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Talc-Rich Black Tibetan Pottery of Derge County, Sichuan Province, China

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ABSTRACT

Unusual raw materials are used to produce Tibetan black pottery in Puma township of Derge County, Sichuan Province, China. Carbonaceous, calcareous pyrite-rich illitic lakebed clay is mixed in equal proportions with a ferruginous talc-chlorite steatite. A two-stage firing process results in a dark, lustrous surface. The large amount of talc imparts many useful functional qualities to this pottery; most significant are the low thermal expansion and good thermal conduction properties of talc that make these ceramics highly suitable for heating and cooking in this high mountain region. Although used in some modern ceramics, and even in modern stoves, talc is an unusual ingredient in non-industrialized ceramics. Procurement and preparation of this resource adds to the production time but its properties and performance make talc an excellent choice for the well-being and comfort of local Tibetan households.

INTRODUCTION

Black pottery traditions are common in China from about 2200 B.C.E. onwards, and are found in many Tibetan areas. However, unusual raw materials distinguish the black pottery of one particular Tibetan workshop located in Derge County of the Ganzi Tibetan Autonomous Prefecture, Sichuan Province. The raw materials and production methods result in a ceramic that is very well suited to heating and cooking uses, and is in many ways a traditional hand-made pottery analogue to some modern industrial ceramics. This highly functional pottery can be either black or dark grey, with a very smooth, lustrous surface (Fig. 1).

The small pottery workshop is located in the Puma township of the Dzongsar-Maisu (also called Menshö) area of Derge. Derge is in the eastern Tibetan cultural area traditionally known as Kham, now administratively in the northwestern part of Sichuan Province near the border of the Tibet Autonomous Region. The town of Derge, the county seat, is famous as the location of the Derge Parkhang, a historic Tibetan printing house and temple. Puma township is located to the southeast about a half-day drive out of Derge (Fig. 2).

What is most important about the unusual raw material mix is that, even with hand-building fabrication methods and a simple firing procedure, a high-quality ceramic is produced that is well suited for heating and cooking. The local black clay, an illitic ball clay, contains calcium carbonate and carbon. This clay is mixed with about 40-50 vol% of a material the potters call "gold stone" (*sedo* in Tibetan) which is primarily talc. The fabrication of objects is

Figure 1. Pottery of Puma Township in Derge County, Sichuan, is either black, like the stew-pot on the left, or dark grey, like the hot water and tea pot on the right. Both types have a smooth, lustrous, almost greasy surface texture (Y. Xu).

Figure 2. Map of Sichuan Province showing location of the Puma township pottery workshop (C. L. Reedy).

accomplished completely by hand, with the finishing step being careful smoothing of the surface. A two-stage open firing process uses local pine wood as the fuel. The final products can be gray or very black in color, with a lustrous to shiny surface. A wide variety of objects are made, including cooking pots, hot pots and braziers, tea pots and cups, liquid containers, vases, incense burners, and others. The innovative mix of raw materials that includes a large amount of talc, illitic clay, and carbon impacts the properties of the pottery in many positive ways and increases its usefulness and lifespan. Talc at this high level of addition is found in some modern industrial ceramics, but it is unusual in traditional hand-made pottery. Archaeological data are currently insufficient to determine when this talc-rich Tibetan black pottery first emerged.

The pottery technology of Puma township is also an excellent example of community-based cultural preservation. While the tradition is ancient, by 1997 there remained only one elderly potter who had the traditional craft skills. Luore Phuntsok, the founder of the Yothok Yonden Gonpo Medical Association, a Tibetan non-governmental organization (NGO) located in Derge County, responded to help the tradition survive. The NGO was already involved in preservation of traditional Tibetan medicine practices, and it operates a hospital in the Dzongsar-Maisu area where Tibetan medicine is practiced and taught. The NGO set out to also preserve many Tibetan crafts, including pottery. Workshops and training programs were developed to preserve not only pottery, but also bronze casting, weaving and dyeing, thangka painting, wood carving, furniture making, and many other crafts [1].

The pottery teaching workshop was established in 2003 by Tashi Namgyal. His son, Jamyang Gelek, took on the teaching duties in 2010. Today there are about 30 potters skilled in this pottery tradition, and active classes are held at the workshop in Puma (Fig. 3). Students are both local and from as far away as the Tibet Autonomous Region and Qinghai Province.

RESEARCH METHODS

In 2014 our collaborative American-Chinese team surveyed remaining traditional pottery workshops of Sichuan Province, China. In July, 2014, we visited the Dzongsar-Maisu area of Derge County, including the Puma township pottery workshop. Raw material use and processing, workshop organization, pottery fabrication methods, firing procedures, product types, and marketing strategies were studied. Methods used included observation, participant observation, interviews, photography and videography, and collection of examples of raw materials, pottery sherds, and intact finished products. Our sampling strategy was to collect materials at all stages of processing. For raw materials this included ground and unground unfired clay from the grinding shed and from the workshop, ground and unground talc stone additive from the grinding shed and from the workshop, and the ground clay and talc additive mixture. All of these raw materials were from a single season of the workshop's field collection efforts, so there may be some slight variation with the materials collected in other years; however, we endeavored to collect a suite of raw materials representative of those used by the workshop, before and after processing. Ceramic collection included fired pieces from the kiln, wasters from the kiln, and a dozen intact objects of a variety of types (such as braziers, teapots, soup or stew pots, plates, and small vessels, juicers, whistles, and incense burners). Our goal was to collect objects from the full range of traditional and more modern designs and object types made by the workshop.

All of the materials and objects collected in the field were then studied in the laboratory by a variety of methods, and used to support the conclusions reported in this study. For raw materials and sherds, minerals and other non-plastics were identified and studied qualitatively by transmitted polarized light microscopy (thin section petrography) [2] using a Nikon Eclipse 50i POL microscope system. Thin sections were prepared using a blue-dyed epoxy to distinguish pores from clear minerals. Thin sections were also scanned using a Pathscan Enabler 5 geological slide scanner, at resolution of 2.54 µm/pixel (10,000 x 10,000 dpi), for quantitative image analysis of entire thin sections. Image analysis was accomplished using Image-Pro Premier by Media Cybernetics, to examine the amount, size, and shape of inclusions and to measure the Total Optical Porosity and pore size and shape [3, 4].

Other techniques often used in the study of ancient and historic ceramics [5, 6] that were employed include scanning electron microscopy with energy dispersive X-ray analysis (Hitachi S3400 SEM and S4800 FESEM, both with ThermoNoran EDS and NSS software), electron probe microanalysis (Cameca SX100 5-spectrometer probe with backscattered imaging and EDS), refiring tests (Thermolyne 1700 Furnace), and differential thermal analysis (Perkin-Elmer 1700 DTA). We also performed measurements to examine open porosity (ASTM C 20-74), and gloss (Horiba IG-410 Gloss Checker). Hardness testing was performed using the Mohs hardness scale, measured by scratching the surface with a mineral for each hardness number using the procedure recommended to us by Fred Matson [7]. The Mohs stone was first used to scratch the pottery, and then both surfaces were observed for traces of the softer material at 10-30x using a stereomicroscope (Leica E74). The reverse procedure was then performed, with the pottery scratching the stone, followed by similar stereomicroscope observations. Intact objects were studied using Xeroradiography (Xerox Medical Systems Xeroradiograph 125) to examine the internal structure and distribution of particles and pores resulting from fabrication [8]. Performance characteristics were also studied by using pots for their intended cooking, serving, and heating functions, and observing the results.

Figure 3. Interior of Puma township workshop, Dzongsar-Maisu area of Derge County (Y. Xu).

RESULTS AND DISCUSSION

Raw Materials and Processing

The Puma potters use black clay as one of their basic raw materials. There is only one source for this clay, a deep pit located on the mountain behind the nearby Dzongsar Monastery in the adjacent Dama township. Clay mining can only be done when the weather is dry enough. Summer is too wet, and the clay pit fills with water. During the cold season, the clay is too frozen to extract. Since clay mining times are so restricted, a large amount is extracted over two to three days at each visit. Only one or two trips to the clay source are needed each year to fulfill the needs of the Puma workshop.

By eye the clay appears to be very black. However, in thin section it is seen to actually be a very inhomogeneous material comprised of a white clay that appears black macroscopically because it is streaked with black veins, spots, and powdery areas of carbon (Fig. 4). There are veins and crevices of recrystallized calcium carbonate, and some clusters of primary calcium carbonate (Fig. 5, left). There is also a significant amount of accessory pyrite (iron sulfide) present, especially within and near the carbon streaks (Fig. 5, right).

After being brought back to the workshop, the clay is washed, then ground by hand and sieved to ensure a fine particle size. Before use in pottery production, the powdered clay is mixed with another raw material called *sedo* or "gold stone." This stone is obtained from surface deposits further away from the village than the clay deposit, in Duopu Valley in boggy areas near Xinluhai Lake (called Yilhun Lhatso in Tibetan). The round-trip can be done in one day by horseback. The potters say that they add the gold stone because it makes the clay stickier and easier to work with; and because it also keeps the clay from expanding too much during firing, so prevents the pots from cracking or breaking during the first firing stage.

Figure 4. Clay used by the Puma potters is black in hand sample (left) but under the microscope (right, thin section, plane polarized light) is seen to be a white clay that is very inhomogeneous, with some veins and crevices of recrystallized calcium carbonate, some clusters of primary calcium carbonate, and powdery strings of black carbon (Y. Xu, left; C. L. Reedy, right).

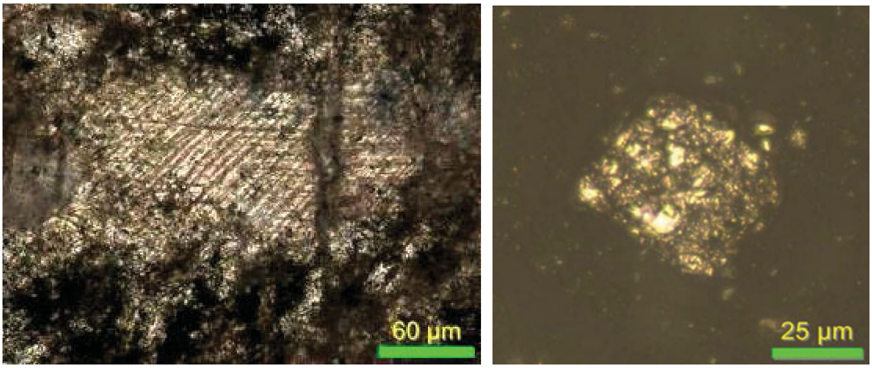

Figure 5. Rhombohedral cleavage of primary calcium carbonate grains can be seen within the clay (left, plane polarized light), and in reflected light the strings of carbon are seen to be dotted with pyrite grains (right) (C. L. Reedy)

The *sedo* stone is ground to a fine powder using a large stone mortar and pestle (Fig. 6), and then mixed with the clay. For small objects, potters say that a ratio of 50-50 clay to gold stone powder is used, and the potters say that they may add even more *sedo* for large pots.

Figure 6. The *sedo* is ground with a large stone mortar and pestle (left) to a fine powder (right). The ground *sedo* is then mixed with the ground black clay (Y. Xu).

Thin section petrography and differential thermal analysis confirm that the primary component of *sedo* is talc (hydrated magnesium silicate), with a significant amount of chlorite mica also present. In addition, the stone contains veins and chunks of iron oxides. These include hematite and iron hydroxides (goethite and limonite) formed as iron oxide hydrated upon exposure to water over time (the stone is picked up from the surface of the ground in a boggy area near a lake), often forming yellow stains over much of the surface of the stone. It is common for talc deposits to contain moderate amounts of chlorite, along with some iron and staining films [9]. Also present is some accessory serpentine, also typical in talc deposits. The chlorite and iron oxide/hydroxides together impart the golden color to the stone. The rock is best described as a ferruginous (iron-containing) steatite, which is sometimes called "soapstone" (Fig. 7). The term steatite is more appropriate than talc schist, because thin sections show that while in some areas of the stone the talc flakes have the strongly preferred orientation of talc schist (with talc grains aligned in the same direction), in many other areas they are instead more randomly oriented.

After the two raw materials are ground, they are mixed together. Water is added (very pure stream water, not yet sampled and analyzed), and the material is ready for the potting shed. In thin section the clay matrix of this mixed material appears completely black, because the carbon has powdered and spread over the entire matrix during grinding (Fig. 8). Many inclusions of the ground talc-chlorite stone are visible, with their iron staining. There are also grains of quartz, polycrystalline quartz, and microcrystalline quartz, liberated from the *sedo* during the grinding process. A few particles have a schistose texture with layers of talc alternating with fine-grained quartz; some are mainly talc but in layers of preferred orientation. Many other particles have a massive (non-layered) appearance. Sometimes chlorite is seen on surfaces, and there are a few serpentine patches.

Quantitative image analysis of a scanned thin section of unfired mixed material shows that particles sand-sized or larger (≥ 0.063 mm in Feret diameter, the caliper length along the major axis) constitute 35% of the total area of the material, with additional smaller silt-sized particles present. This area percentage for the *sedo* particles does not conflict with the workshop report that they mix powdered clay and powdered *sedo* in equal amounts because experiments with image analysis of clays with known amounts of temper additives have shown that multiplying measured area image analysis results by 4/3 calibrates to how a potter originally measured by volume a temper additive [3]. Applying that calibration factor here results in 47%, quite close to the 50-50 ratio the potters say that they aim to reach. The calibration factor is necessary because of known discrepancies between target and measured amounts due to several

Figure 7. *Sedo* stone hand sample (left); in thin section (right, plane polarized light), most of the stone is seen to consist of colorless talc, with scattered dark grains and veins of iron oxides/hydroxides (hematite, goethite, and limonite) as well as yellow patches that are a mix of chlorite mica flakes and limonite staining (Y. Xu, left; C. L. Reedy, right).

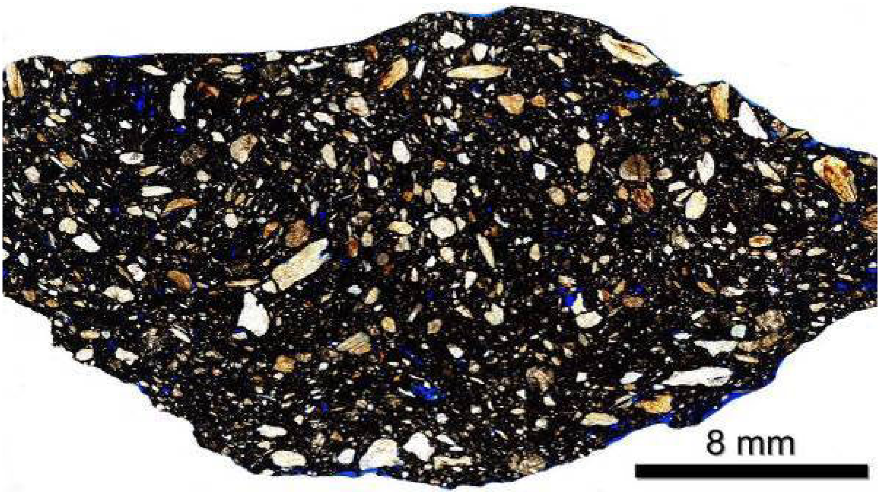

Figure 8. Scanned thin section (plane polarized light) of mixed clay and *sedo* particles (unfired) (C. L. Reedy).

factors: (1) the volume of air surrounding the loosely packed additive particles, which is no longer present after kneading; (2) the ground particle volume also varies depending on the effort put into tamping down grains; (3) dry powdered clay can also vary in volume by as much as 30%, depending on tamping effort; and (4) many particles in thin section will not be cut through their largest diameter. Statistically, the average diameter will be .785 times the actual diameter, which can affect area measurements [10].

It is also clear that even though the *sedo* was ground to a powder, the grinding process leaves a wide range of particle sizes. The quantitative image analysis shows a size distribution from silt (< 0.063 mm) up to 2.8 mm Feret diameter, which can be categorized as fine gravel. Most of the particles in all of the size categories are more elongated than equidimensional (with an average aspect ratio of 2.0).

Fabrication

Fabrication of objects is done by hand, sometimes using molds, to build pots from preformed molded elements, coils, and slabs on a slow, hand-turned pottery wheel (Fig. 9). Potters make use of a combination of hand building, paddling, and smoothing to use coils and slabs, and they sometimes incorporate pieces, for instance, with dragon motifs, that are made in metal piece molds for the spouts and handles. Fired ceramic, convex molds are often employed for the lower parts of vessels. *Sedo* powder is used to keep the potter's hands and the molds and tools from sticking to the clay during fabrication, so potters keep bowls of this golden powder near their workstation.

Figure 9. Vessels, such as this incense burner, are built by hand using a small hand-turned, tabletop wheel and incorporating the use of convex molds. Bowls of powdered *sedo* are used to prevent molds and the potter's hands from sticking to the wet clay body (C. L. Reedy).

The surface of a finished object is carefully smoothed, first with a thin yak hide tool, then with a smooth pebble that has a curved shape with one side convex and the other concave for finishing large radius surfaces on the interiors and exteriors; it also has one area with a very small radius and another with a slightly larger radius for finishing small interior surfaces. Other tools are hand-made wooden ones and pieces of a cow hide (Fig. 10). Potters say the meticulous finishing is done to make the surface shiny. This finishing step causes the talc particles on the surface to become more aligned parallel to the surface and the clay particles to become compacted and aligned, giving the clay body greater strength and the surface its lustrous, almost greasy texture. This burnishing step also lowers the porosity of the surface, making the object a better conductor of heat. This quality will cause it to radiate heat more effectively, and is an important property for the cooking and serving vessels and for braziers that are used to heat homes.

The workshop reports that the fabrication of pottery can only take place during the summer months. At other times of the year it is too cold to work, and the wet clay will also freeze or develop an unworkable consistency. The potters plan to construct a heated workshop in the future so that production can increase by extending the working period to year round.


Figure 10. Tools, wheel, pot, and talc on wooden table with padded seat to upper right. Pot made by Vandiver, shown prior to the smoothing and burnishing step. The tools are, lower left to upper right, interior base forming tool, wooden and stiff-hide forming and trimming tool, rectangular stiff-hide forming and smoothing tool, special smoothing and shaping rock near wheel, and, in the background, powdered talc (*sedo*) for use in making the clay body less sticky and for smoothing the surfaces of the pots (C. L. Reedy).

Some apprentices can learn the craft in three or four years, but others need more training time. After training, many potters stay and work for the master of this workshop. If they set up their own workshop, it must be in this general area, because this is the only location where the necessary raw materials for this type of pottery are found.

Once complete, the objects are dried indoors at the back of the workshop for about 10 days (Fig. 11). While there is a roof, the door and windows are open, and no additional covering is used. This drying is a crucial step, because if there is too much water remaining in the clay due to incomplete drying, when encountering the sudden temperature increase of firing, water boils within the walls of the pots and causes them to crack and occasionally blow up. The other problem is freezing during cold nights, causing the wet or damp clay to disaggregate into layers that sluff off the surface during drying. However, fabrication of objects takes place mainly in the summer when it is warm enough to work, and rainfall is often heavy. Under the humid conditions of summer, it appears that complete drying in the workshop is difficult to achieve, which likely contributed to the development of the two-stage firing process described below.


Figure 11. An array of finished objects drying inside the workshop (C. L. Reedy)

Firing

Firing is done about once a week, for all of the objects that have been drying inside the workshop and are considered ready. Local pine wood is used as the fuel. Firing is done as a two-stage process. The first firing is at a relatively low earthenware temperature, and appears to be mainly to ensure that all remaining water held in pores within the objects is fully released and preliminary sintering has occurred. For this firing, objects are placed on a metal grate raised above ground, in an open but sheltered structure (Fig. 12). This grate looks somewhat like a large barbeque grill, with wood placed in slots just beneath the grate. This firing lasts for two hours, with the heat increased very gradually to very slowly release remaining water in pores in order to prevent cracking. The objects are left in place and allowed to slowly cool for one full day. Each object is then checked for cracks, and any cracked pieces are discarded. The potters report that usually about 10% of the objects fail to survive this first step, so it is a critical stage.

The second, higher-temperature firing takes place in a shallow pit dug into the ground adjacent to the metal grate (Fig. 13), with wood piled around the objects. For the most traditional wares, which are very black, sawdust is also added for surface reduction. The sawdust is placed in empty spaces between pieces of wood, and ensures that air is more completely preheated and that as high a temperature as possible is achieved. This reducing atmosphere produces pottery with very black surfaces. The potters say that some clients prefer a gray color rather than a deep black surface, so for those objects the sawdust is left out.

Figure 12. Kiln (left) with slots for inserting pine wood fuel, and firing trench with metal grate (right) where pots are placed during firing; piled charred wood at lower left marks the location of the second kiln, a pit kiln that fires to a higher temperature (C. L. Reedy, left; Y. Xu, right).

Figure 13. Closer view of the second, higher-temperature, firing location, a shallow pit kiln into which pottery objects are placed with wood and sawdust surrounding them (C. L. Reedy).

Structural, Compositional, and Thermal Characteristics

Xeroradiography shows some of the structural features of the fabrication process and the variation in texture of the ceramic body (Figs. 14 and 15). For example, Fig. 14 shows a teapot and stew pot with lower bodies molded in pieces and strips over convex molds. The teapot was joined to a molded upper-body with vertical smoothing marks on the interior of the joint. The neck also shows evidence of vertical smoothing, but, based on our observations, the neck was probably made by coiling, paddling, and smoothing — however, traces of these operations have been obscured in the radiograph by the vertical smoothing marks. The handle and spout were molded in two-piece cast brass molds with dragon motifs, and the lid (Fig. 14 left, lower right, top view), was handmade. The upper part of the stew pot was made by coiling, paddling, and smoothing. Fig. 15 shows a brazier made with a molded base construction method.

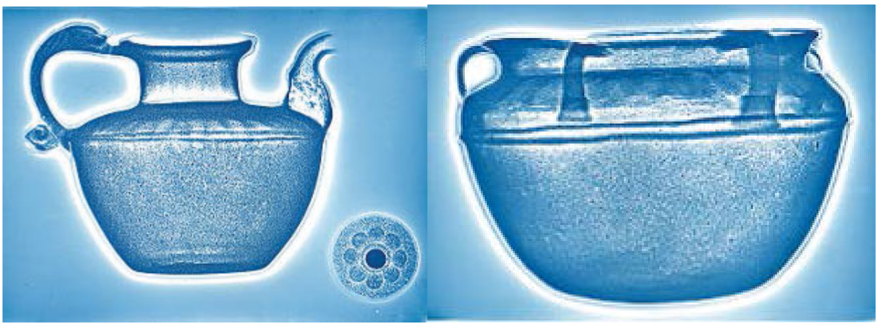

Figure 14. Xeroradiographs of teapot and lid (left) and stew pot (right) showing coarse texture and similar fabrication techniques with molded base joined to molded or handbuilt upper body, vertical interior compression of joint; handles on stew pot and lid were made free hand, whereas spout and dragon handle were made in two-piece molds (P. B. Vandiver).

Compositional analysis by energy dispersive X-ray spectrometry shows the body to be made of a magnesium-silicate with some alumina and iron oxide (*sedo* or golden stone), and an illitic clay with iron, potassium, magnesium, and sulfate, shown in Table I. For clay mined at about 4000 meters altitude most fluxes are usually depleted; however, the amount of fluxes is high in this clay and is more similar to a humic, lakebed deposit found at sea level. The areas of raw materials sampled by EDS did not contain calcium, but the fired clay body did contain about 7.7% CaO. This anomaly is due to the inhomogeneity of the clay raw material, as highlighted by the thin-section petrography. In order to obtain an average composition for the fine matrix material, the EDS analysis intentionally avoided inclusions such as the calcium carbonate ones. These are relatively large and unevenly distributed so easy to miss at the EDS magnification of 400-500x.

Using differential thermal analysis of the talc, fired from room temperature to 1100°C, heating 70 grams at 10°C/min., the decomposition reaction for the talc occurs at 962.8°C, in agreement with published data [11, 12]. The clay, however, is complex with a major but broad decomposition endotherm of about 1° between 868 and 875°, indicating illite, and possibly convoluting with some calcium carbonate; and two broad major exotherms of about 1° at 445°

and 605° indicating burnout of two organic or carbon-containing materials. The baseline deflects slightly upwards at about 220°, and this deflection could indicate the onset of the burnout. Based on this data, a ball clay is suggested. However, two other endotherms are present, one of about 1° at 520° that is a return to near the baseline, perhaps indicating that one carbon-containing material has completed burning and another one has not yet begun. The second endotherm is a very small one of 0.2° at 790° that could be the decomposition of a minor amount of calcium carbonate, but curiously where the peak of the calcium carbonate endotherm should be at about 800-820°, the curve increases to a maximum. The complex undulating pattern could also indicate that a minor amount of montmorillonite might be present, perhaps as a mixed illite-montmorillonite clay structure. No quartz inversion peak is found at 572°, indicating a lack of this mineral. This heterogeneous, complex clay requires further testing by DTA and X-ray diffraction once the carbon-containing fraction is removed. However, disaggregating the carbon fraction from the clay by Stokes' Law separation, unexpectedly, was not successful.

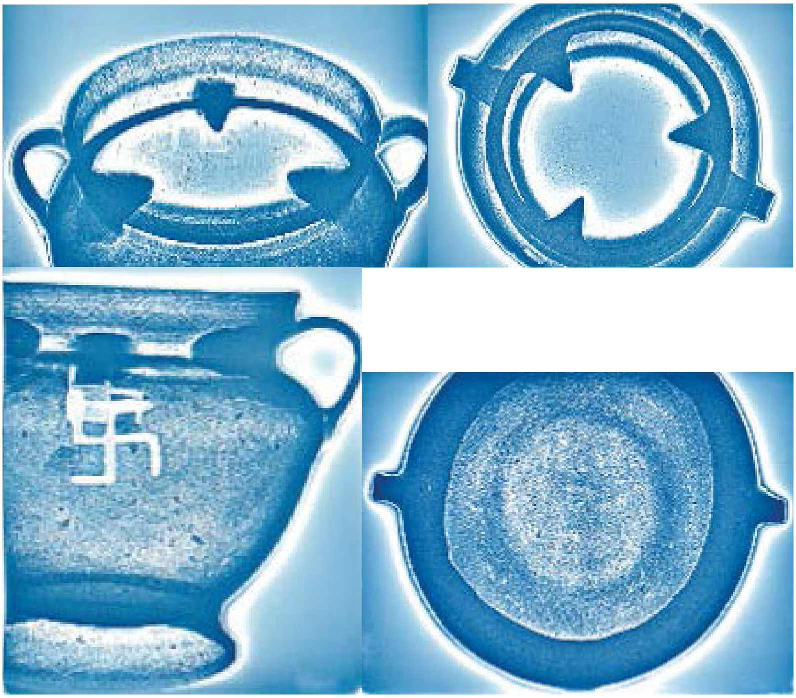

Figure 15. Brazier showing (lower left) coarse texture of body, holes cut for inflowing air, two handles reinforced from above, decorated flaring rim, triple lug pot support, and decorated ring base. Top-left image shows joint between rim section and body as a line of porosity below the lugs. Upper right shows reinforcement around the triple lug supports for stew or tea pots. Lower right image shows molded base of stew pot with random alignment of porosity, indicating clay wads were added to the convex mold during construction (P. B. Vandiver).

Based on refiring experiments in both oxidation in air and reduction firing in nitrogen from 700° to 1200°C in increments of 100°C with a 10-15 minute ramp and a 15 minute soak at each temperature, the microstructures most resemble the original sherd at 1100 ±50°C. The original sherd is a vitreous dark gray to black matrix with facets from the polycrystalline inclusions that vary in size and proportion. By 1000°C the talc has broken into friable plates and layers. When the unfired body is fired to 1000°C, the ground matrix is sintered but not as vitreous as the original fired bodies. Refiring to 1200°C produces, in oxidation, a vitreous clay and talc body, and in reduction, a very vitreous and bloated ceramic body, indicating that the kiln did not reach this temperature.

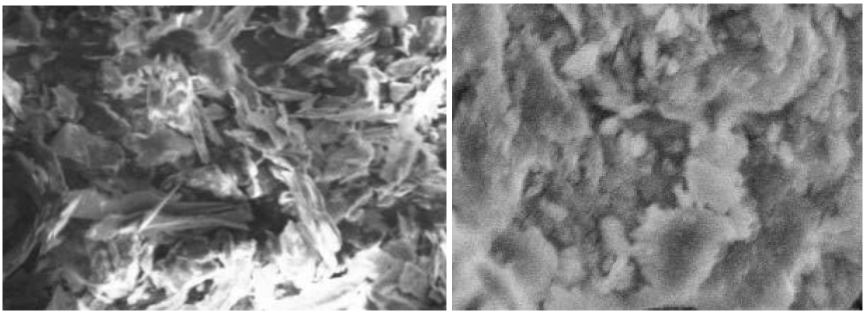

Figure 16. Microstructure of raw materials: Talc with sharp, angular, platy structure (left, 500x); clay with a wide range of poorly formed clay particles, 0.5-12µ (right, 8000x) (P. B. Vandiver).

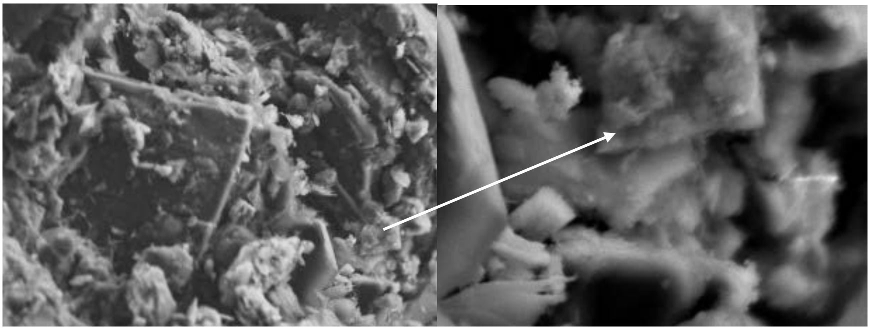

Figure 17. A fresh fractured surface from a serving plate exhibits a fired ceramic microstructure at 670x (left) and 10,000x (right). Edges of talc particles have begun to soften and to lose their angular crystalline shapes. The clay has begun to sinter to the talc particles and to lose surface definition when fired at the estimated firing temperature of about 1100°C. The square platy particle on the right is also present in the lower right of the image on the left. These images were taken of a fractured surface made parallel to the pot's surfaces in order to detect the alignment that occurred during fabrication. Compared to Fig. 17, right, significant alignment and increased fracture strength is attained by the application of shear force during fabrication (P. B. Vandiver).

The microstructures and particle size ranges of the raw materials, ground talc, and unground clay are shown in Fig. 16 and the fired microstructures are shown in Fig. 17. The ground talc has broken into angular plates that can measure a few microns thick and up to 3 mm maximum diameter. The poorly formed clay particles measure 0.5-12µ, a wide range of particle size. Illites are usually well formed with many 120° angled edges, and the particle size range usually varies from 5-10µ; the wispy, fuzzy, cloudlike structures are characteristic of montmorillonite clays, with average particle size about 0.1-3µ [5, p. 234-5]. This suggestion agrees with a fine fraction Stokes' Law sedimentation test in which fine clay particles were still suspended one week after the test was begun. Even though unexpected in this alpine area, the most likely structure is a mixed illite-montmorillonite clay, but this result requires further testing by X-ray diffraction.

Table I. Approximate compositions of the fine matrix phase of the unfired raw materials and the fresh-fractured cross-section of a fired serving plate, collected over the whole area at 400-500x by EDS at 15 KV, 80 nA, for 3 minutes.

Compound	SiO_2	Al_2O_3	K_2O	Na_2O	CaO	MgO	Fe_2O_3	TiO_2	SO_3
Sedo, Talc, Golden Stone	65.01	2.29	0.30	0.20	0.00	29.89	2.08	0.00	0.23
Humic, Illitic Clay	58.38	22.92	5.03	0.40	0.00	2.45	7.62	0.00	1.27
Fired Pot, Body	53.89	16.21	3.58	2.01	7.69	6.71	8.76	0.60	0.55

The talc-clay composite body composition falls within the enstatite ($MgO \cdot SiO_2$ with a composition of 66.6% SiO_2 and 33.4% MgO) phase field in the MgO-Al_2O_3-SiO_2 phase diagram with two eutectics at 1345°and 1360°C and incongruent melting behavior [13]. Enstatite with an orthorhombic crystal structure is one of three polymorphs, each with a different structure that makes transformation kinetics sluggish [14]. Enstatite, once formed, is stable below 1260°C, and with impurities present it forms as low as 1140°C, but we found no enstatite in thin section, and very little glass has formed to sinter the clay and talc. Kingery states that impurities, such as soda, potassia, calcia, iron oxides, and titania both lower and widen the fusion range and that with even 10% clay addition, protoenstatite crystals can be produced in a primarily silica liquid matrix at about 1000°C [13]. The Derge raw materials contain 2.81% fluxes in the talc present as K_2O, Na_2O, Fe_2O_3, and SO_3, and 14.32% in a special deposit of clay that is unusually rich in fluxes for a mountainous, glaciated region. The answer has to be that insufficient time at the 1100°C peak temperature has failed to develop sufficient glassy bond in the ceramic, and that this is intentional. Singer reports three industrial steatite body compositions used in the twentieth century that approximate our composition, but that are fired higher, as follows:
(1) Steatite Body, cone 7, 1210°C: 24wt% ball clay, 58% steatite talc, and 18% potassium feldspar; (2) Italian Steatite Cookware Body, cone 10, 1260°C: 26.3% China clay, 11.2% ball clay, 50.6% talc, 11.9% potassium feldspar, with water absorption measured at 14.5%, and a low volumetric expansion coefficient of $2.05 \times 10^{+6}$; and (3) German Flame Resistant Cookingware, cone 12, 1310°C: ball clay, 22%, talc, 49%, feldspar, 12.8%, alumina hydrate, 16.2%, self glazes if doped with 3.2% ZnO [14]. He also differentiates between steatite talc and yellow stone talc, without explaining the difference.

Can we argue that the Derge ceramics represent a ceramic body engineered and optimized through trial and error and that not only the raw materials selection, functional design, and fabrication process but also the firing technology is optimized? If so, what are the engineering compromises that make the performance of this body optimal for heating and cooking?

(1) Thermal Conduction and Radiation: We know that, for opaque materials, small, flat pores have better thermal conduction than large closed pores that insulate, and that more porosity leads to poor thermal conductivity. We find that the conscious effort of the potters in their working methods leads to pores being compressed, closed, and elongated. We know that micro-cracks, as in the 50 vol% talc, promote thermal radiation [13, 640-646]. We also know that the talc stone selected for the additive incorporates two forms of talc that have different fracture patterns when mined: one is laminar that splits into layers just below 1000°C and begins to fuse again at 1100°C, and another that is cross-bedded and that does not fracture. Without extensive grinding and milling, differential shrinkage around particles and particle laminations occur. We know that particle size and size distribution control total shrinkage, but not the differential shrinkage encountered with anisotropic materials. Blending talc particles of different shapes and sizes reduces differential shrinkage, and we find this practice at the Derge workshop [14].

(2) Thermal Shock: The orthorhombic talc has anisotropic thermal expansion, lower in plane than normal to it, and the ends of plates tend to be pinned or sintered with glass. We propose that this property of the bowing of plates responding to rapidly applied thermal stress may be useful for thermal shock, because the talc platelets are weaker than the glassy bonding phase [13]. The reported linear expansion coefficient for a vitreous steatite body is high, at 6-10 x 10-6 mm/mm/°C with an average of 7.7 at room temperature; the rate of increase is expected to decrease at elevated temperatures. The porosity is also a sink for micro-cracking from thermal stress. Thus, under-firing makes the body more able to withstand thermal shock.

Great effort is expended to grind and mix this talc in a stone-trough mortar with a large counterweighted stone. Apprenticeships last a long time and each operation is taught to exacting standards, from thorough grinding and mixing to extensive plastic deformation of the pottery walls in shear, the working and melding of joints, and the smoothing and burnishing of surfaces. Apprenticeships take a far longer time than is necessary to teach the operations and the rate limiting steps. This consistent level of workmanship and dedicated practice indicate that making this functional pottery is a risky undertaking and that knowledge and experience of all phases of the process are necessary for success. We argue that this ceramic has the characteristics of an engineered ceramic. Future research will look at the extent to which the processes developed in the Derge workshop might have been engineered and optimized for functional performance of the end products, and to what extent they may be more closely tied to social practices and structures surrounding the process of production.

Properties of the Products

The raw materials and firing processes result in objects that are moderately hard (Mohs hardness of 5). The lustrous surfaces are relatively glossy (gloss of 7.9 ± 3.7, n=5). Sherds from fired objects have only a modest number of large and very visible pores (Fig. 18 and Fig. 19). Image analysis shows that the Total Optical Porosity for the vessel sherds in thin section averages only 5%, whereas open porosity of two small plates was measured at 15.29% ± 0.2. In thin section the larger pores are shown to be isolated rather than connected, resulting from shear force applied during forming. At the surfaces of pots, burnishing and smoothing steps have reduced the porosity, and the pores are primarily located on the interiors. A large number of rounded pores are not necessary in this case for helping to absorb and halt the cracking process, since that function is served instead by the large number of coarse talc particles.

Many of the larger closed pores are somewhat elongated and wavy or tapered (Figs. 18-21). This is a typical appearance of pores that form during effective forming of the clay body in which shear force aligns fine particles, pores, and coarse temper. Some of the smaller pores that are less visible in the scanned thin sections formed around talc grains (Fig. 20 and Fig. 21). As the clay dried it sometimes shrank away from large particles, leaving a narrow pore area alongside some of the talc particles.

Some of the talc particles in the thin sections of fired sherds that attained a lower firing temperature show enhanced parting and splitting between layers (Fig. 21), compared with the unfired material and higher fired sherds. The thin voids left between these split layers account for additional fine porosity (Fig. 22). This splitting occurs in particles or areas of the talc that show preferred orientation, rather than in the areas that are randomly orientated. Chlorite mica originating from the *sedo* remains quite visible on the surface of some talc particles (Fig. 23).

Figure 18. A scanned thin section from a fired sherd (C. L. Reedy).

Figure 19. Scanned thin section of a second fired sherd which is thinner and has more elongated and aligned talc particles (2.8 – 4.5 aspect ratio versus the mean of 2.3 for Fig. 18) (C. L. Reedy).

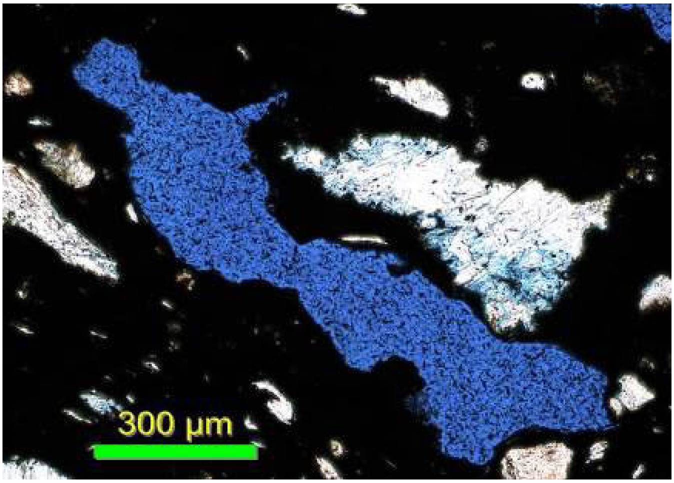

Figure 20. Isolated wavy pores often form as the clay body is formed, raised, and thinned by shaping. Finer pores not visible on the scanned thin sections emerge along the edges of some of the talc grains, as the clay shrinks away from the particles during drying (C. L. Reedy).

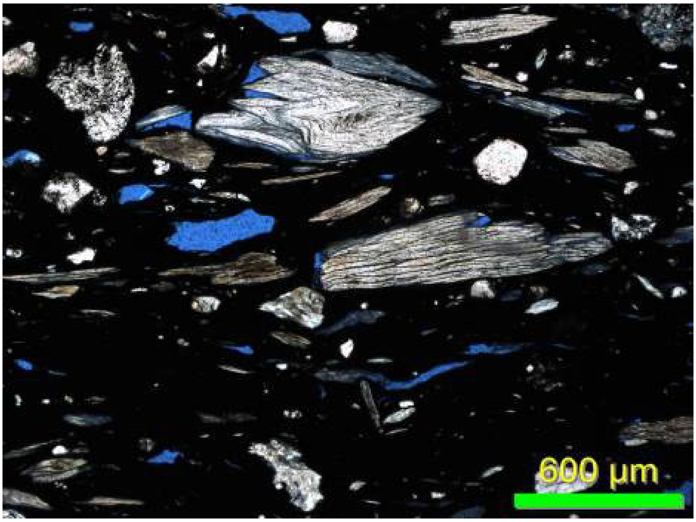

Figure 21. In thin sections of fired sherds, especially those fired below 1000ºC, there is enhanced parting and splitting between layers of some of the talc particles that occurs with loss of water of hydration. These underfired talc particles are friable until fired at a temperature above 1000ºC (C. L. Reedy).

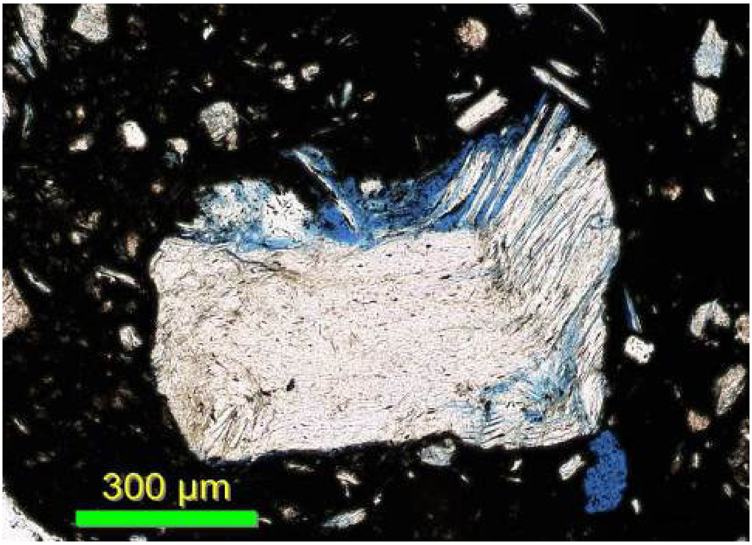

Figure 22. Particles or areas within talc particles showing preferred rather than random orientation may show enhanced parting and splitting between layers; thin voids left between these split layers account for additional fine porosity (C. L. Reedy).

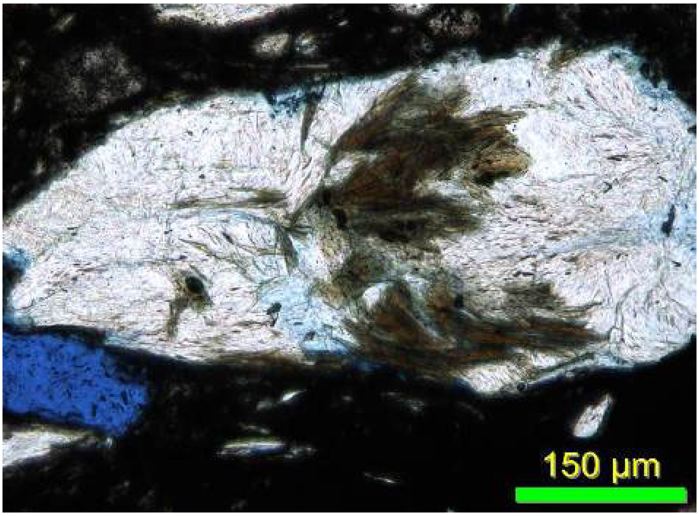

Figure 23. Long tabular grains and fan-shaped aggregates of chlorite on colorless talc surface (sherd thin section, plane polarized light) (C. L. Reedy).

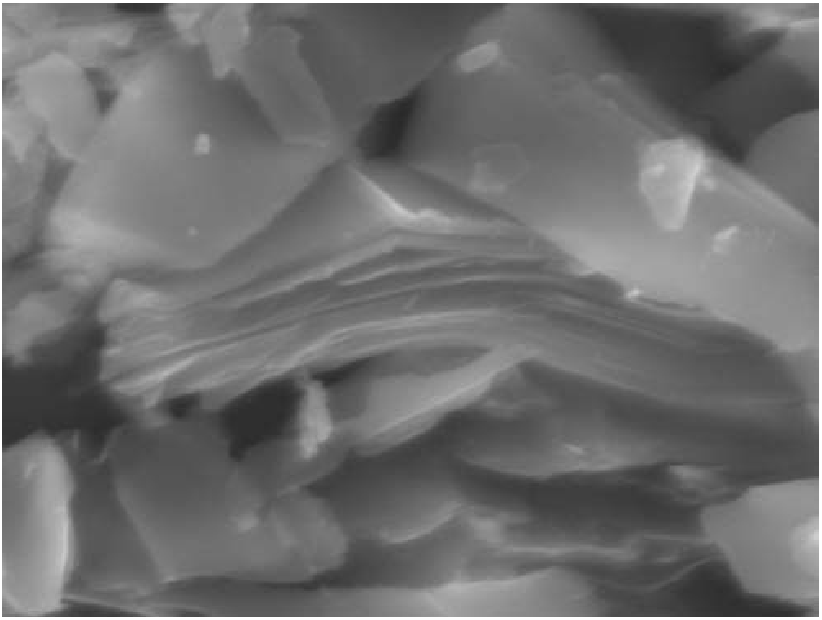

Figure 24. Microscopic, multi-layer talc particle in a 3-point bend configuration that has relieved the strain by propagating a longitudinal crack—illustrating a critical mechanism that avoids catastrophic thermal expansion and thermal shock of Derge pots, especially the stove-pots (15,000x). The bent particle in the center is 0.7µ long and 0.12µ thick. (P. B. Vandiver).

The characteristics and behavior of talc described above adds to the argument that thermal shock resistance and low thermal expansion of the ceramic body is achieved, even though most talc structures have a high thermal expansion. The mechanism of accommodation of thermal strain is shown in Fig. 24 in the delamination and cracking of talc layers that have been pinned together by glass that has formed primarily at edges, rather than surfaces. A scenario of microstructural development during firing reads as follows: Fig. 17 shows that the talc platelets (Fig. 16 left) are sintered with a dark black clay, with plastic properties similar to a ball clay, that contains a wide range of particle sizes as well as humic organic constituents (Fig. 16 right). Particle sizes span the wide range of montmorillonites to kaolinites. The amount of flux is high, about 17%, or more if CaO is present. The glass, which develops by heating the clay, sinters together primarily the edges of talc particles. The firing is stopped at about 1100ºC before a continuous glassy phase has formed. During use the fine talc, as well as pores and microcracks, provide a mechanism for relief of thermal stresses in the body prior to catastrophic failure. Some twentieth century accounts of underfired steatite electrical porcelain report degradation by a "dusting" mechanism, as expected to occur in the Derge ceramics. We assume the same observable mechanism occurs in old cookpots, braziers, and pots that serve as stoves, although we did not think of asking to see any of them during our visit.

Design Issues, Product Variation, and Markets

A wide variety of objects are made (Fig. 25). Some of these are very traditional designs with traditional functions that have been used by local people for hundreds of years including cooking pots, medicine containers, tea pots and cups, containers for storing and serving liquids, and braziers. These objects are sold locally and to Tibetan communities further away. Other products made in the Puma workshop are objects with modern designs and functions, intended to appeal to new markets of a wider national or international scope. Sold under the *Door of Tibetan Arts* designation, these new designs include juicers for apples, whistles, incense burners, small plates and dishes, and large flower pots. This is a similar dichronic transition to that detailed by Dean E. Arnold [15] for the ceramic production of a Maya community in Ticul, Yucatan, México. To design and market these newer product lines, the workshop and the local NGO collaborate with an external design team that includes professionals with formal design training and with knowledge of the wider outside market. This external team also has the expertise to market products in Beijing, on an internet website, and through Weibo. The design team works closely with local people who know the local traditions to ensure that the special Tibetan characteristics of the pottery are retained.

The main goal is to develop an expanded market for the Dzongsar-Maisu area products, to help keep the tradition alive, but at the same time retain the most crucial special characteristics of this Tibetan pottery tradition. Some of the requirements are that all products must be made by hand in Tibetan areas, by Tibetans, using the traditional raw materials; they must be produced in an environmentally sustainable way; and they must include fair trade practices so that those who participate in making them are fairly compensated for their work. This commitment to preserving the special Tibetan characteristics of the pottery tradition, while at the same time finding ways of also allowing for it to change and evolve to ensure that it will continue and even grow with an expanding market, is one significant aspect of this particular pottery tradition. The Tibetan NGO in Derge County provides strong local leadership in heritage preservation that ensures that design and marketing changes can occur without destroying the most important principles behind the cultural heritage that connects the local people to their traditions and environment.

Functionally Interesting Performance Characteristics

The most significant aspect of the Puma pottery technology is the innovative mix of raw materials. These raw materials impact many properties of the resulting products. The carbon in the clay produces the black color of pottery that is valued by many eastern Tibetans. The very large amount of powered talc from the steatite stone (*sedo*), combined with additional fluxes present in the clay and the *sedo*, promotes initial sintering and some vitrification of the clay body at about 1100°C that is reached in the second firing in the pit kiln. An increase in sintering and decrease in porosity lead to an increase in thermal conductivity [16], but considerable fine and elongated porosity is present. The powdered talc, however, is the most significant component in many ways [14, 17]. It improves properties that help in production of the objects, by adding more platy particles that increase plasticity and simplify forming, by opening the body during drying to provide paths for water to evaporate, and by providing large anisotropic particles that reduce shrinkage, and thus possible cracking, of the clay body during drying and primary firing. It also impacts the appearance of objects, by imparting a smooth and lustrous surface texture. The talc also increases the lifespan of pottery by a hysteresis loop of minor amounts of anisotropic expansion and contraction that improves thermal shock resistance for greater durability over long-term use. The large volume fraction of talc particles produces a secondary phase of layered and laminated particles and cross-bedded crystals throughout the material that absorb energy if any micro-cracks form, thus improving the mechanical performance of the pottery [16].

The presence of a large proportion of talc particles and thin sheared pores also improves the performance of the pottery in other ways. It adds both thermal insulating and radiating properties, respectively, that help with retention of heat during cooking, simmering, and serving, and giving better heat distribution to prevent burning of food [17]. Vessels made from this extremely talc-rich material heat contents very quickly using a very small amount of fuel, while resisting cracking and thermal shock. In contrast, more common earthenware bodies require slower heating of their contents, or the vessel may crack. These properties are enhanced by engineering of the pot shape described below (Fig. 26).

Figure 25. The Puma ceramics are made in a variety of both traditional and modern designs and functions (C. L. Reedy).

Traditional braziers made with this talc-rich material are a very efficient way to provide a stove and perform the multiple and continuous cooking tasks that are typical in many Tibetan homes. Cooking experiments show that small pieces of wood in the cavity of the brazier will quickly heat a cooking vessel placed above it, efficiently cooking stews or other food (Fig. 26, left) and immediately providing heat to the room and its inhabitants. When the food is fully cooked, the upper vessel can be removed and another, such as a water-filled teapot, set in its place (Fig. 26, right). The cold water filling the teapot, when placed on an already hot brazier, could cause cracking in a typical earthenware vessel, but not in this talc-clay composite one. Instead, in this talc-rich material, the teapot will not crack, and the water in it will quickly become hot. The cooked food in the vessel it replaced will retain its heat for a long period of time, even after being removed from the hot coals. The lower brazier, now filled with the coals, radiates heat very effectively and helps keep a small room warm for hours. The ring base raises the bottom of the brazier off the floor; the base stays cool, and only the bowl heats up, thus protecting the Derge wooden houses from risk of fire.

Figure 26. A talc-rich Puma brazier requires only a few small twigs to heat and is ideal for quickly cooking food (left) and heating water for tea (right); the material is very crack resistant even when cold water is set above an already-hot brazier (C. L. Reedy).

CONCLUSIONS

The thermal properties described above make talc an important addition to modern industrial ceramics; however, it is rare in traditional hand-made pottery. While talc is sometimes found in traditional contexts [18-21], it is a rare ingredient in non-industrialized ceramics. This particular combination of black carbon-rich calcareous clay mixed in equal proportions with a crushed iron-rich talc-chlorite stone additive, used for objects built completely by hand and wood-fired in a pit kiln, is unique. The Derge pottery technology produces high-quality ceramics that are very effective for heating and cooking, for retaining heat during cold winters at high altitude, and for resisting cracks and thermal shock. These qualities are particularly useful in the Tibetan households of the high mountains of the Dzongsar-Maisu region of Derge.

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Figure 27. We especially thank the Puma pottery workshop potters, pictured here, for their hospitality, and for permitting us to observe, photograph, and participate in their work.

Figure Credits

The map in Fig. 2 was produced using data provided by C. L. Reedy and was finalized and polished from rough draft status by Elsevier Webshop Illustration Services (http://webshop.elsevier.com/illustration-services/). All photographs are by the authors: Y. Xu (Figs. 1, 3, 4 left, 6, 7 left, and 12 right; C. L. Reedy, Figs. 4 right, 5, 7 right, 8-11, 12 left, 13, and 18-23, 25, and 26; P. B. Vandiver, Figs. 14-17, and 24; and Ting He, Fig. 27.

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