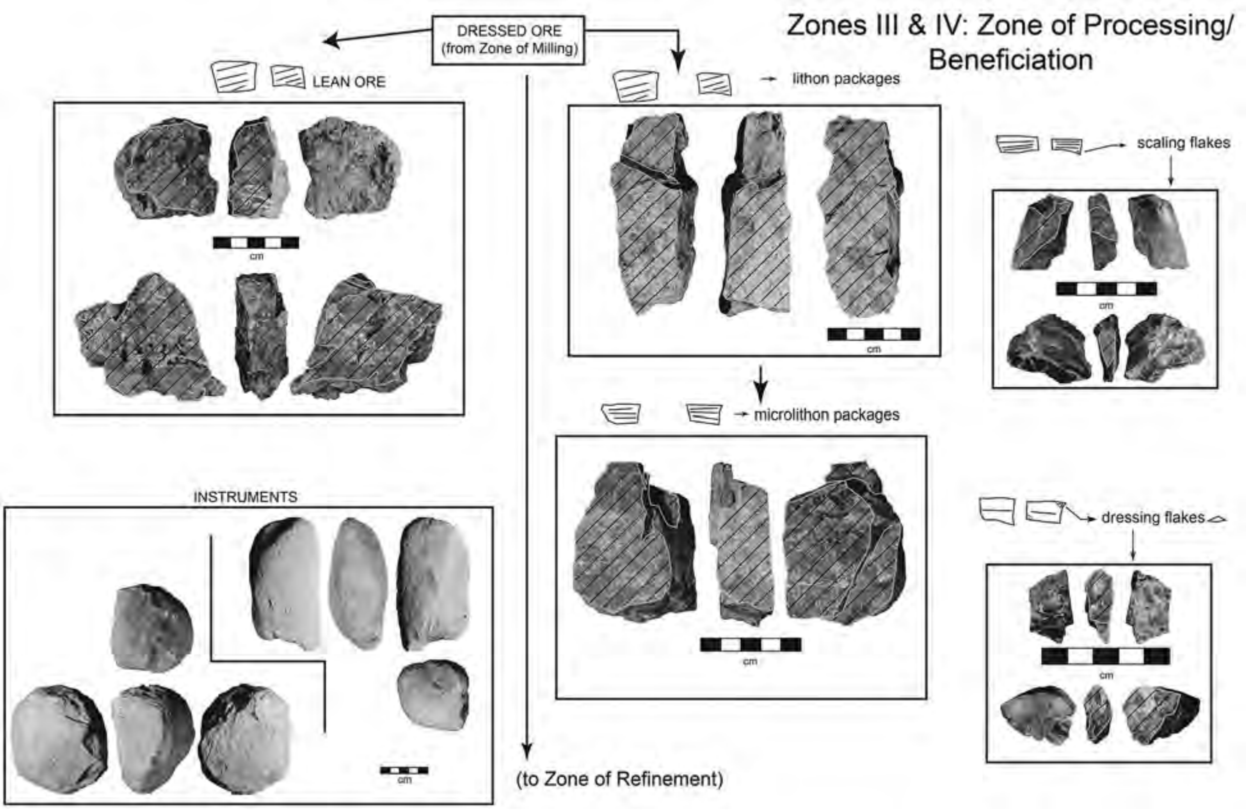

Fig 5. The following are artifacts classified as Zones III and IV (Zone of Processing/Beneficiation) artifacts from the LaPorta Prehistoric Quarry Model. Note: the hatching represent domains. Graphic design: Philip C. LaPorta and Scott A. Minchak.

Zone of Ore Processing

At Zone 4 dressed ore is inferred as being inspected for imperfections, which may appear again during the phase of biface thinning. The chert is sorted and the primary instrument type is the refinement hammer, which is usually fashioned from very elastic metaquartzite (Fig. 5f and Table 1). The hammers can be held within one hand easily and may be employed, along with a small class of focal chisel, to split lithon packages into utilizable units (Fig. 5b). The expression 'washing table' is adapted from current mining literature and represents the cleaning of hand sorted ore, which is divided out for specific needs. In order to accomplish this task, the microlithons are wetted, and closely examined for minute imperfections. The presence of broken ceramic vessels occurring at the base of this zone, lends credence to the hypothetical washing table. Other than the hand-held hammers and focal chisels, a variety of portable and portable anvils, including shoe, flat, convex, and lap anvils, are called upon for this task (Tab. 1). Formal excavations have yielded caches of both dressed ore, as well as microlithons and microlithon packages, resulting from the final stages of comminution of the domain bounded chert.

Zone of Ore Refinement

Zone 5 instruments include a non-portable anvil, usually fashioned from meta-conglomerate. These are, as mentioned above, the remnants of ruptured impactors removed from Zone 1 activities. Distributed radially around the anvil are split and rejected microlithons and microlithon packages, occasional middling cores, and the first taxonomic flake scars (Fig. 5g). It is at Zone 5 where the microlithon, for the first time, is flaked or thinned between domains into bifaces, bifacial cores, and other tools (Fig. 5b, c, e and f). Associated with the large anvil are smaller convex anvils, more portable shoe, flat, and lap anvils. They are derived from the rupture of impactors and occasionally milling tools and as such are fashioned from metaconglomerate, quartzite, meta-argillite or arkosic sandstone. The additional instrument types include every small class of focal chisels and highly elastic circular hammers fashioned from metaquartzite (Fig. 5h, 5i and Table 1). The circular hammers are, in general, four to five times as long and wide as they are thick and are commonly referred to as controlled flaking hammers. Small chert hammerstones and focal chisels fashioned from chert and quartz pebbles do occur at this zone.

Quarry Chain of Operation

The chain of operation is an outgrowth of the statistical analysis of discrete populations of quarry tailings and represents a critical component in determining the spatial relationships of the task subdivisions. This analysis of the chert, combined with the morphological, petrological, and petrofabric analysis of the quarry instruments and tools, serve to make diagnostic the five-phase quarry model for the First Tectonic Cycle.

Arranged in a linear fashion, the sequence is initiated with the successful extraction of chert bearing ore blocks or block boudinage from Zone 1. The ore blocks are approximately 1.5– 2.0m in length, and may weigh upwards to 2,000 lbs. Irregularities and jagged edges on the ore block are removed with retooling hammers, resulting in a platform covered with ruptured impactors, wedges, chat, focal chisels, chocks, rejected ore blocks and dolomite flakes (Fig. 4). The slightly refined ore block is dressed at Zone 2, with elongate, blunt milling hammers employed in separating the dolomite beds from chert. The resulting crushed ore blocks and middling blocks are about 25–50cm in diameter and are bound on all sides by domains. At this location, an ore block will occasionally not yield to cobbing and instead resist breakage. This is largely due to the presence of numerous, closely spaced, resealed domains, recrystallization fabric, heterogeneity imparted to the chert through diagenesis, or possibly due to the presence of pressure solution passing through the chert block. The ore block is set to the side where it serves as a middling ore block (Fig. 4d). The middling ore block can be re-visited for the volume of utilizable chert that it may possess as economic needs change. Eventually over time, the middling block will evolve into a faceted middling core block (Fig. 4e) of substantial size; however, it never leaves Zone 2. The surfaces of many of the Wallkill Valley quarries, and the associated mounds of backfill, are veneered with tailings piles comprised of dolomite blocks, chat, middling ore blocks, middling cores, focal chisels, ruptured tools and instruments, and the architectural elements of the former episodes of extraction (Fig. 4 and Table 1). Principal Zone 2 products include middling ore blocks, middling core blocks, middling cores, large focal chisels, struts, and chat (Fig. 4).

Half products resulting from the initial phases of comminution are passed to Zone 3. The focus of activity at this zone is to split domains from the more homogenous areas of the chert. This is accomplished through the application of meta-argillite and ortho-/metaquartzite cobbing or dressing hammers (Tab. 1). The products emanating from Zone 3 include considerable quantities of dressed ore, microlithon packages, microlithons, and small block cores (Fig. 5). The domain strength of the average dressed ore is approximately 10–15cm. The backfill exhibits rounded and circular beneficiation hammers with flat or blunted upper edges, chat, thin splinters of dolomite and inferior grades of chert (Fig. 4 and Tab. 1).

Zone 4 may be associated with the partial washing of dressed ore, and lithon packages prior to distribution to Zone 5. The products of Zone 4 are largely smaller classes of microlithon packages and microlithons (Fig. 4). The domain strength at this position is approximately 2–5cm. The backfill contains ruptured flat anvils, remnants of caches of lithon packages, and microlithons, various types of anvils, all associated with chat and a class of very small quartz and quartzite focal chisels (Fig. 4 and Tab. 1). These refined products are washed, then sorted, and eventually arrive at Zone 5 for manufacturing into finished products such as bifaces, bifacial cores, and utilizable flakes (Fig. 6). In general, domain strength at this location is 1–2cm for single microlithons, 2–4cm as for two microlithon units and 3–6cm for the three microlithon packages. In general, one microlithon unit serves for the production of projectile points; while two microlithons as for hand held bifaces and bifacial cores; while three microlithon packages are generally polyhedral cores.

Lastly, the discovery of small, thin, heat treated, vitrified, quartzite discs in the empty declivities of Zone 1 has cause for concern (Tab. 1). The discs are circular, half-moon and crescent shaped. They are ground along all edges and most evidence of flake scars has been removed by repeated grinding. Rarely, one of these objects is discovered fashioned from friable garnet muscovite schist, which does not occur in local glacial till, and may provenance from a distant source. The discs are lodged at the base of the Zone 1, neatly between the vertical joint planes of two contiguous ore blocks or block boudins. They have no apparent function; however, they may be fashioned from exhausted elastic thinning hammers which source to Zone 5 activities. The objects may represent a ritualized offering or 'giving back to the Earth' process.

Conclusions

Prehistoric bedrock quarries are first and foremost a geological entity. The geological setting of the raw material; the tectonic, structural and stratigraphic factors responsible for the genesis of the ore under examination, control how the material was extracted from bedrock and how prehistoric technicians worked the material into a product of choice. This investigation represents a successful attempt at using the petrofabric approach to prehistoric quarry investigations for the purpose of creating a successful model for the organization of prehistoric bedrock quarries and

Table 1. Attribute table for instrument and tool types for extracting and processing chert in the Wallkill River Valley: 1–meta conglomerate; 2–orthoquartzite; 3–metaquartzite; 4–meta-argillite; 5–meta-arkose; 6–granite; 7–gneiss; 8–syenite; 9–arkosic sandstone; 10–ultrabasics; 11–graywacke; 12–chert; 13–quartz.

Type	Zone(s)	Material	Weight	Form	Purpose
Impactor	1	1, 2, 3, 4,5,11	11-43 kg	ovate/circular	crushes ore blocks away from the quarry face
Impact Wedges	1	2, 3	9-36 kg	triangular	focused compressive stress on Joint Surface
Flat Wedges	1	1,2,3,4,5	10-12 kg	thin ovoid/ triangular	driven into joint surfaces to aid the impactor in accentuating master joints
Scaling Bar	1	6, 7, 8, 9	1-2.5 kg	elongate	retooling hammer/Removing jagged edges from walls of Zone1declivity
Struts and Chocks	1	1, 2, 4	2-6 kg	irregular fragments	recycled fragments used to support or pry the bed outward
Ceremonial Objects	1	2,3	.25-1.25kg	circular, half moon, crescentic	gift giving, giving back process
Milling Instrument	2	2, 4, 6, 7, 9	4-11 kg	elongate rectangular	designed to apply the full weight of the object to a more focused area of the ore block
Retooling Hammer	1, 2, 3	1	1-3 kg	elongate/ rectangular	smaller tools used to maintenance Impact wedges and impactors
Focal Chisel	1, 2, 3, 4, 5	1, 2, 3, 4, 5, 6, 7, 8, 9, 12, 13	0.03-1 kg	circular/ wedge	converge compressive stress of instruments
Large Faceted Wedge	1,2	1, 2, 4, 5	8-16 kg	plano-convex	focused compressive stress on joints separating two ore blocks
Faceted Wedges	1,2	2, 3, 4	5-11 kg	elongate triangular	serves to further accentuate the join between two opposing ore blocks
Ore Dressing Instrument	2,3	1, 2, 3, 4, 5, 6, 7, 8, 9, 10	1-4 kg	rectangular/ square, sub-rounded	removing the irregularities from milled ore
Ore Processing Hammers	3, 4	2, 4	1-2 kg	ovate/circular	thin, mildly ovate to circular highly elastic hammers designed for thinning bifaces and bifacial cores
Beneficiation Hammers	3,4	1, 2, 3, 6, 7, 9	1-5 kg	ovate/circular	designed for dull impact on fressed ore blocks and dressed ore
Convex Anvil	3,4,5	2, 4	4-6 kg	plano-convex	designed for the remoaval of flawed microlithons
Refinement Hammer	4, 5	1,2, 3	0.5-1.5 kg	circular	hand-held, employed with small class of focal chisels, split microlithon packages into utilizable packages
Lap Anvil	4, 5	2, 5	2-4 kg	mildly plano-convex	separating and crushing lithon packages
Shoe Anvil	4, 5	3, 4	3-6 kg	lentil shaped	splitting microlithons
Elastic Flaking Hammer	4,5	3	0.5-1 kg	circular	fine flaking of bifaces and bifacial cores
Flat Anvil	4,5	4,5,9,11		tablet shaped	crushing microlithons
Stationary Anvil	5	1, 2, 4	18-41 kg	strongly convex	stationary control preparation of finished tools

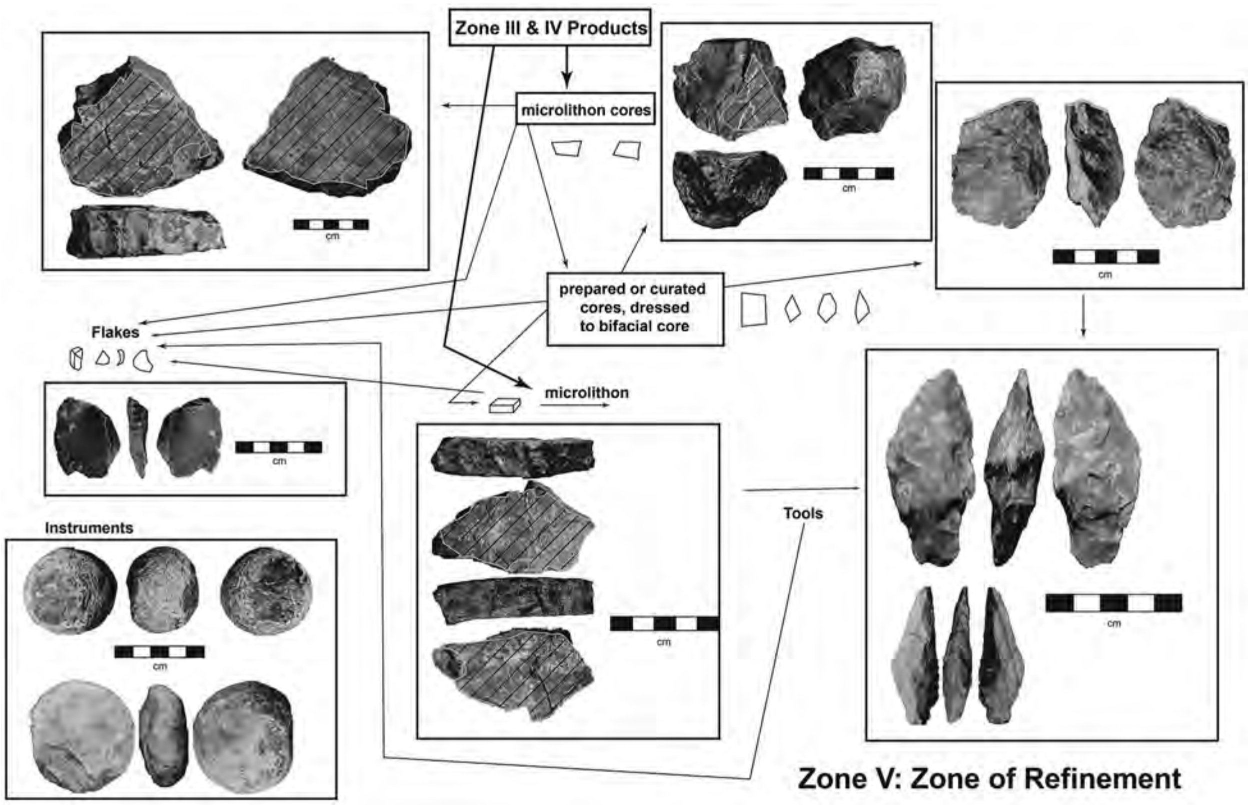

Fig 6. The following are artifacts classified as Zone V (Zone of Refinement) artifacts from the LaPorta Prehistoric Quarry Model. Note: the hatching represent domains. Graphic design: Philip C. LaPorta and Scott A. Minchak.

developing a complete chain of operation stemming from the quarry face to the final product.

Within the First Tectonic Cycle of the Wallkill Valley, prehistoric bedrock quarries are most elaborately developed within the normal fault and fold-thrust domains. Within these structural domains, quarries are best developed in the Wallkill Member of the Leithsville Formation, the Crooked Swamp Member of the Rickenbach Formation, and the Beaver Run and Harmonyvale members of the Ontelaunee Formation. All four of the most prominent quarry bearing horizons correlate with sea-level draw down and the preservation of thick, chert replaced evaporites, and related shoreline facies in a sabhka-like setting. Neither the stratigraphy, nor the structural geology, of the raw material individually controls the availability of the raw material for extraction. However, it is the interplay of the various aspects of the geology that creates unique, yet predictable, circumstances controlling accessibility, extraction methodology, and processing of the raw material.

The First Tectonic Cycle chain of operation, from the perspective of petrofabric analysis of the chert, may contain as many as 40 to 50 steps of comminution towards the production of finished tools. Coincident with the established chain of operation is an equally as sophisticated inventory of instruments and tools employed to comminute rock along planes of weakness in an effort to obtain utilizable units of chert. The proposed petrofabric framework, and associated multitask subdivision quarry plan, represents a serious departure from the traditional perspective of raw-material extraction and refinement strategies. This research has adopted a terminology derived almost entirely from economic geology and ore deposit studies, converting the stark monochromatic landscape of earlier quarry-workshop investigations into a vivid panorama of prehistoric subsistence related activities generating a three-dimensional, life-like depiction of quarry subsistence.

Lastly, the systematic nature of quarry development throughout the Wallkill Valley suggests that indigenous peoples were intimate with their natural surroundings and the whereabouts of their natural resources. The presence of theorized ceremonial objects recovered from Zone 1 excavations, possibly represents a giving back process. This suggests that a folk geology approach to landscape analysis may have been practiced by native peoples and possibly archived in ritualized behavior.

The embodiment of this behavior is contained within the most heavily curated object at the quarry, the hammerstone or curated quarry instrument.

References

Agricola, G. 1950 [1556]. *De Re Metallica.* Translated by Herbert C. Hoover and Lou H. Hoover. New York, Dover Books.

Amick, D. 1982. *Topsy: Late Archaic Biface Manufacture on the Buffalo River, Southwestern Highland Rim, Tennessee*. Knoxville. University of Tennessee.

von Bernewitz, M. 1931. *Handbook for Prospectors*. New York, McGraw-Hill.

Binford, L. and Quimby, G. 1963. Indian Sites and Chipped Stone Materials in the Northern Lake Michigan Area. *Fieldiana* 36: 277–307.

Chatterjee, K. K. 1993. *An Introduction to Mineral Economics*. New Delhi, India, Wiley Eastern Limited.

Church, T. 1994. *Lithic Resource Studies: A Sourcebook for Archaeologists* (Special Publication #3, Lithic Technology). Oklahoma, Department of Anthropology, University of Tulsa.

Crabtree, D. 1972. *Introduction to Flintworking*. Occasional Papers of the Idaho State Museum, No. 28, Pocatello, Idaho.

De Sitter, L.U. 1956. *Structural Geology*. New York, McGraw-Hill.

LaPorta, P. 1994. Lithostratigraphic Models and the Geographic Distribution of Prehistoric Chert Quarries within the Cambro-Ordovician Lithologies of the Great Valley Sequence, Sussex County, New Jersey. In C. Bergman and J. Doershuk, (eds), *Recent Research into the Prehistory of the Delaware Valley*. *Journal of Middle Atlantic Archaeology* 10: 47–66.

LaPorta, P. 1996a. *The Tenor of Ore*. New York, Albany. Paper Presented at the First Appalachian Integrated Highland Conference

LaPorta, P. 1996b. Lithostratigraphy as a Predictive Tool for Prehistoric Quarry Investigations: Examples from Dutchess Quarry Site, Orange County, New York. In C. Lindner and E. Curtin (eds), *A Golden Chronograph for Robert E. Funk*: 47–66. Occasional Publications in Northeastern Anthropology, No. 15.

LaPorta, P. 2005 A. Geological Model for the Development of Bedrock Quarries, with an Ethnoarchaeological Application. In P. Topping, and M. Lynott, editors, *The Cultural Landscape of Prehistoric Mines*: 123–139. Oxford, Oxbow Books.

LaPorta, P. 2009. *The Stratigraphy and Structure of the Cambrian and Ordovician Carbonates of the Wallkill River Valley: The Nature of the Diagenesis of Chert and Its Archaeological Potential.* Unpublished Ph.D. thesis, City University of New York.

LaPorta, P., Minchak, S. and Brewer-LaPorta, M. 2007. *Task Quarry Subdivisions of the First, Second, and Third Tectonic Cycles of Eastern North America.* Abstract. Implement Petrology Group 2007 Conference, York, England, Paper Presented at the Conference.

Munford, B. 1982. *The Piney Branch Quarry Site: An Analysis of a Lithic Workshop in Washington, D.C.* Unpublished M.A. thesis, George Washington University.

Pryor, E. 1965. *Mineral Processing*. New York, Elsevier.

Richards, R. 1903. *Ore Dressing*. New York, The Engineering and Mining Journal.

Richards, R. and Locke, C. 1940. *Textbook of Ore Dressing*. New York, McGraw-Hill.

Scholz, C. 2002. *The Mechanics of Earthquakes and Faulting*. Cambridge, Cambridge University Press.

Simons, T. 1924. *Ore Dressing: Principles and Practice.* New York, McGraw-Hill.

Tarr, W. A. 1930. *Introductory Economic Geology*. New York, McGraw-Hill.

Whittaker, J. 1994. *Flintknapping: Making and Understanding Stone Tools*. Austin, University of Texas Press.