

GLAZE BOWLS

*a*: Glaze I Red. *b*: Glaze I Yellow. *c*: Glaze II. *d*: Glaze III. *e*: Glaze IV. *f*: Glaze V.  
*g*: Glaze VI. (*ca* 1/4 except *f*, which is *ca* 1/6.) Paintings by T. Amsden.

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NUMBER SEVEN

THE POTTERY OF PECOS

GLAZE-PAINT, CULINARY, and OTHER WARES

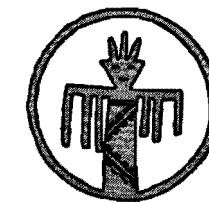
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## THE POTTERY OF PECOS

Volume II

I  
THE GLAZE-PAINT, CULINARY, AND OTHER WARES  
BY  
ALFRED VINCENT KIDDER

II  
THE TECHNOLOGY OF PECOS POTTERY  
BY  
ANNA O. SHEPARD



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tauthla Polychrome and the apparently transitional Little Colorado-Rio Grande material which Mera calls Los Padillas Polychrome.<sup>1</sup> She states, for example, that the sherd whose glaze was analyzed spectrographically by Dr. Zies (p. 364) belongs to a group of doubtful affinity, its paste bearing superficial resemblance to Little Colorado types, but containing shreds of mica schist which are seemingly not characteristic of those types. The problems regarding the origin of the Rio Grande Glazes raised by these classes of pottery are considered in the concluding section of the present book. It is planned that fuller description of the specimens in question will be published as an appendix to the final volume of the Pecos series.

<sup>1</sup> 1935, p. 31.

## PART TWO

### THE TECHNOLOGY OF PECOS POTTERY

By ANNA O. SHEPARD

#### PURPOSE OF THE TECHNOLOGICAL STUDY

The immediate purposes of a ceramic technological investigation are to identify materials and locate their sources, to study the indications of workmanship, and to describe properties by reference to exact, impersonal standards. There are two ultimate aims in the interpretation of technological data. The first is to trace the history of the potter's craft; the second is to recover more accurately and in greater detail than is possible by other methods the evidence which pottery preserves of cultural development, contacts, and influences. In one case, technology opens an almost untouched field; in the other, it offers a new approach to an old problem. The study is necessarily intensive and detailed, but its chief advantage lies in the fact that it is based upon principles and procedures of the exact sciences.

Pottery is of fundamental importance in archaeological research, and the time and energy which have in the past been devoted to ceramic studies have undoubtedly been commensurate with their importance. All features, however, have not been studied with equal thoroughness; attention has been centered upon those characteristics which are most readily recognized and described and whose definition requires no special methods of analysis. Consequently, shape, decoration, and the general appearance of pottery have been carefully recorded, and great strides have been made in defining the geographic and chronologic occurrence of styles. But there has been little progress in the study of composition and the technique of manufacture. This is not surprising, for clay is exceedingly complex and variable both in chemical composition and physical properties, and its qualities are completely changed by firing; furthermore, few identifications can be made by megascopic examination alone.

A comprehensive study generally covers four features of pottery: paste, surface finish, shape, and decoration. This division arises from a consideration of characteristics apart from the processes and methods by which they were produced. When pottery is studied as a craft, a somewhat different approach is necessary; two principal aspects, the technological and the stylistic, become apparent. The technological aspect is concerned with the potter's knowledge of materials and the skill with which she uses them; it involves analysis of clays, tempers, and pigments, study of their sources, combinations, and proportions, observation of the marks of workmanship left in the moulding, shaping, and finishing processes, and study of the indications of firing methods. The stylistic approach is concerned primarily with general appearance and particularly with aesthetic standards and development

as exemplified in shape, finish, color combinations, and decorative design. It is this branch of ceramics which has been emphasized and which, with the usual methods of investigation, has been most fruitful of results. The origin and development of decorative design present a fascinating chapter in culture history. Stylistic features have also furnished the fundamental criteria for classification whenever pottery has been used for culture correlation. The study of technical properties, particularly the composition of the paste, has been less profitable, partly because interpretation of the evidence has been uncertain. This phase of the study demands laboratory facilities and expensive apparatus, in addition to special training and experience not otherwise required by the archaeologist. The value of results should, therefore, be carefully weighed. In what way is our knowledge of pottery and its archaeological significance increased, and what if any new evidence is presented, by such a study?

Potsherds are of great archaeological significance because they reflect subtle changes in skill and taste while remaining comparatively uniform for a given time and place. There are wide variations in the characteristics of pottery made by the people of an extensive territory, and because of this fact it is possible to identify, in a given ceramic group, specimens which were obtained by trade. Fragments of broken vessels, once they are discarded on the refuse heap, remain in stratigraphic position an abundant and imperishable record. This evidence has been studied largely without reference to technological data. The extent and volume of trade have been recognized whenever the exterior features of pottery were distinct. But megascopic methods have failed to show how much exchange there was among people having the same culture traditions. Thus, for example, in the study of Pueblo history it has been possible to gauge the amount of pottery a Rio Grande village obtained from the Little Colorado region, but there was no way of estimating the quantity that came from neighboring settlements within a radius of perhaps fifty miles, since the wares of this area are practically identical in outward appearance. Culture unity must have been preserved by constant contact, but the very fact of standardization renders stylistic studies and megascopic observations valueless as a means of determining the extent of exchange by which this unity was perpetuated, nor do such studies reveal whether one Pueblo produced as much pottery as another, each being virtually independent, or whether certain villages specialized in particular wares. It is in the solution of these problems that the technological data is particularly applicable, for with every difference in geologic formations there are changes in clays, tempers, and even ores used for pigments. Specific identification of such variations of materials and the location of sources will, therefore, prove origin. The possibility of importation of material, as well as of pottery, must always be considered, but the sum of evidence seldom leaves doubt as to the interpretation of technological data. The value of these data is dependent therefore upon accuracy of identification and systematic geologic field work. If such an investigation is thorough and is consistently carried out, it will contribute new evidence to the solution of broader problems as well as increase the certainty of all classification and correlation.

The history of the potter's craft in itself is worthy of thorough study, and obviously the technological aspect must be included if such a study is to be com-

plete and comprehensive. Clay, as few other materials, has tested human skill and knowledge and has offered almost limitless possibilities of refinement in method and new discovery. When primitive woman first found that she could shape wet clay as her need or fancy dictated, and that it became hard and serviceable when subjected to heat, she originated a craft which through the ages has grown into one of the important industries of modern civilization, an industry which for its full development is still enlisting the best efforts of specialists in many branches of science. The archaeologist has studied the beginnings of this industry mainly as an art. But because the use of clay demanded craftsmanship and intelligence or stimulated experimentation, pottery preserves the record of an important phase of man's development. It is the specific field of the ceramic technologists to decipher this record.

The technological approach, though essential for the adequate description and satisfactory understanding of pottery, is not advocated primarily for the purpose of classification; nor are technological features, particularly composition, considered logically satisfactory criteria upon which to base major subdivisions in a system of classification. The systematist endeavors to recognize fundamental similarities and relationships and to group his material accordingly for the sake of convenience and common understanding. If he fails and imposes an artificial system, confusion and profitless effort follow. The archaeologist faces in the classification of pottery a very different problem from that recognized by the biologist, who deals with evidence of descent and organic relationship. The composition, shape, finish, and decoration of a vessel are influenced by available materials, skill and purpose of the potter, her independence or originality, and the customs and traditions of the society of which she is a member; none of these factors resemble organic descent either in the control which they exert or the limits which they define. In view of the purpose of ceramic studies in archaeological research, it seems logical to base major classes upon characteristics which most directly reflect the styles dictated by tradition and which can at the same time be recognized by the field archaeologist and are least subject to errors of personal judgment. Laboratory analysis is essential for specific classification and final description, and there is no reason why the archaeologist should attempt to judge properties which actually require microscopic, chemical or other special laboratory technique for accurate measurement. The major subdivisions should, therefore, be based on the principal surface characteristics, finish, decoration, and form, while paste should be considered primarily for the minor subdivisions which define groups by specific geographic location.

The principal objection that has been raised to such a system of classification is the fact that the archaeologist frequently deals almost entirely with sherds and is, therefore, unable to study form or design, whereas no matter how small the fragment, paste is always represented. This argument is somewhat misleading. As long as non-laboratory identifications of paste are unreliable and not sufficiently specific or definite to be significant, such classification is out of the question. The study of design and form is hampered when only fragmentary material is available; nevertheless, much evidence regarding both features can, by conscientious study, be recovered. Curvature, shape of rim, motives of design, framing lines, and brush

technique have all repeatedly and effectively been used in archaeological studies. Even more important is the fact that finish, color and manipulative technique are unmistakably evidenced on the sherd. Classification has actually been based upon these characteristics in the past because they have proved by experience the most practicable, logical and intelligible. A consideration of the fact that the same paste may be used for a cooking-pot and for a slipped and painted food bowl is sufficient and final proof that a basic ceramic category cannot be defined primarily by paste.

The importance of the technological study is in no way minimized by its inadequacy for serving as a primary basis for a system of classification. Its particular contribution, the possibility which it offers of exact quantitative description, is none the less essential because it represents the final and most detailed phase of ceramic study. The collector or connoisseur frequently asserts that properties can be recognized intuitively though they cannot be described so unmistakably that one unfamiliar with the specimen in question can visualize or understand it. Since pottery is particularly difficult to describe, the same attitude is sometimes expressed by the archaeologist. But it has been demonstrated repeatedly in the history of the sciences that the naming of categories before their characteristics or relationships have been fully investigated has invariably caused error and confusion. The need for specific designation is never so urgent that neglect of adequate description is justified, and it becomes the problem of the technologist to facilitate classification by developing adequate standards of description.

The technological investigation is essentially both humanistic and experimental in its approach. There are many questions which arise in the study of pottery which are apt to be countered by speculation but which can actually be conclusively answered by direct test, and the habit of experimentation prevents needless elaboration of unsound theories and much futile argument. But it is not sufficient simply to analyze; it should also be possible to duplicate characteristics of wares, and a great deal can be learned from the synthetic test. When constant study of every stage in the process of pottery making is necessary, the part which the potter plays can never be overlooked.

The present attempt to formulate and test a procedure for the technological analysis of pottery has been made possible through the inspiration and aid contributed both by students of the exact sciences and by archaeologists.

Many phases of the study and their specific applications were discussed years ago with Wesley Bradfield, who realized the need for such an investigation and gave much thought and study to the subject. Although he did not live to see the materialization of his plan, the present endeavor originated under his influence. Resort to methods of the exact sciences was a natural expression of his uncompromising insistence upon thoroughness and accuracy; with clear vision he regarded the technological study as a most effective instrument for the reconstruction of a phase of culture history.

The opportunity to put theory into practice came as a result of Dr. Kidder's appreciation of scientific method. He has given his entire support that possibilities might be fully tested. At all times he has been patient with long, slow, experimental

processes, and his interest and constructive criticism have been a guide and stimulus in every phase of the work.

Mr. Jesse L. Nusbaum, Director of the Laboratory of Anthropology, has given the project his support.

Since the work has been primarily a problem of adapting principles and procedures of the exact sciences to the study of pottery, it is to specialists in these related fields that acknowledgment is especially due.

My father, Mr. H. Warren Shepard, a research chemist, has given technical advice and assistance, without which the work would hardly have been possible. He has devised methods of analysis, designed apparatus, conducted experiments on organic pigments, and made many of the physical and microchemical tests. His presence in the laboratory has been a constant reminder of the standards and ideals of the scientist.

It has been particularly important in the initial stages of the investigation to compare and test the applicability of as many of the procedures of petrography and chemistry as possible. Dr. Frederick E. Wright, recognizing this fact, suggested study at the Geophysical Laboratory of the Carnegie Institution of Washington. This unparalleled opportunity was made possible, through the interest of President Merriam, Dr. Wright, and Dr. Kidder, by the coöperation of the Carnegie Institution with the Laboratory of Anthropology.

Not only was there afforded, during four months of study, constant opportunity to observe the techniques and apparatus for which the Geophysical Laboratory is outstanding, but Dr. Wright and many of his colleagues also contributed to the solution of specific problems. Dr. Wright directed the study of techniques of measuring optical constants of fine-grained material and experiments to develop a mineral temperature scale applicable in the study of pottery; Dr. E. G. Zies demonstrated the value of spectrographic and other methods for the analysis of small samples; Dr. H. E. Merwin illustrated the use of refractive indices in measuring the lead content of glazes, and Dr. J. W. Greig advised regarding pyrometric practice and checked equipment. Direct aid in a particular undertaking is more easily acknowledged than are the guidance and inspiration which come from association with individuals actuated by scientific ideals. It is for the illustrations of habits and principles of research that appreciation is most deeply felt.

#### METHODS OF TECHNOLOGICAL ANALYSIS

There is no simple procedure for the technological analysis of prehistoric pottery, nor should the chemist or ceramist alone be expected to determine all that can be learned about it. The primitive potter's methods and the consequent properties of her wares are, in fact, so totally foreign to the experience of the commercial ceramist that he often does not visualize conditions nor appreciate the questions they raise. But petrography, chemistry and ceramics each contribute valuable methods, the neglect of any one of which leaves the investigation incomplete, while

the archaeologist brings to the study the essential knowledge of occurrences and the recognition of problems. Various procedures of the exact sciences must, therefore, be coöordinated and adapted to the specific purpose of the archaeologist. It is evident that a complete and final outline for technological analysis cannot be given now nor at any future time, for as progress is made in correlated sciences the ceramic technologist must be ready to adapt and expand his methods accordingly. Then, too, new and different archaeological problems will continue to arise.

The present discussion is not given with any idea of laying down procedures which must invariably be followed or of treating fully the entire scope of the subject, but rather in the hope that it may be suggestive of the varied aspects and possibilities of the work, and that it may bring out the importance of thoroughness and exactitude. Certain of the tests outlined are fundamental and essential; they will apply in the study of any group of primitive pottery whatever its provenience, while other methods and problems considered are related specifically to the Southwestern field. The results of the Pecos study will serve to illustrate the significance of the technological data, but it must be remembered that the interest and value of the data are directly related to the state of ceramic advancement represented; the more highly specialized the technique and the greater the number of materials used the more there is for the ceramic technologist to learn.

#### STUDY OF BODY AND SLIP CLAYS

Clay is exceedingly difficult to analyze and describe because it is very fine-grained, its composition and properties are complex and highly variable and when heated its characteristics are completely changed. The study of clay in pottery is further complicated by unknown firing conditions. How is one to know, for example, when comparing two fragments of pottery whether differences in color and hardness result from the use of distinct kinds of clay or from different firing treatment? Even the texture and the finer mineral inclusions of pottery paste are not necessarily those of the clay, for the potter frequently added non-plastic material to counteract shrinkage and it may be impossible to distinguish the finer part of this artificially included mineral matter from that which occurred naturally in the clay. One cannot always be certain, consequently, whether the clay of a paste was originally sandy or relatively fine-textured. It is not surprising therefore that the archaeologist should consider clay a single, even though variable, substance and treat it in the most general terms.

It is nevertheless important for the ceramic technologist to understand the properties of clay and to be able to distinguish the various types. In the first place there is the specific problem of description and classification; clay, the basic ceramic material, can hardly be ignored by the systematist, yet of the statements regarding pottery clay which have appeared in archaeological literature few indeed are definitive. In the second place we should be able to distinguish the characteristics of pottery which reveal method from those which are the result of the quality of the material used and for this purpose a knowledge of clay is indispensable. In the third place the accurate identification of clay and the location of its source may give

valuable evidence of the provenience of pottery. It is, of course, much simpler to identify and locate the source of the mineral inclusions in the paste. But if tempering material comes from a formation distant from the site where the pottery was found, the question arises whether the material or the vessels were imported. If it can be proven that both clay and temper came from the same immediate locality, the probability that the vessels, rather than the raw materials, were imported is greatly strengthened. Finally there are many questions of general interest and significance which can be answered only when the properties of clay are understood. To what extent has the quality of available clays influenced the progress of the potter's craft? What does the number of distinct kinds of clay used reveal as to the versatility of potters of different periods? How much judgment is shown in the kind of clay selected for particular wares? We have hardly stopped to consider these questions principally because we know so little about clay.

A brief review of familiar facts relating to the origin and properties of clays may serve to illustrate the possibilities of differentiating distinct kinds of clay and of explaining common characteristics of the paste.<sup>1</sup>

Clay is usually recognized as a very fine, compact, earthy material which in its purer state has a soapy feel and when moist a characteristic odor. It has played an important role in man's cultural development, principally because the plasticity it acquires when wet makes it an ideal material for modeling, and the changes produced by heat give it strength, hardness and some degree of impenetrability. The great variability in color, composition and texture of clay is explained by the many modes of its formation. All clays are originally derived from the decomposition of igneous rock. Weathering is a universal cause of rock decomposition and formation of clay in the outer zone of the earth's crust. At far greater depths rocks are altered through the action of hot vapors and gases given off by molten rock magma. The kaolin deposits of Cornwall are examples of this kind of clay formation. Deposits of this type are often extensive because the products of alteration are not removed by erosion as they frequently are when rocks at the earth's surface are disintegrated and decomposed. In the outer layer of the earth's crust subject to weathering, mechanical, chemical, and even biological forces are active agencies in rock alteration. Daily and seasonal changes in temperature cause rocks to expand and contract, with resultant fracturing and gradual disintegration. The minerals thus exposed to the chemical action of air and water are slowly attacked, bases are removed in solution and new and more stable compounds are formed by the addition of oxygen, carbon dioxide and water.

Acid igneous rocks high in feldspar, such as granite and pegmatite, contribute chiefly to the formation of clay, but it is also formed from the decomposition of basic igneous rocks. The alteration of granite illustrates the changes which occur

<sup>1</sup>For fuller discussion and reference the following works are suggested:

General: Ries, 1927; Searle, 1929-1930; Wilson, 1927.

Formation of clay: Leith and Mead, 1915.

Effect of heat on clay: Bleininger, 1911.

Origin and properties of the clay minerals: Ross and Kerr, 1931, 1931a; Ross and Shannon, 1926.

when rock is weathered. The feldspars, which constitute on an average 52% of the minerals of granite, become hydrated and lose their alkali as carbonate or bicarbonate, together with some silica. The hydrated aluminum silicate which remains is a relatively stable compound and forms the basic material of clays. Iron from the decomposition of biotite, hornblende, and other ferromagnesian minerals, forms hematite or limonite which colors the clay. The calcium and magnesium liberated from various minerals unite with carbon dioxide and are deposited as limestone and dolomite. Soda is carried off in solution eventually reaching the sea. Quartz is the most stable mineral and largely remains as grit or sand, the relatively small amount which is leached out by solution being redeposited as chert. The end products of alteration are therefore clay, quartz sand, iron oxides, calcite, dolomite and the salt of sea water. Clay is the proponderant product.

Two general types of surface clay are recognized, residual and transported or sedimentary. Residual clays occur *in situ*, where alteration took place, while the sedimentary clays have been transported and redeposited by water, wind, or glaciers. In beds of residual clay, a gradual transition from clay down through disintegrating rock to original unaltered rock may be recognized, while transported clays bear no relation to the underlying rock and, unlike the residual clays, are stratified. Water is the chief agency in the transportation of clays which are reworked and sorted by its action, the fineness of sedimentary clays depending upon the velocity of the current. Residual clays usually contain grit and fragments of unaltered rock.

Sedimentary clays are classified according to the conditions under which they were formed as marine, estuarine, lake, river terrace, glacial, and aeolian. Marine clays, which are deposited some distance from the shore, usually form extensive beds, but as material from more than one drainage contributed to their formation, their composition varies in different parts of the deposit. Lake clays are found in relatively shallow, basin shaped beds. Terrace clays formed along river benches in the flood season are frequently sandy. Glacial clays, not having been subject to the sorting action of water, are often gritty and full of stone. Aeolian clays are characteristic of extreme arid conditions.

Changes may be produced in clays after their formation. They may be consolidated by mechanical forces, such as tilting, folding, and faulting, and so altered to shale. Shales which have been formed principally by pressure can be ground and plasticity again developed, but if subjected to heat as well as mechanical force, they are converted to slate and are no longer of value to the potter. Clays may also be affected by chemical forces. Contact with air oxidizes the iron in clay, changing its color from gray to yellow or brown. This effect is particularly noticeable in the outer layers of a deposit. Iron may be carried in by percolating water, and substances may be removed in solution, as, for example, lime by water charged with carbon dioxide and iron by water carrying carbon dioxide and organic acids.

The basic substance of clay is hydrated aluminum silicate, but the ratio of alumina to silica, as well as the number of molecules of water of crystallization, is variable, and consequently there are a number of distinct clay minerals. These clay minerals are very difficult to identify because their crystals are exceedingly minute and rarely found in a pure state. Some idea of the confusion which has existed in

the classification of clay can be gained from the fact that in 1914 sixty-one names had been applied to hydrous aluminum silicates and many of these varieties were not properly established. Recent studies by Ross and Kerr of chemical composition, optical properties, x-ray defraction patterns and dehydration curves have greatly clarified the properties and relationships of the clay minerals and reduced the number of established varieties.<sup>1</sup> These writers classify the clay minerals in four groups, two of which—the kaolinite and the beidellite-montmorillonite—they have described. Kaolinite, which forms minute vermicular or thin platy crystals, is the principal clay mineral in residual white-burning clays and is also found in sedimentary beds where it has been redeposited from the erosion of primary deposits. It is commonly formed by the profound weathering of feldspathic rock. Since residual white-burning clays are of mixed or variable composition they are properly called kaolins and the term kaolinite restricted to the mineral whose properties and composition have been specifically defined. The word *kaolin* is derived from the Chinese *kao lin*, meaning *high hill*, the name of a locality where clay was obtained for the manufacture of porcelain. The beidellite-montmorillonite clay minerals occur in many soils and marine shales. Montmorillonite is the characteristic mineral of bentonite, a clayey material formed from the decomposition of volcanic glass. Bentonite is highly adsorbent and is used commercially as a decolorizer. Deposits of this material are common in some parts of the Southwest, and when used as body clay or slip by primitive potters, its distinct optical properties distinguish it from a kaolinite-bearing clay.

Many mineral impurities occur in clay, only the commonest of which need be mentioned. Quartz is the most ubiquitous and varies in amount within wide limits. In residual clays it is a remnant from the disintegration of the parent rock; and in sedimentary clays it has frequently been introduced from various sources by the transporting agency. Quartz reduces the plasticity, shrinkage and strength of clay. The micas, muscovite, sericite and less frequently biotite, are present in many clays. Very finely ground mica has been used to substantiate the theory that platy structure is an important cause of plasticity but coarse mica reduces plasticity and its fusion point is above the temperature range of primitive firing. Iron compounds are largely responsible for the red color of burned clay. Hydrated iron oxide (limonite) occurs in yellow clay, ferric oxide (hematite) in red clays and ferrosoferric compounds in certain bluish clays. Pyrite (iron sulphide) and siderite (iron carbonate) are also present in some clays. Ferric oxide acts as a gradual flux while ferrous oxide acts as a violent flux combining with silica to form ferrous silicate, the slag of the open hearth furnace.

Other minerals occur in clays in small quantities and may affect their firing behavior. In attempting to explain the properties of a fired clay, therefore, one must remember that a number of materials and a variety of factors have influenced the result.

The effect of heat on clay is clearly summarized in the following statements by Hewett Wilson:<sup>2</sup> "From the chemical standpoint, dry clay consists of a large variety

<sup>1</sup>1931, pp. 55-65

<sup>2</sup>1927, p. 142

of silicates in various conditions and stages of combination. When clay is heated, some of the compounds are broken down, water vapor and other gases are evolved, while oxygen is taken into combination. Finally, when portions of the mass attain the fused condition, a new variety of complex alkali, calcium, magnesium, iron, and aluminum silicates are formed."

Three periods of firing are recognized, dehydration, oxidation, and vitrification. When clays are heated the mechanically combined water, that which remains after air drying but is not a constituent part of the clay substance, is first driven off. During this stage of dehydration, generally called water smoking in commercial ceramic practice, a low temperature should be maintained, otherwise steam may form more rapidly than it can escape through the pores of the vessel and the walls will be shattered by pressure. The primitive potter, who uses a direct fire and attains maximum temperature in a very short time, often avoids the risks of too rapid dehydration by first heating her pots around a bonfire. Mechanical dehydration takes place at temperatures between  $20^{\circ}$  and  $150^{\circ}$  C. and from  $150^{\circ}$  to  $600^{\circ}$  C. the chemically combined water of the clay substance is removed. The rate of dehydration is influenced by the texture of the clay, being slower for a dense compact clay than for a sandy open-textured one. The temperature at which the plasticity of the clay is lost varies from  $400^{\circ}$  to  $800^{\circ}$  C. depending upon the type of clay.

The oxidation period extends from a temperature of  $350^{\circ}$  to  $950^{\circ}$  C. It therefore overlaps the dehydration period, but while dehydration requires heat alone, oxygen as well as heat is necessary for oxidation. During the oxidation period any organic matter present in the clay is broken down and the carbon thus liberated unites with oxygen passing off as carbon dioxide gas. The effect of oxidation is seen in color changes; light and dark gray clays become whitish, buff or red, as carbonaceous material is burned out and iron is brought to its highest state of oxidation. The color of fired clay is, therefore, affected by firing atmosphere as well as by temperature and chemical composition. The same clay, for instance, may fire either buff or gray at a given temperature depending upon whether there is free circulation of air, and examples of red paste found among sherds which are ordinarily gray do not necessarily indicate a higher firing temperature.<sup>1</sup> The rapidity with which carbon

<sup>1</sup>A comparison of the original color of a paste with that produced after it is fired in an oxidizing atmosphere shows whether or not the clay was fully oxidized by the original firing for the temperature maintained in refiring, but sweeping conclusions regarding the original firing atmosphere are not justified by this test, unless the character of the raw clay and the time and temperature of the original firing are known. The condition of iron in clays differs and the amount of carbonaceous material they contain is variable, moreover, even with the same atmosphere, results obtained with short firing at low temperatures cannot be expected to be comparable with those obtained with longer firing at higher temperatures. With primitive methods the character of the firing atmosphere—the volume and proportion of the reducing gases, carbon monoxide and hydrocarbons—will necessarily vary during different stages of firing and from one firing to the next; it may be reducing in effect at the start and oxidizing at the close or more strongly oxidizing at one time than another. A difference in color between core and surface zones of a paste shows that a given atmosphere and temperature were not maintained long enough to complete the change but here also caution should be observed in the interpretation of observations; for example, a gray core with red margins would ordinarily be considered the result of partial oxidation of a gray paste but tests have shown that certain red clays fired in an oxidizing atmosphere develop a gray core at low temperatures and with short firing. The oxidation of carbonaceous

is removed during firing depends upon its condition and upon the density of the clay. Vegetable matter, common in surface clays, is generally readily oxidized. Bituminous matter, more frequently found in shales, evolves volatile hydrocarbons, increasing the difficulty of firing; if the temperature is too high the pressure of gas may shatter the vessel wall or the gas may flash into flame, raising the temperature too rapidly. If the clay is dense and oxygen does not penetrate fast enough to supply the carbon, it will remain unburned and form a black core; such unoxidized central streaks are common in many types of Pueblo pottery because they were given a short firing at relatively low temperatures and with insufficient draft. A high percentage of carbon may indirectly cause the paste to fuse and bloat. Ferrous oxide, a violent flux, is not oxidized until all carbon is removed, and if the temperature becomes high enough to vitrify the paste, carbon will be trapped and carbon dioxide or monoxide, which continues to form but cannot escape, will cause bloating. This combination of conditions may explain vitrification and bloating of some types of Pueblo pottery.

After volatile matter is removed during the dehydration and oxidation periods and before vitrification takes place, the fired clay body attains maximum porosity. Vitrification, the melting and reacting of certain components of the clay, increases the strength and reduces the porosity of pottery. Vitrification commences before the appearance of the pottery gives any evidence of the change. In the incipient stage just sufficient sintering takes place to cement the clay particles. The ware will still have an earthen fracture and a porosity of 15% or more. As the temperature is raised, more of the material of the body is drawn into the melt, pores are filled and porosity is reduced to 1%. With still higher temperatures, complete fusion and melting occur and the body no longer stands its own weight. Vitrification is affected by a number of factors, most important of which are the silica-alumina ratio, fluxing impurities, the texture and grain size of the body, homogeneity of the mass, and the conditions of firing. Very high temperatures are required to melt pure aluminum silicate, but various impurities, such as alkalies, ferrous iron and lime, reduce the fusion point. The vitrification of primitive pottery is, therefore, explained by these fluxing impurities rather than by excessively high temperatures.

With these general facts in mind we may ask how much the ceramic technologist can learn of the origin and properties of clay in pottery and what tests can be applied to distinguish clays and identify their sources. At the outset the importance of preserving all samples of potters' clay found in the course of excavation cannot be overemphasized. A survey should also be made of the clay resources in the immediate area of the site being worked. By studying the thermal behavior of these

material in clay has been used in the present study as a simple means of comparing the relative oxidizing effect of a firing. A short cylinder moulded from a standard mixture of clay and lampblack is fired with the pottery. When the cylinder is cut in half the width of the zone from which the lampblack has been burned out furnishes a basis for comparing total atmospheric effect of the firing. This test has proved useful not only in comparing modern Pueblo firings but also in experimental work with different methods of firing. We have little reason to doubt that there were consistent and significant changes in character of firing atmosphere during Pueblo history and some intelligent control exercised to produce the various specialized wares. These remarks are intended only to emphasize the factors which must be considered before we can prove what changes did take place.

raw clays and their properties when fired, comparisons can be made with the clay of vessels and original sources thus often located. Such a study offers the most practical means of ascertaining the geological classification and position of the clays used in pottery as well as their original properties.

In the study of either raw or fired clays, many different methods may be employed, including petrographic and chemical analysis, the determination of physical properties, thermal behavior, x-ray defraction patterns and ultramicroscopic examination. No single method can be expected to give all of the information desired, and the problem becomes that of combining methods so that distinct clays can be recognized and defined by a number of characteristics, in spite of the difficulties arising from impurity of material and highly variable and uncertain firing. The study of optical and physical properties together with thermal behavior has been most useful in the present investigation. Chemical analysis may be justified in specific cases. The other methods have not been applied in archaeological studies, and the data obtained may not warrant the expense involved.

The optical properties of clay (color in transmitted and reflected light, refractive indices and birefringence) are studied with the petrographic microscope.<sup>1</sup> Clay particles are so minute that measurements of optic sign and extinction angle can seldom be made, and in fired clays, particularly, aggregates rather than individual particles must be studied.<sup>2</sup> The color of the paste is affected by firing temperature and atmosphere, and as these may differ considerably even within a type, the observation is of limited value unless specimens are refired to bring them to a comparable state of oxidation and give them the same heat treatment. Refractive indices and birefringence have been found the most significant of the optical properties. In determining refractive indices, it is necessary to let the powder stand in the liquid long enough for the part measured to become saturated; otherwise the refractive index of clay and air is recorded and the value will be low. Experimentation is the best guide in deciding how long the particles should be immersed, for the time required as well as the difference in values will depend to a considerable extent upon the character of the clay. Data on optic properties of the principal clay minerals are given by Ross and Kerr.<sup>3</sup> These determinations are for the pure clay minerals, all samples having been carefully selected and tested. The same purity of material cannot be expected in pottery; moreover, optic properties are changed upon firing. Birefringence will be destroyed if the firing temperature has been high enough to break down the crystalline structure of the clay or to dissociate the aluminum silicate, but for many pottery types this temperature was not reached. The strength of birefringence is one of the most reliable means of differentiating montmorillonite from kaolinite. The refractive indices of these two clay minerals

<sup>1</sup> Training in the principles of petrographic technique is required for this phase of the investigation. The purpose of this discussion is merely to point out certain applications of petrography to the archaeologists' problem.

<sup>2</sup> Occasionally platy particles of clay are rearranged when a slip is polished and aggregates of similarly oriented particles are forced into a position parallel with the surface. When this condition is found an approximate determination of extinction angle can be made.

<sup>3</sup> 1931, 1931a.

are also widely separated, those of montmorillonite being lower. But upon firing, the values undergo repeated change depending upon the temperature attained. Preliminary experiments have shown that in general the indices of the kaolins and red-burning alluvial clays increase consistently, the change being relatively slight in the temperature range of the primitive potter, but the indices of bentonite, which is composed largely of montmorillonite, undergo sharply defined increases and decreases so that at certain temperatures, values may be the same as those of kaolinite, while at other temperatures they may be as low as when the clay is in the raw state. Therefore, low refractive indices (1.500 to 1.530) in a paste are evidence of the presence of montmorillonite or related clay minerals, but since the values of these may reach those of kaolinite at certain temperatures, refractive indices alone will not invariably reveal the presence of montmorillonite. Although this data may seem involved and detailed, in the Pecos investigation it has proven useful for distinguishing clays and locating their sources, and the results of this study will illustrate its application.

A comparison of physical properties of pastes cannot differentiate clays unless the firing conditions have been identical. Thus red-, buff-, and white-burning clays might all be medium gray if burned with a smoky fire at the Indian's comparatively low temperatures, but if the sherds are refired to critical temperatures the significant differences will develop. Exact temperature control is of course essential for this phase of the investigation. Heating in a blow pipe flame is of little value, for although the sherd may be oxidized the heat treatment is too uncertain and variable to furnish a sound basis for comparison. The color of the clay when oxidized at temperatures within the potter's range can be brought out by heating sherds at 850° C. for half an hour. More striking color differences are usually developed at higher temperatures, 1000° to 1200° C. for example. It will sometimes be found that of two neutral gray sherds one will burn red and the other buff, which fact definitely establishes a difference in the clays.

The refractoriness of clay, determined by the degree of heat which it will stand without melting and deforming, is a significant and important property. If pottery is refired to critical temperatures, its hardness and porosity will give some indication of its relative refractoriness, for both hardness and density increase with the progress of vitrification. But the refractoriness of a pottery paste is influenced by the kind, grain size and amount of tempering material which it contains as well as by the refractoriness of the clay base. In order therefore to compare the clay base of different specimens the temper must either be the same or the error which it introduces must be determined experimentally. Tempering material may affect the fusion point of the paste in two ways: it may raise it by coarsening the texture, so that it is loose and open and clay particles lacking close contact do not readily sinter and bind; or it may reduce it if the tempering material itself has a low melting point. The effect of easily fusible temper is illustrated in the Pecos study; two gray pastes, one untempered and the other tuff-tempered, became upon firing to 1200° C. a brick red and were discovered to be non-refractory, but porosity tests proved that the tuff-tempered specimens were more completely fused than the untempered ones. Upon heating samples of tuff it was found that the edges of flakes were softened

and rounded at 1000° C. and distinctly melted at 1200° C. So the presence of this easily fusible temper had promoted vitrification of the paste, and the clay of the untempered and tuff-tempered sherds could not be compared in this way. The extent to which temper affects vitrification can be determined experimentally for particular clays. Test pieces can be made, keeping all factors except temper constant, then by varying successively kind, grain size and amount of temper, the effect upon porosity produced by each can be measured and compared with the differences recorded for pastes. For example, with a red-burning alluvial clay fired to 950° C. a reduction in amount of sand temper from 25 to 10% reduced porosity 6%, and when the grain size of the sand was changed from 50% coarse—50% medium to 100% fine the porosity was reduced 0.8%. Therefore, even though tempering materials differ, if it is ascertained that the difference in porosity of the refired pastes is considerably greater than the possible variation produced by temper, a difference in the refractoriness of the clays is established.

Color, density and refractoriness form the basis of the ceramist's classification of clay. This system might be simplified and adapted to the archaeologist's requirements, for it offers a means of designating and comparing the actual properties of the clay used in pottery irrespective of differences resulting from the varied and uncertain methods of the potter. Three color divisions may be used and the range of each defined by the Ridgway standards (see pp. 430-432) as follows:

White-burning—Colors nearer white than Ridgway's *f* tones.

Buff-burning—All *f* tones, *d* tones from 9 to 19, *b* from 15 to 19.

Red-burning—All colors darker than *b*.<sup>1</sup>

Sherds must be refired in an oxidizing atmosphere to definite temperatures to define color. In the present investigation sherds were heated at 850° C. for half an hour and also fired to 1200° C. Intermediate temperatures were used for special problems.

Density and refractoriness are relative terms and the distinction between dense-burning and open-burning, refractory and non-refractory, depends upon the purpose for which the clay is to be used. A clay which is refractory to the porcelain manufacturer may be non-refractory to the primitive potter. Therefore, special definitions are required for their application in the study of prehistoric pottery. Tentatively, until more general tests can be made, a clay which fluxes below 1200° C. (or cone 4) is considered non-refractory and one which has 10% or more apparent porosity at 1200° C. is classed as open-burning. The importance of considering the effect of temper if these two tests are used to compare the clay base of pottery rather than pastes, has already been pointed out. Although this system of classification necessitates firing experiments and special tests, it is based on significant properties which are easily measured, whereas the facts necessary for a geological or mineralogical classification cannot always be determined with certainty from the pastes alone.

Chemical analysis is used by the ceramist to determine the presence and amount of elements which will affect the properties of the fired clay; for example, a high

<sup>1</sup>These definitions are essentially the same as those suggested by Dietrich for commercial purposes: 1928, pp. 251-252.

percentage of alumina indicates a refractory clay, a large amount of silica is characteristic of a sandy clay, the percentage of iron and its ratio to certain other elements largely influence the color of the clay, the presence of carbon and sulphur shows the rate of firing necessary for complete oxidation and the prevention of bloating and black-coring. Many of these properties can be measured more quickly and directly by firing experiments, but the chemical analysis is perhaps particularly advantageous for determining the impurities which cause defects in firing. In the study of pottery, chemical analysis would facilitate the identification and comparison of clays, were the body clay unmixed with tempering material, but as most pastes were tempered, (a great variety of materials and different quantities having been used for the purpose), chemical analysis can give only bulk composition. If the mineralogical composition and quantity of temper is determined petrographically, it is possible to calculate from this data and the bulk analysis the approximate composition of the clay. However, these results are seldom sufficiently accurate for comparative purposes. Slip clays unlike body clays were rarely tempered and therefore a chemical analysis gives their true composition. But slips are usually thin and it is a tedious and difficult task to remove sufficient material, free from paste, for chemical analysis. This method may, therefore, be regarded as a last resort in the study of pottery clays.

All of the tests, with the exception of the porosity determination, which have been suggested for the study of body clays are also applicable to the study of slip clay and since slip clays are in general untempered their texture and mineral inclusions represent those of the clay itself and should be recorded. The principal properties considered in the selection of a slip clay are color, hardness and texture. There are conspicuous examples among Pueblo wares of the use of clays unsuitable for slips, such as the "fugitive red" slips, which were not made permanent by firing, and the soft slips of Mimbres classic, Black-on-white ware, which scaled and were soon abraded with use. The fact that clays which will burn to a light and pleasing color are not common in the Pueblo area probably resulted in the use of many which in spite of good color had other marked disadvantages. The permanence and durability of slips depend largely on the hardness which the clay attains on firing, while the smoothness and the degree of luster which can be produced by burnishing are influenced by texture. These properties should therefore be accurately recorded (see suggestions pp. 442-443).

The procedures for the study of clay which have been discussed relate to the properties of the fired body but give no idea of the working qualities of the raw material. Occasionally slight indirect evidence of these is preserved in the pottery itself. One of the potter's first problems is to prevent her vessel from cracking when it is dried, and the addition of tempering material, which reduces shrinkage, accomplishes this purpose. Thus, if one paste is heavily tempered and another sparsely tempered it is probable that the former had higher shrinkage than the latter, although the proportion of temper used is only suggestive, because clays admit considerable variation, which also necessarily resulted from the potter's methods. Evidence of the use of a short or non-plastic clay is sometimes observed in the cracks along the edge of a coil in corrugated ware, but if the coil was flattened without

developing cracks the clay must have had good plasticity. Direct tests of the raw clay are essential, however, for a satisfactory understanding of its working quality. Hence the importance of preserving all ceramic materials found in ruins and of investigating the clays of the immediate vicinity. If the identity of any of these raw clays with the pottery clay can be established by comparing their thermal behavior and physical and optical properties at given temperatures, then the original working quality of the pottery clay can be tested.

The properties of the raw clay which most directly concern the potter are plasticity and shrinkage. Not only has plasticity never been satisfactorily defined or fully explained, but an exact, standard method for its measurement has never been devised. The experienced potter judges plasticity by feel. Simple tests are also sometimes made, such as forming a ball between the palms of the hands and observing how much it can be flattened without developing marginal cracks or rolling out a coil of clay and ascertaining how thin it can be made without breaking apart. But these are only rough estimates. More direct methods, such as measurement of the stress which can be applied, are not highly accurate because of the difficulty of keeping the clay in a uniform condition with regard to moisture while the test is being made. Indirect tests, such as measurement of colloidal content and the amount of water required to bring the clay to the plastic state, have been proposed, but although these properties affect plasticity their relation to it varies and therefore they cannot be considered satisfactory. A simple method which gives an estimate of cohesiveness and furnishes a basis for comparison has been used in the present investigation. The procedure is as follows: the clay is first air dried and screened through a No. 40 sieve. Water is then added and the mass kneaded until it develops a given resistance to pressure. This standard condition is reached when a rod weighted to 250 grams, sinks a distance of 26 mm. into the clay in thirty seconds. In order to reduce friction against the sides of the rod a wider tip is used, the diameter of the rod being 2.6 mm. and the tip, 4 mm. in diameter by 2 mm. in height. An estimate of cohesiveness is then made by measuring the weight which a rope of clay will hold without breaking. Clay which has been worked to the standard consistency is placed in a grease gun having an opening 12 mm. in diameter through which the clay is forced. In order to attach a small pail to receive the weight, the clay is pressed into a cage (made from a wire coil) having the same diameter as the opening of the grease gun. A hook on the disk at the bottom of the cage holds the pail and the clay which is squeezed between the wire coils gives a better hold than a clamp. After the cage has been attached, a rope of clay 22 mm. long is forced out, and No. 8 shot poured at uniform rate into the pail until the rope breaks. Cohesiveness is then expressed by the number representing the weight in grams required to break the rope.

The water required to bring the clay to its best working condition, called water of plasticity, bears some relation to the plasticity of the clay, for in general the more plastic the clay the more water will be required to develop the best working consistency. The per cent water of plasticity is calculated as the difference in weight of a test piece in the plastic condition and when dry, taken in terms of its dry weight.

Shrinkage is an important property of clay since if excessive it causes vessels to crack upon drying. Shrinkage is affected by the per cent water of plasticity because the greater the amount of water taken up the greater the loss and consequent contraction upon drying. Either volume or linear shrinkage can be measured. Linear shrinkage is determined by placing two sharp marks accurately spaced on a test piece when it is in the plastic state; the distance between the two marks is measured when the piece is dried and the per cent drying shrinkage calculated by taking the difference in distance between the marks on the wet and dry test piece in terms of the original distance. The greater the distance between marks the more accurate will be the estimation and if a simple unit of one hundred is taken calculation will be simplified. Fifty millimeters have been found a convenient distance.

The study of clays is involved and difficult and a review of even a few of the factors to be considered and the cautions to be observed is very likely to leave an impression of hopeless confusion and uncertainty. Many of the procedures discussed are tentative and represent merely an effort to make a start in the study. The most promising procedures are the study of optical and physical properties at known temperatures while color, density and refractoriness offer a convenient and significant basis for classification. The study will progress in proportion as exact tests are applied and the actual complexity and variability of clay will often prove an aid in identification and always a stimulus to research.

#### IDENTIFICATION OF TEMPERING MATERIAL

Pottery is seldom made from clay alone. The modern ceramist adds to his clay powdered silica and feldspar or grog. The primitive potter likewise has generally used some form of non-plastic material unless her clay was naturally sandy or gritty. A great variety of inclusions have been found in prehistoric pottery including sand, crushed rock, volcanic ash, ground potsherd, limestone, and shell, the material used depending both upon the custom of the potter and what was afforded by her environment. This non-plastic material or temper, as it is called by American archaeologists, serves several purposes. It reduces shrinkage and the danger of cracking both mechanically and by lowering the total surface area of the particles of the mass and consequently the amount of water required to bring the clay to the plastic state. Temper also lessens the stickiness of clay and unless low in plasticity the tempered clay is easier to handle. More important is its function in firing; by coarsening and opening the texture of the body it permits the more rapid escape of gases which if held in the dense clay would cause spalling, blistering or bloating. The effect is especially important when vessels are heated rapidly as in primitive direct firing. Whether or not the primitive potter recognized the value of temper in firing we have no way of knowing, but experience must have taught her some of its advantages and correction of shrinkage is undoubtedly the most conspicuous one. The one disadvantage in the use of temper is the fact that it weakens the clay. Archaeologists have sometimes erroneously referred to temper as a binder, probably

visualizing it as forming a bond because it prevents cracking; but clay with its high cohesion is obviously the binder and the temper simply prevents excessive shrinkage.

The study of tempering material is of interest to the student of pottery who would trace changes in technique because of the wide variety of materials utilized, but it is also of more general interest because it frequently gives the clearest evidence of the provenience of pottery. The sands and rocks used are often so distinctive that their exact source is established beyond question. But such data demands exact and detailed identification. A hand lens has often been used to detect tempering material and in the coarser-textured pastes it is sometimes possible to distinguish by this means fragments of rock, sand, or sherd. Exact petrographic determination of the temper in pottery types which are described in archaeological literature, shows, however, that many of the identifications made with a hand lens are incorrect. Repeated tests by experienced individuals, moreover, prove that the method is not entirely reliable. In the technological description of Pecos types, the proportion of sherds in which the kind of temper can be identified with a 10-power lens, and the particular characteristics which should be observed, are discussed. It will be found that the temper cannot invariably be recognized megascopically in any of the types occurring at this site, with the possible exception of certain of the culinary types; none of the fine-textured types can be identified with the hand lens, and the paste of half of the sherds of decorated wares is fine-textured. This partially illustrates the limitations of megoscopic examination. An equally serious objection is the fact that specific identification can never be made in this way. The kind of tempering material used reflects the custom of the potter, but in order to discover the source of materials a detailed analysis of the mineralogical composition is necessary; the accessory minerals in a sand, for example, may show the drainage from which it came, or rock temper may be definitely traced to a particular outcrop by detailed petrographic analysis. The petrographic microscope is essential and invaluable in this phase of the work. The importance of microscopic analysis in ceramic studies is well established. It is used in modern ceramic investigations, particularly in the study of thermal changes of ceramic bodies, to determine, for example, the degree of solution of quartz and the formation of mullite and sillimanite. Likewise its application in archaeological studies is not new, for Nordenskiöld reported the analysis of thin sections of Mesa Verde pottery in 1893 and more recently Linné has published results of petrographic examination of South and Middle American types.<sup>1</sup> Nevertheless, the possibilities of this method as a means of revealing the technological history of pottery have been barely touched.

The use of the petrographic microscope, no less than chemical analysis, requires specific training. Minerals are not identified by their appearance as viewed in polarized light, but by exact measurement of certain optic properties, and the importance of accurate identifications cannot be overemphasized. Descriptions of inclusions which "look like quartz" or "are green and probably either hornblende or a pyroxene" have occasionally appeared in archaeological literature and are obviously worthless. If an accurate determination cannot be made it is better to wait than to give a report this fallacious guise of scientific method.

<sup>1</sup> Nordenskiöld, 1893, pp. 78, 81, 84. Linné, 1925, pp. 29-60; 1929, pp. 261-269.

Since the principles of optics and petrographic methods of analysis are fully covered by texts and constitute a special study, only certain adaptations need be discussed here. The method of identifying mineral inclusions in pottery does not differ essentially from the geologist's procedure in studying a thin section of rock, for primitive pottery was not fired high enough to develop artificial minerals and relatively few—certain hydrous minerals and carbonates—are changed. However, the mineral fragments are often exceedingly small and it is necessary to acquire experience in determining optic properties of very fine-grained material. The petrographic microscope is used for the examination of both thin sections and powdered materials immersed in refractive liquids. The thin section shows the shape, arrangement, size and quantity of inclusions, and the texture and relations of paste, slip, paint and glaze. In some instances even, the thin section is necessary for the identification of temper; potsherd fragments can seldom be recognized in powdered paste and while the mineral components of a rock may be identified in this manner the rock itself cannot be studied. Although the preparation of the thin section requires time and a certain degree of skill it furnishes a valuable and permanent record.<sup>1</sup>

The study of powdered material immersed in liquids of known refractive index is also an essential part of microscopic technique and is used especially in determining refractive indices, since in thin sections this property can be estimated only by comparing the unknown with the mounting medium or an adjacent mineral. The thin section shows a relatively small sample, and it is often advantageous to examine a large amount of powdered material in incident light with the binocular microscope; then particular minerals can be picked out with a needle, immersed in a refractive liquid and all of their optic properties recorded. The refractive liquids save considerable time when it is necessary only to identify the minerals present.

General classes of tempering material can be determined with the binocular microscope in all but the finest-textured sherds. Sand, sherd, volcanic ash and different colors and textures of igneous rock can be distinguished, but this instrument does not give the mineralogical detail necessary to locate the source of materials, and it is most effectively used in conjunction with the petrographic microscope. The binocular microscope is particularly useful for classifying large lots of stratigraphic material, after the types have been fully defined by the petrographic microscope, which should always be at hand to check doubtful specimens.

<sup>1</sup>The softness and friability of pottery necessitate impregnation with bakelite for the preparation of thin sections. The method is described in the following papers:

Ross, 1924, 1926. Legette, 1928.

It is often desirable to slice the sherd diagonally through the vessel wall, since a cross-section gives only a small specimen and a longitudinal section does not include slip or pigment, nor are the possible paste variations occurring from core to margin represented. A number of grades of bakelite, varying in viscosity, color and the rapidity with which they can be hardened, is on the market. Legette recommends C.V. 1305 which has been found satisfactory for impregnating pottery but a thin lacquer (B.L. 3128) has certain advantages; it is lighter colored and can be heated more rapidly. As it is less viscous the pottery chips, which have been soaked and air-dried, are given a second dip to leave a reasonably thick coat on the surface. More complete penetration of bakelite is obtained if chips are boiled in bakelite solvent previously to impregnation. The impregnated chip can be heated with less danger of blistering if first thoroughly air-dried.

The identification of the rarer mineral inclusions is facilitated if they can be concentrated by separation from the paste and more common minerals. This is particularly true in the case of sand-tempered wares in which accessory minerals may serve to differentiate the sand of different drainages. Methods of separation developed in petrographic studies, and applied particularly in the study of sediments, may be useful. Separation with an electromagnet and with heavy liquids have both been tried, but the success of the latter method especially depends upon completeness of separation of minerals from paste, since particles of porous clay adhering to small mineral grains cause them to float in the heavy liquid. The applicability of the method for pottery analysis is partially determined by the softness of the paste. With very low-fired wares it may be possible to effect a more complete separation by preliminary digestion in sulphuric acid, which would attack some fired clays but few of the principal minerals. The procedure has not been checked in the Pecos study because most of the types are relatively well fired and electromagnetic separation has been more satisfactory than heavy liquid separation.

The approximate percentage of tempering material in a paste can be estimated from thin sections. The Rosiwal method employed by petrologists to calculate the percentage of given minerals in rocks is useful for this purpose. It is based on the principle that "along any line of adequate length drawn on a plane surface—the ratio of the sum of the linear intercepts of any given mineral to the total length measured across the rock-surface is approximately equal to the volume-percentage of that mineral in the rock."<sup>1</sup> The total length of the lines along which constituents are measured should be at least one hundred times the average diameter of the particles measured. In order to insure greater accuracy, a line two hundred times the average diameter of the constituents was taken in the Pecos study. Measurements should be made at uniform intervals over the section to avoid any unconscious tendency to select fields, and to insure an even sampling of the section. Both margin and core of the sherd should also be included in the count.

The accuracy of this method when applied to ceramic determinations was tested with pastes of known composition. Test pieces were prepared with clay from Zuñi tempered with 15 and 25% by volume of sand, rock and sherd, the rock and sherd being sifted and recombined after grinding to duplicate sand in grain size. These samples, together with untempered clay as a control, were fired to 1030° C. and thin-sectioned for counts. The results showed that a high degree of accuracy cannot be claimed for the method when applied to pottery but errors are small compared with the variation in amount of temper present in different sherds of the same type. When well prepared sections, in which the temper can be clearly distinguished from the paste, are used and the utmost care is exercised in counting, the average error does not exceed 10%, that is, the count will give a minimum of 22.5% in a sherd which actually contains 25%. Compared with this error the amount of temper in sherds of a single type has been found by this method to vary from the average anywhere from 18 to 60%. The average variation for nine representative Pecos types was 28%. In other words, the more sparsely tempered sherds of a type

<sup>1</sup> Holmes, 1930, p. 311.

averaging 25% temper will contain only 18% and in extreme cases no more than 10%. The Rosiwal method can be used to determine the percentage of all granular-textured temper but is not reliable for platy or needle-like material, especially as these were sometimes oriented when the vessel was shaped. Tuff and mica are the only examples of this type of temper so far encountered. Mineral matter occurring naturally in the clay is not distinguished from the artificially introduced temper in these counts, but the non-plastic material of the clay generally constitutes a very small percentage of the total mineral inclusions. The unequal change in the volume of temper and of clay caused by firing shrinkage introduces a comparatively slight error. The two principal sources of error in the application of the Rosiwal method are careless sampling and inaccurate measurement. A sufficient number of measurements must be taken in each section to insure an exact record of that specimen and furthermore enough sherds should be measured to represent the type. Difficulty in measurement may arise either from indistinct boundaries or from similarity of the clay base and temper. If the boundary of a crystal is oblique to the plane of the thin section there will be an overlapping film of clay and the edge of the crystal will not be sharply defined. Moreover certain types of temper may be so like the clay in color and texture that they are not seen, as for example sherd tempering fragments which are similar in appearance to the clay base. Judgment must therefore be exercised not only in sampling but also in deciding whether a type can be measured with sufficient accuracy to give reliable data. Under favorable conditions the calculated percentage approximates the proportion of temper used by the potter and forms a basis for comparing the average amount of temper in different wares and also the degree of variation within a ware.

The possibility of removing certain kinds of temper by chemical treatment offers another means of calculating the proportion of temper in a paste. If a non-calcareous clay, for example, is tempered with calcite, limestone or shell, the amount of temper can be estimated by removing the calcium carbonate with hydrochloric acid and comparing the original weight of the paste with either the weight of the washed and dried residue left by acid treatment or with the calcium carbonate precipitated from the filtrate.

Since volume of temper can be calculated there is need for specific definition of quantitative terms. On the basis of experience with Pueblo wares the following terms have tentatively been applied:

Sparsely tempered	under 15%
Moderately tempered	15 to 30%
Heavily tempered	over 30%

The average grain size of tempering material has been calculated by averaging the diameters of one hundred grains in a section. To avoid unconscious selection only the grains which come under the micrometer scale are measured, and the slide is shifted to bring the scale on fields uniformly spaced over the section. These estimates of grain size can be used to compare types but are lower than the true value because the thin section cuts through the greatest diameter of only a portion of the grains, others being only grazed and cut in all positions intermediate between

these two extremes. Petrographers have worked out a formula for correcting this error, but it applies to specimens in which the grains are of nearly equal size and consequently cannot be used to correct estimates for sherds in which there are great differences in grain size. The maximum diameters measured will represent the true maximum if a large enough section is used to insure interception through the center of some of the largest inclusions. It was found in the study of Pecos material that the average grain size often varies but slightly for sherds which differ noticeably in distribution of sizes of inclusions; thus a high proportion of fine material will equalize the average for sherds with large amounts of medium-textured grains and those with a moderate amount of coarse material. A determination of the percentage of fine, medium and coarse material is therefore more significant than the calculation of the average size. Definition of textural terms is necessary for this purpose and the following standards, based on those used by petrographers for the description of sediments, have been adopted for this study:

<i>Textural Terms</i>	<i>Diameter of grain in mm.</i>
Very fine	0.05-0.10
Fine	0.10-0.25
Medium	0.25-0.50
Coarse	0.50-1.0
Very coarse	1.0 and above

In geological usage the limits here specified for coarse, medium, and fine define these grades of sand; and very fine corresponds to coarse silt. Coarse sand falls between the limits of 1.0 and 2.0 mm. and gravel between 2.0 and 10.0 mm.<sup>1</sup> Five hundredths of a millimeter has been taken as the lower limit in the definitions adopted because in this range an increasingly large proportion of the grains may have occurred in the clay and, since we are concerned with the temper, an arbitrary limit must be fixed. The largest of the medium particles can be seen with the unaided eye, and the medium and largest of the fine with the aid of a 10-power hand lens under favorable conditions, that is, with distinct color contrast between paste and inclusions. But it is not necessary or practicable to base the definition of terms upon the range of sizes detected megascopically because these will differ with the degree of color contrast in materials. Some workers will find that the definitions proposed do not correspond with their conception of these grades. In certain Mississippi Valley pottery types, for example, much of the temper is considerably coarser than 2.0 mm. Experience will prove whether it will be advisable to expand the standard definitions evenly to divide the entire range of grain sizes found in pottery, or whether it will be more practical to use special terms for these somewhat exceptional materials. The first alternative would have the disadvantage of making too broad the terms which cover the range found in the majority of pottery types. The word gravel might possibly be used, or textural terms applied to an exceptional kind of temper could be defined independently; "coarse shell," for example, might describe

<sup>1</sup>See Holmes, 1930, p. 197.

a different size than "coarse temper." The problem will have to be worked out by those familiar with the range of materials, and the number of subdivisions required in the Mississippi Valley. The subdivisions established in geological usage have been found adequate and satisfactory for the description of both Southwestern and Middle American paste textures.

The number of sherds which should be analyzed for the petrographic description of a type will naturally be decided to a certain extent by its variability. Usually an examination with the binocular microscope will show the range of textural and mineralogical variations occurring within a type defined by surface features and so furnish a guide for the more detailed study.

The results of petrographic analysis of pottery cannot be fully interpreted without a knowledge of the geology of the locality from which it comes. In many regions available geological data do not give the detail necessary for the exact location of sources of material and in such cases special studies must be made. The nature of these will be suggested by the particular ceramic materials found. Often it will be desirable to compare the sand of streams draining different formations and to study the minor textural and mineralogical variation in igneous outcrops.

Temper is one of the most diverse of ceramic materials and it is also the most readily and accurately identifiable. The Pecos study will give some idea of the character and importance of results which can be obtained when a large variety of materials were used and geological provinces are sharply defined. It is believed that these data justify thorough analysis correlated with systematic geological field work.

#### ANALYSIS OF PIGMENTS

The study of ceramic pigments involves, in addition to the identification of the substances used, a consideration of the viscosity or spreading quality of the raw material, the physical relations and possible chemical reactions between pigment and clay, and the effect of firing upon composition, color and permanence of the pigment. Chemical analysis, thermal experiments and microscopic examination all contribute to the investigation. Microscopic examination shows the thickness, texture and homogeneity of the paint and its depth of penetration; chemical analysis offers the most satisfactory means of identification, and when the composition is known, thermal experiments aid in the study of effects of firing and causes of permanence. One of the principal difficulties in identification is that of obtaining a sample of sufficient size for chemical analysis yet free from slip or body clay, for the paint is often exceedingly thin and sometimes penetrates and stains the slip or body so that it is practically impossible to distinguish pigment from discolored clay. A number of investigators have reported analyses of Pueblo ceramic pigments; the work of only a few need be reviewed to illustrate the various methods which have been employed.

One of the earliest chemical analyses was published by Nordenskiöld in 1893.<sup>1</sup> He determined that the paint of certain Mesa Verde vessels has an iron base and

<sup>1</sup>p. 84.

inferred, from the discovery of a mixture of hematite and resin on a stick, that the paint was applied in the ferric state and reduced during firing by the admixed organic matter. Nordenskiöld does not describe the method of analysis used, nor does he seem to have discovered that the paint of classic Mesa Verde ware is organic in composition. The pigments of certain Black-on-white types from Chaco Cañon and Mesa Verde were analyzed by Germann, the material for these tests having been removed from the sherd by digestion with hydrofluoric acid previously to analysis and the form of oxide present determined by the magnetism of the paint particles.<sup>1</sup> A simple means of distinguishing between organic and iron paint by oxidation was used by Hawley.<sup>2</sup> This method depends upon the fact that many pigments containing iron will redden when treated with hydrofluoric acid and heated in an oxidizing atmosphere, while under the same conditions carbonaceous matter burns out, leaving only the ash. The test is therefore non-technical and has since been adopted by a number of archaeologists. But it is limited to the determination of only two kinds of paint and often more refined methods are desirable. Also certain theories—as, for example, the supposition that plant juice was always used with mineral paint, and that the permanence of organic paint was due to a protective silicate film—were advanced without experimental demonstration and consequently have been misleading and have resulted in erroneous conclusions. Gonyer substituted for the oxidation method the potassium ferrocyanide test for iron, applying the reagent directly to the paint surface which had previously been digested with acid.<sup>3</sup> Although the ferrocyanide test for iron is preferable to oxidation, the application of acid and reagent to the sherds is not to be recommended because it is impossible with this procedure to keep the pigment free from slip.

Most investigators have used acid, either hydrofluoric or a mixture of hydrofluoric and hydrochloric, to loosen the paint from the clay surface previously to analysis. Digestion with hydrofluoric acid is also recommended for the Hawley tests because the paint is then more readily oxidized. Hydrofluoric acid, however, attacks the clay as well as the pigment, and although the latter is usually the more soluble of the two, an indefinite amount of clay will be included with the sample if it is removed with acid treatment. On the other hand, if the test is made on the sherd and, as with either the Hawley or Gonyer methods, acid is allowed to flow across the surface, some of the pigment may be carried off in solution. Hawley discusses the solubility of clay and pigment and mentions certain very necessary precautions.<sup>4</sup> But even with experience and caution the procedure is not always reliable. The mechanical removal of paint is an alternative for acid treatment, but requires care and patience. The process should be observed with a binocular microscope to avoid cutting into the clay, and a steel tool cannot be used if iron determinations are to be made.<sup>5</sup> A crystal of carborundum properly mounted makes a convenient scraping tool, since it cuts rapidly, being considerably harder than either steel or quartz. Carborundum is an artificial compound of carbon and silicon, and

<sup>1</sup>1926, pp. 480-482.

<sup>2</sup>1929, pp. 731-754.

<sup>3</sup>Cosgrove, 1932, p. 94.

<sup>4</sup>1929, p. 74.

<sup>5</sup>The possibility of removing extraneous iron with an electromagnet was tested, but the method proved unsatisfactory because the iron adheres to the particles of pigment, and the greater part of the sample is consequently attracted by the magnet.

though these two elements would be introduced into the sample with the abrasion or flaking of the scraping tool, they do not interfere with the determination of the metallic elements. Certain types of mineral paint which have no relief and appear to have penetrated the clay as freely as would soluble organic paints are particularly difficult to remove by scraping. In such cases a drop of hydrofluoric acid carefully applied will loosen the surface and upon drying, the pigment can be removed by scraping. The particular method which is selected for removing paint will depend upon the nature of the materials and the problems involved, but it is often advisable, as a final precaution against contamination of the sample, to test the slip as well as the paint; then if the principal elements found in the paint sample do not occur in the slip, the analysis represents the composition of the paint. If the same elements are present in both slip and paint, special care and judgment must be exercised in obtaining the sample and interpreting results.

Techniques which have been developed for the analysis of minute quantities of material are distinctly advantageous in the study of ceramic pigments. Microchemical analysis has been found satisfactory for the qualitative determination of many elements occurring in paints and glazes. The polarizing microscope is utilized in this method to identify elements, principally by means of reaction in which readily identifiable crystalline compounds are formed.<sup>1</sup> Microchemical analysis does not generally require separation of the sample, as in the usual procedure for qualitative analysis, and consequently substances which interfere with certain reactions may be present. This restriction necessitates a thorough knowledge of all reactions and possible effects of interfering elements. Tests which have been found reliable in the study of Pueblo pigments include the potassium thiocyanate test for iron, the sodium bismuthate test for manganese, the potassium iodide test for lead and the potassium mercuric thiocyanate test for copper. Spectrographic analysis is especially adapted to exact qualitative analysis of small samples and may also be used for approximate quantitative determinations, but the expense of equipment limits the use of this method for archaeological work.

Quantitative analysis is sometimes necessary for the solution of specific problems, but requires larger samples than qualitative determination. If the composition of the clay is known, the amount included in a sample of mixed pigment and clay can be determined and deducted from the analysis. It might appear feasible, therefore, to calculate the composition of the paint in this way, rather than to obtain a sample of paint free from surface clay. The method is not generally practicable, however, because a hard, thin slip is almost as difficult to remove as the paint; moreover, the mixed sample of pigment may contain an uncertain amount of body clay, as well as slip clay. It is therefore advisable to work with unmixed samples and it has been demonstrated that, with highly accurate instruments and experience in dealing with small samples, the usual procedure for quantitative analysis can be carried out with a ten milligram sample.

Pueblo potters used both organic and mineral paints; the former were of vegetable origin and the latter included oxides of iron and of manganese, and ferruginous

<sup>1</sup>For a discussion of microchemical methods and description of tests see Chamot and Mason, 1931.

and white-burning clays. Black was produced with either vegetable or mineral substances, while reds, yellows and whitish colors were obtained with clays. Each type of paint presents specific problems. The argillaceous paints are usually similar in composition to slip clays, having been chosen for their color and texture. Methods for their identification and description are, therefore, covered in the section on clays. The iron and manganese paints are readily identified by microchemical tests and oxidation is the simplest means of recognizing an organic pigment.

One of the principal requirements for a ceramic pigment is that it withstand firing; consequently, the decoration of pottery with organic matter seems anomalous. Various theories have been advanced to explain why the carbon from a vegetable paint is not burned out in firing. Tests made in an effort to learn more about the conditions favorable to the successful use of organic paint will illustrate the fact that identification of the substance is only one of many problems which arise in the study of ceramic pigments. The standard black paint used by present-day Pueblo potters of San Ildefonso, Tesuque, Cochiti, and Santo Domingo is an extract of the Rocky Mountain Bee Plant (*Perioma serrulatum*), commonly called *guaco* by the native peoples. The preparation of this paint by San Ildefonso potters had been described by Guthe.<sup>1</sup> *Guaco* is also used by Zuñi potters as a vehicle for mineral paint.<sup>2</sup> It is reported that the Hopi mix the concentrated juice of a species of tansy mustard (*Sophia sp.*) with mineral paint.<sup>3</sup> As a result of the general use of the Bee Plant the idea has become prevalent that it possesses some peculiar properties which make it especially suitable for ceramic purposes. There is no excuse for the persistence of this idea, which is almost akin to a superstition, for the question whether the juice of certain plants only will produce black when applied to raw clay and given short rapid firing is very easily answered by experiment.<sup>4</sup> A number of organic substances including the concentrated extract of a species of chenopodium, mock orange, dandelion, licorice, sugar, glucose, honey, glue, starch and gum tragacanth have been compared with *guaco*; applied on the same clays and with the same firing treatment, they produce black or dark gray similar to that obtained with *guaco*.

The fact that substances as different in appearance as sugar and the dark gummy juice of the *guaco* will both fire black has been recognized by certain of the Pueblo potters, for they sometimes add sugar to their *guaco* paint. There are a number of things in addition to fired color which may account for the use of a particular plant for vegetable paint: abundance, succulence and ease with which the juice is extracted, spreading quality, rate of drying and color before firing. The Bee Plant is an abundant annual in the vicinity of the Pueblos. The concentrated juice has sufficient body or viscosity to flow well from the brush and being of an olive color

<sup>1</sup>1925, pp. 25-26. <sup>2</sup>Stevenson, 1904, p. 375.  
<sup>3</sup>Hawley, 1929, p. 738. Colton, June, 1931, p. 3.

<sup>4</sup>Some years ago Mr. K. M. Chapman became interested in this question and tested various plant extracts. He fired paints made from the concentrated juice of dandelion, mock orange, a species of chenopodium and also licorice, and could distinguish none of these from *guaco*. Mr. Chapman also recognized that Santo Domingo slip held organic paints better than some other slip clays used by the Pueblos.

shows up against the clay. It also dries quickly. A sugar solution, of the same concentration as the *guaco*, being more fluid tends to spread. It is also nearly colorless so that the design cannot be clearly seen and as it dries slowly, care must be taken to avoid smearing it. On the other hand, gummy substances such as glue or starch paste are so cohesive that they peel off upon drying, unless very thinly applied. Even *guaco* may increase the crazing of certain slips by its excessive contraction and this effect is lessened by the addition of sugar. While *guaco* possesses advantages its use has also been fixed by custom, which undoubtedly enters into many of the ceramic practices of the Indian.

A plant extract such as *guaco* consists primarily of carbon, oxygen and hydrogen united in complex organic compounds. When heated these compounds are broken down, volatile matter is driven off, and free carbon is deposited on the clay. The chief problem in connection with these paints is to explain why the carbon does not also burn and so escape as carbon dioxide gas, leaving only a trace of plant ash. As a matter of fact, these paints can be burned out with prolonged heating under oxidizing conditions; but the rapidity and completeness with which they burn varies considerably; thus a gray streak remains on some after they have been held at a temperature between 800° and 840° C. for half an hour, while no trace is left on others.<sup>1</sup> It has been found that organic paint is much more easily oxidized if it is first treated with hydrofluoric acid. In explanation of this fact it has been suggested that the carbon is protected by a very thin coat of an alkali silicate formed by the reaction of alkali salts in the plant ash with the silica of the clay.<sup>2</sup> A partial analysis of ash from an organic paint, containing 28.5% ash, of which 8.2% was silica and 32.5% alkali, is given in support of this theory.<sup>3</sup> An incipient glaze is not visible on the surface of these organic paints even upon microscopic examination; moreover, after *guaco* paint is fired, a coat of powdery ash, which is easily brushed off,

<sup>1</sup>Clays having a very low vitrification point may begin to sinter at the temperature employed in Pueblo firing and if this occurred organic matter would be trapped and protected. Sintering of the clay may possibly explain the tenacity with which organic paint is held on some types of prehistoric sherds but was seldom an important factor.

<sup>2</sup>Hawley, 1929, p. 739.

<sup>3</sup>Hawley, 1929, p. 739. The Hawley analysis would have been more significant had the history of the sample been known, for the amount of ash in organic pigments varies within wide limits, depending upon the method of preparation. The plants, as gathered, contain a variable amount of siliceous dust. Furthermore, after concentration by boiling, the liquid is air-dried or sun-dried, during which time it is exposed to dust. Any organic extract handled in the same way might have a high silica content. Paint made from Bee Plant which was washed before extraction and the extract concentrated indoors contained 0.45% silica as compared with 8.2% found by Hawley. When the juice of the Bee Plant is concentrated by boiling, an insoluble salt separates. This salt may amount to 13% of the sample, though part is sometimes included with the paint; but when calcined it is reduced one half, so adds only 6.5% to the ash. It is composed principally of a calcium salt, which was not positively identified. However, it is none of the common, sparingly soluble, salts of calcium—the sulphate, carbonate, phosphate or oxalate. When burned to an ash it yields calcium carbonate, equivalent to the amount obtained from burning calcium citrate, and when the salt is dissolved in hydrochloric acid it is not precipitated by the addition of ammonia except on boiling. This reaction is characteristic of calcium citrate. Paint in which the soluble salt had been retained was compared with that from which it had been rejected and no positive effect of this part of the ash upon the carbon was noted. In preparing paint from the Bee Plant it was found that the juice becomes dark and less soluble if dried at 100° C.

usually covers the surface; therefore, it is evident that at least a considerable part of the ash does not enter into the formation of a glaze. The theory of the protection of carbon paint by a thin silicate film was tested in three ways: by comparing the permanence of ash-free organic substances with that of *guaco*, by determining whether the relative permanence of ash-free substances was improved by the addition of salts equivalent to the ash of *guaco*, and finally by testing the effect of partial removal of ash from *guaco*.

Sugar was selected as an ash-free substance for comparison with *guaco*. Solutions of each were prepared in the same strength (29 parts of pigment to 71 parts of water, which is the concentration used by a Cochiti potter). Lines were drawn with the two solutions on various types of slip clay, the brush being dipped for each stroke. The slips were prepared by mixing the same weight of clay in a given amount of water and each trial piece was given the same number of applications and the same degree of polish. Test pieces were fired in an electric resistance furnace with accurate temperature control to 850° C. in thirty minutes. Under these conditions, in which all factors were constant except composition of paint, the depth of black on the different clays varied greatly whereas the sugar and *guaco* differed but slightly, the former being a little deeper and more even in color on those clays which took the organic paints most effectively, and somewhat weaker on the clays which did not hold any organic pigment well. As an additional test, the trial pieces were broken in two; one part was refired to 850° C. and held between this temperature and 840° C. for twenty minutes. Also duplicate trials were carried to 950° C. in thirty minutes. The results of these two heat treatments were hardly distinguishable; the carbon had been completely oxidized from some clays, while a dark gray streak remained on others; likewise the *guaco* was stronger in color on certain clays while on others the sugar was more resistant to oxidation.

The effect of the addition of alkalies and silica to ash-free organic substances was tested by adding sodium carbonate and sodium silicate to sugar and to lampblack in amounts equivalent to that in the *guaco* analyzed; 25 and 40% solutions of wood ashes were also added to these two substances. To eliminate the possible effect of soluble salts in the clay, both body and slip clays were washed by repeated decantation with distilled water. The solutions were compared with sugar alone and with *guaco* by painting them on test pieces which were fired to 850° C. and held for twenty minutes. The substances to which alkali and silica had been added were no more resistant to oxidation than the normal sugar solution.

An attempt was made to remove the alkali from *guaco* by dialysis, but some of the salts are evidently organically combined and cannot be extracted in this way. But a dialyzed sample of *guaco* from which 27% of the original ash had been removed was compared with normal *guaco*. When fired rapidly to 850° C. and also after being held at this temperature for twenty minutes the normal and dialyzed *guaco* were indistinguishable.

Another possible effect of the ash in plant extracts was considered; that is, even though not combined as a silicate or fluxed, it might have a protective or fire-proofing effect on the carbon. It is a common practice in the determination of ash to dissolve the coating of fusible salts if the carbon is difficult to oxidize, for

after this treatment the carbon burns off readily. The coating of ash on organic paint might also considerably prolong the time required for oxidation. To test this theory trial pieces were painted with *guaco* and fired rapidly to 850° C. One of these was then boiled in distilled water for twenty minutes, while the coating of ash on the other was undisturbed. Subsequent refiring to a temperature of 850° C., which was held for twenty minutes, oxidized the undisturbed specimen as fully as the one from which the ash was entirely removed.

These experiments show conclusively that organic paint of the type used by the Pueblo potter is not protected by a silicate film and that ash is not an important factor in reducing the rate of oxidation of carbon during the firing of these pigments. Other factors should be considered in explaining the minor differences noted between *guaco* and sugar in resistance to oxidation. It is well known that carbon from different sources varies and that some kinds burn more readily than others. Lampblack from the partial combustion of oil and carbon black from natural gas are common examples of the variation in carbon. The coking of coal is analogous to the combustion of organic paint; most bituminous coals yield soft coke and comparatively few yield a hard metallurgical coke capable of sustaining the load in the blast furnace. There is practically no ash in petroleum coke, yet the carbon left in the final breaking down of some tars is hard and dense and has the appearance of having been melted. The carbon from the dialyzed *guaco* was more dense than from the normal *guaco* and required three hours to burn to a white ash under conditions which would have burned the carbon from undialyzed *guaco* in approximately twenty minutes. According to Mellor, the temperature at which combustion begins depends greatly upon the physical condition of carbon, being spontaneous for very fine carbon but not beginning until a temperature of 660° C. is reached for carbon approaching the density of graphite.<sup>1</sup> It is possible that with more detailed study the characteristic form or condition of the carbon together with the particular mineral salts present will specifically identify the source of certain organic paints. The assumption that the Rocky Mountain Bee Plant was always used by prehistoric Pueblo potters is not justified.

The marked variation in depth of color of *guaco* paint, when applied to different clays, has been mentioned. These differences show very plainly that certain properties of the clay perform an important part in the protection of the carbon. The clays tested include Santo Domingo and Laguna slip clays, the carbonaceous pottery clay of Zuñi, buff-burning Cretaceous clays from the Galisteo Basin, red-burning alluvial Tertiary clays from the Tesuque valley and bentonites from Santa Cruz and Vallecitos Creek. The clays which held the *guaco* longest were those which had the highest per cent water of plasticity and shrinkage. Thus the bentonites gave a black at 850° C. and dark gray corresponding to Ridgway's 15<sup>5555</sup>m on refiring for twenty minutes or firing to 950° C.; the Santo Domingo slip and a clay of similar properties, found in the Galisteo Basin on the bank of the Jara at the mouth of the Cañoncito Colorado, also protected the carbon well, having the color of Dusky

<sup>1</sup>Mellor, 1916, p. 722. Page 718, ignition temperature of charcoal in oxygen, 300°-500° C.; of graphite 650°-770° C.

Neutral Gray (Ridgway's *m*) with the short firing and Neutral Gray or Light Neutral Gray *b* with the longer or higher firing. The Santo Domingo and Jara clays have high adsorption and shrinkage, though they are less extreme in these respects than the bentonites. They resemble the bentonites in optic properties. Their origin has not yet been determined but they do not show the ash structure of true bentonites. The sedimentary clays having average per cent water of plasticity and shrinkage are unsatisfactory for the *guaco* paint, as it fires to Neutral Gray, 15<sup>'''</sup><sup>b</sup> (Light Mouse Gray) or 17<sup>'''</sup><sup>b</sup> (Light Drab) at 850° C. and leaves only a faint trace or disappears completely on longer firing. It is also with this class of clays that a poorer black is obtained with sugar as compared with *guaco*.<sup>1</sup> Similar tests were also made with the Jara clay and a white-burning commercial clay obtained from Coors Porcelain Company. These two clays were used as slips and mixtures of the Jara with 25, 33, 50 and 75% of the Coors clay also were used. With the firing treatment previously described the Jara fired to Dusky Neutral Gray at 850° C. and to Neutral Gray on being held at this temperature for twenty minutes, while the Coors clay retained only enough carbon to give a Pallid Neutral Gray *f* on the first firing and burned out completely on refiring. The mixtures of the two clays showed a relatively even gradation in color from one extreme to the other.

The relation of the strength of organic paint to the type of clay used has been recognized by the Pueblo potters, for Santo Domingo slip is preferred by modern Tewas using organic paint, and the San Ildefonso potters obtain it in trade from either Santo Domingo or Cochiti Indians who both use it.<sup>2</sup> Potters of Zia, Laguna, Isleta, Acoma and Zuñi, having open-textured slips which do not retain an organic paint, decorate with mineral pigments. It would be interesting to determine whether the distribution of organic paints in prehistoric times bears a direct relation to the occurrence of clays of the type upon which this paint is most effectively used.

Some clays have the property of adsorbing dye from solution and are used as decolorizers. Clays which are satisfactory for organic paints might be expected to adsorb a larger proportion of the vegetable extract from solution. The relation of the adsorptive property of clays to their protection of carbon was, therefore, tested

<sup>1</sup>The following figures will give an idea of the range in water adsorption and shrinkage of these various types of clay:

	% water of plasticity	% linear shrinkage
Zuñi clay	38	12
Cretaceous clay	32	10
Galisteo Basin	30	10
Tertiary Clay	62	18
Tesuque Valley		
Jara clay	86	So extreme that they cracked badly and measurements could not be made.
Bentonites		
Vallecito Creek		
Rio Oso	92	

<sup>2</sup>Guthe, 1925, p. 23. This slip absorbs and holds organic matter so tenaciously that it is necessary to avoid handling a vessel before it is fired, since oil from the fingers is absorbed and leaves a black finger print upon firing.

by adding a *guaco* solution to different types of clays in a water suspension. But the bentonites and clays of similar type did not remove any more of the color than did the common sedimentary clays.

Experiments, in which *guaco* was painted on test pieces given preliminary firing, also prove that the preservation of *guaco* is due to properties of the raw clay. A test piece slipped with Jara clay was fired to 850° C. and then painted; upon refiring to 850° C. (the temperature at which a good black was obtained from *guaco* painted on raw Jara clay) only a faint trace of gray remained. A series of test pieces of Jara clay was then prepared and fired to temperatures ranging from 200° to 500° C. with intervals of 50 degrees between trials. The shrinkage, loss of water, decrease in plasticity and rate of slaking was determined for each. They were then painted with *guaco* and refired to 850° C. in thirty minutes. A direct relation was shown between the strength of the *guaco* paint and the degree of dehydration and consequent shrinkage and loss of plasticity of the clay. The plasticity of the Jara clay was not entirely destroyed until a temperature of 450° C. was reached and the *guaco* was noticeably paler on test pieces which had been fired to or above this temperature. If the permanence of the *guaco* were dependent primarily on the formation of a silicate film, preliminary heating of the clay should have no effect on the depth of color. The two properties of clay which clearly bear a relation to the permanence of organic paint are the water of plasticity and shrinkage, which fact means that a given amount of clay will take up more of the *guaco* solution and that upon drying the clay particles are drawn tightly together thus protecting the films of pigment which surround them.<sup>1</sup> The effect of hydrofluoric acid used in the Hawley tests to facilitate oxidation is readily explained by this theory of the adsorptive and protective effect of certain clays, for the acid attacks the clay, opening and loosening the surface and thus exposing the carbon.

The firing atmosphere, as well as temperature and length of heating, have, of course, an important effect upon the preservation of an organic paint. If a reducing atmosphere is maintained, the carbon will not be oxidized, and a higher temperature and longer firing than is possible with an oxidizing atmosphere may be employed. The atmosphere of the dung firing of the modern Pueblos was compared with that of the electric resistance furnace by using cylinders made of clay to which 5% of lampblack was added. After firing, the cylinders were cut through the middle and the thickness of the zone from which the lampblack was burned out gave a basis for the comparison of firing atmospheres. The dung firing was found to compare favorably with the conditions maintained in the electric resistance furnace. The loosely

<sup>1</sup>Some San Ildefonso potters believe that *guaco* produces a better black if it is aged at least a year before it is used (Guthe, 1925, p. 25); and aging has been suggested as a possible explanation of the differences in organic paints of various types of prehistoric Pueblo pottery (Amsden, Vol. I, p. 23). However, tests with freshly prepared and well aged *guaco* (kept over five years), in which all other conditions were kept constant, failed to show any difference. It seems very probable that the notion of the importance of aging originated from an attempt to explain a failure when the true cause could not be determined with certainty; and so the explanation may have become fixed, just as the idea that a cake batter should be stirred only in one direction, and similar culinary superstitions, persist among cooks.

laid chips and numerous open spaces give a good draft in the ordinary dung firing and organic pigments are exposed to oxidizing conditions during the greater part of the firing. It is entirely possible, however, that in the firing of certain prehistoric types a less completely oxidizing atmosphere was maintained. The two primary factors to be considered in explaining organic paints are therefore the firing conditions (temperature, time and atmosphere) and the properties of the clay upon which the paint is applied.

The surface texture of an organic paint is ordinarily quite different from that of a mineral paint. The solution of organic matter penetrates the paste without destroying the arrangement of clay particles, even though a coating of organic matter remains on the surface. Upon firing, the surface deposit is largely removed by oxidation, the adsorbed pigment imparts the color and the surface clay is left in its original condition. Thus if the vessel has been polished previously to painting, the polishing strokes will be uninterrupted by paint lines, which gives the impression that the vessel was polished after painting. This point has been proven experimentally. It was found difficult to polish the moist paint surface without smearing the lines; and the dried organic matter on clay becomes hard and resistant to burnishing, but paint applied on a highly polished surface has a luster comparable with that of the slip. This peculiarity of organic paint should be kept in mind in describing the workmanship of prehistoric types. It does not apply to mineral, particularly argillaceous, paints, for they can be, and certainly were sometimes, polished. Mineral paints are applied as a suspension rather than a solution; they, therefore, coat the surface and cover the clay. This difference between organic and mineral paints is clearly seen in thin section; the carbon paint does not stand up as a superficial layer but discolors the clay for some depth; whereas the mineral paint generally forms a distinct outer coating upon the vessel surface.

Minor peculiarities of the organic paint of certain types of Pueblo pottery may require experimentation before they can be explained. The blurred outline noticeable on certain Mesa Verde vessels, for example, may be due to any one of a number of causes; a paint of slightly different composition which diffused more readily, a more permeable paste, application of the paint on a moist surface, or redrawing a line with a thinner solution. Only trials with material similar to the original will show which factor, or what combination of factors, produced the effect. Another peculiarity is found occasionally on vessels which were exceptionally well fired and well oxidized; the painted surface takes on a distinctly brownish cast and the slip near it may also be discolored. A similar effect has been produced on certain clays with excess alkali when fired to the higher range of Pueblo temperatures. A minor cause of variation in depth of color is the thickness of the paint solution. Mixtures either half or double the strength used in the experiments described (29 parts of pigment to 71 parts of water) were paler in color, for with double strength, the solution was too thick to penetrate well, while with half strength there was insufficient coloring matter. When a line was painted twice with a half strength solution, however, a deeper color was obtained than with one application of normal strength solution because of more complete penetration.

Organic paints have been discussed at length because they illustrate the variety of problems which remain to be solved after the coloring matter has been identified and they also prove the importance of synthetic tests in this phase of the work.

Mineral no less than organic paints present a variety of problems. Quantitative analysis is particularly applicable to this group, not alone for comparative purposes but also to determine the nature of the binder and as an aid in locating the source of the material. The principal black mineral pigments of Pueblo pottery are either oxides of iron or manganese or a mixture of the two. In mixed pigments the ratio of ores may be of value for identification.

One of the interesting questions in connection with mineral paint is the nature of the binder. Finely ground iron oxide alone does not flux or sinter upon firing at temperatures within the Pueblo range. Paint of this type consequently remains in a powdery condition and is easily rubbed.<sup>1</sup> The ground mineral mixed only with water is also difficult to apply. Some modern Pueblo potters add *guaco* to the ore which gives it good spreading quality and also binds it when dry and before firing, thus making it easier to handle. Hawley has assumed that a vegetable paint was also used with all prehistoric iron paints and that the postulated silicate films supposed to be formed on the firing of organic paint also served as a binder for the mineral paint.<sup>2</sup> Evidently on the basis of this assumption the oxidation test for iron was called by this writer the "iron and carbon test," though it gives no indication whatsoever of the presence of carbon. The ferrocyanide test for iron is described as an alternative for the oxidation test to be used in doubtful cases, and in this connection the statement is made that if carbon is present it will be seen as minute black particles floating in the solution; also in doubtful tests for organic pigment the determination of carbon with an aspirator is suggested, but there is no assurance that actual tests for carbon were made for all the prehistoric types which have been classed as iron and carbon paints. Anyone who has used ground mineral paint both alone and mixed with plant extract will appreciate the advantage of the latter in consistency and even flow from the brush and will realize that this one advantage justifies its use, even though its function ceases there. However, not all modern Pueblo potters follow this practice. The women of Zia Pueblo at present prepare pigment from small oölitic iron manganese concretions which they find in the débris from a weathered stratum of Cretaceous sandstone six to eight miles from their village. Some potters use only the ground mineral, others mix it with ocher clay to improve its spreading qualities and permanence. Paint of the former type especially is not made permanent by firing, but the potters claim that when it is soaked in water (which is hard), it is fixed, and, as a matter of fact, the paint is not easily rubbed on vessels, which they show to substantiate this statement. This is a distinct

<sup>1</sup>The relative impermanence of iron ore alone is illustrated by the class of pigments commonly referred to as "fugitive reds" which are found particularly on Pueblo pottery from early horizons. It is probable, though still to be proven, that these paints differ from the later, permanent reds which replaced them in the ratio of ferric oxide to clay. Hematite relatively free from clay has no binder, is rubbed or washed from the vessel, and is readily attacked by acids. A ferruginous clay which has a high enough iron content to burn to a bright red is bound by the clay which is not easily soluble in acids.

<sup>2</sup>1929, pp. 736, 741-742.

problem in itself. It may be that the loose pigment is washed off or that with the evaporation of water some salts which act as a mechanical binder are deposited on the surface. The addition of clay, of course, tends to bind the pigment but the amount required gives the paint a distinct grayish cast. The practice of the Zia potters serves to emphasize the fact that the mixture of organic paint with mineral in prehistoric times requires proof. However, the absence of carbon in mineral paint will not necessarily show that it was not used, for in some instances it may have been so completely oxidized that only the mineral matter remained.

The evidence which has been presented regarding the relative inactivity of the ash in organic paint applies equally to the assumption that organic matter served as a binder for mineral paint after firing. Moreover, this theory has been checked experimentally. *Guaco* in various percentages has been added to Zuñi and Zia pigments and in no instance did it bind or increase the permanence of the mineral paint. It is possible that natural fluxes, as alkalies, or borax, occurred with the ores or were introduced into the mineral paint; and the fact that certain of the mineral paints are occasionally glazed or fused in places lends support to this theory. It is also interesting to note in this connection that the addition of an alkali such as sodium carbonate to mineral paint improves its consistency, so that use of a plant gum is entirely unnecessary. It is possible that some iron was reduced to the ferrous state, in which it would flux at a much lower temperature than in the ferric. Hawley describes the iron paints as "red iron oxide ( $Fe_2O_3$ ), or yellow iron oxide ( $2Fe_2O_3 \cdot 2H_2O$ ), which burns to  $Fe_2O_3$ ," and evidently thinks that magnetite would not be oxidized or ferric oxide reduced in firing.<sup>1</sup> But it has been demonstrated experimentally that the condition of the iron may be changed in firing and its original condition can only be proved by the discovery of the unfired pigment. Paint stones, mortars with paint adhering to them or unfired pottery, which may be found in excavations, would answer this question. Hematite heated in a reducing flame becomes magnetic while magnetite or ferrosoferric oxide loses its magnetism upon heating in the oxidizing flame. It is of interest, therefore, to learn whether iron paints are magnetic. Magnetic property is tested by scraping some of the paint free from the surface and determining whether it is attracted by a magnet.

The questions relating to mineral pigments, though of an entirely different order than those considered under organic paints, also require synthetic experiments and show the importance of firing conditions and physical and chemical changes in clay and pigment.

#### DETERMINATION OF FIRING TEMPERATURE

The temperatures attained in the firing of pottery in prehistoric times have long been a matter of speculation. Some idea of the possibilities can be obtained by measuring the temperatures used by primitive potters of the present day and by experimenting with various methods of simple, flame-exposed, non-kiln firing. For this purpose a reliable means of determining temperatures is required. The pyrometric cones used in commercial ceramic work are unsuitable because they are

<sup>1</sup>1929, p. 736.

affected by reducing gases sometimes present in the firing atmosphere and also by length of heating as well as temperature—with a slow fire they will bend at a lower temperature than with a rapid fire. A thermoelectric pyrometer has proved to be the most accurate and convenient instrument for temperature measurement, both in the field and in the laboratory. A portable type is used with a "chromel-alumel" thermocouple. This instrument is based on the principle that two different metals in contact set up an electromotive force when heated, the current produced being directly proportional to temperature. The thermocouple, made of two wires—one of which is a nickel-chromium alloy and the other a nickel-aluminum alloy—fused at the ends but insulated for the remainder of their length and covered by a protecting tube, is placed at the point at which temperature is to be recorded. The free ends of the wires are connected with the binding posts of a potentiometer or pyrometer, which records the current in millivolts or is calibrated to read temperature directly. The simple tube of the thermocouple does not arouse the suspicions of the Indian, and temperatures are read at short and regular intervals so that a time-temperature curve of the firing can be plotted. If a porcelain protecting tube is used, it is necessary to calculate the lag which it produces; a silica protecting tube is more satisfactory because it introduces no appreciable lag and will not crack with sudden and extreme changes in temperature.<sup>1</sup>

Excavations have yielded no evidence as to the way in which the prehistoric Pueblo potter fired. Her modern descendant goes to our refuse heaps for tire rims, flattened springs, scraps of sheet iron and other odds and ends with which to make a grate and to cover the pots. Fuel, too, has changed, for the prehistoric potter did not have the cow or sheep dung now used by the Pueblos. In spite of these differences there is much to be learned from the modern potter, and experiments can be made with wood fuel to compare temperatures and results. Juniper wood furnishes the best fuel generally available in this region. It gives a much less smoky fire than either pine or piñon. Factors which determine temperature are rate of combustion and amount of heat lost through radiation; the rate of combustion is itself influenced by the kind and condition of fuel and by draft. Dung burns out very quickly because the combustible material is in a fine state of division. A wood fire will burn longer than one of dung if reasonably large pieces of wood (four to five inches in diameter) are used, and length of firing as well as maximum temperature affects the hardness of the vessel. Dung contains a much higher per cent of ash than wood,<sup>2</sup> and the ash left on the surface of dung chips acts as an insulator; radiation is thus reduced, but if fresh fuel is added on top of the old, less heat passes inward to the pottery. With the same fuel and method of firing, the highest temperatures can be attained when there is a strong wind giving a good draft. The potter, however, would avoid firing on a windy day because of the difficulty of controlling the fire, the danger of uneven heating and of suddenly chilling and cracking the vessels. With these conditions in mind, the question of the minimum and maximum temperatures used by

<sup>1</sup>For a discussion of principles and methods of high temperature measurement see Foote, Fairchild, and Harrison, 1921.

<sup>2</sup>From 14.8 to 29.2% of ash was found in cow dung—the variation being due to amount of dust collected in drying—and 0.92% of ash in seasoned juniper.

the primitive potter can partially be answered. The minimum temperature will be limited by the necessity of firing the clay sufficiently to produce a strong and durable vessel and will vary with the degree of refractoriness of the particular clay used. Many clays would disintegrate in water unless heated above 600° C. The lowest temperature so far recorded from the Pueblos is 625° C. This was at Santa Clara Pueblo in the firing of a large *tinajon* made from a non-refractory, red-burning, alluvial clay. The highest Pueblo firing temperature recorded to date is 940° C., which was attained by a Zia potter when firing forty small bowls on a windy day. The maximum temperature which has been obtained to date in experimental direct firing is 1020° C. This was with juniper fuel on a moderately quiet day, and maximum temperature was reached in thirty-eight minutes.

It is evident from the above firing records that the prehistoric Pueblo potter had a possible temperature range of at least 400° C. It becomes therefore a matter of considerable interest to compare the firing temperatures used for different wares and in different periods. Were some types of pottery intentionally fired higher than others? Is there evidence of improvement in firing as time advanced? Or were there simply low firings and high firings in every period, just as there must have been careless and careful craftsmen? These questions justify the effort to determine how vessels were fired. But this cannot be done as simply and directly as temperatures are measured, nor can as definite and exact results be expected. The problem becomes one of recognizing evidences of temperature in the condition of either the clay or the mineral inclusions. Geophysicists have devoted much time to the development of what has been called a "geologic thermometer," that is, a series of minerals which have two or more forms depending upon the temperature at which they crystallize and whose presence in rock, therefore, shows within certain limits the temperature of the original molten rock magma. It is possible that similarly a "ceramic thermometer" may be worked out when the changes produced in minerals by the particular kind of heat treatment received in primitive firing has been fully investigated. A few of the most promising temperature indicators have been studied.

The changes produced in minerals by heating are of two kinds: changes in crystal form and molecular arrangement—termed inversions—and changes in chemical composition, such as loss of water or carbon dioxide. Quartz furnishes a good illustration of inversion; at 572° C.  $\pm$  5° C. its crystal form is altered and it undergoes a 2% change in volume; at 870° C. it changes to tridymite, which in turn changes to cristobalite at 1470° C.<sup>1</sup> All four forms are identical in chemical composition, but their physical and optic properties differ because of molecular rearrangements. In view of the abundance and ubiquitous occurrence of quartz, these inversion points would be particularly useful temperature indicators in ceramic investigations were it not for the fact that they are reversible and often take place sluggishly and only under favorable conditions. Consequently, inversion might not occur with short, rapid firing and even if it did the quartz would in time reassume its original and more stable form. The change in volume which accompanies the low temperature inversion sometimes shatters the quartz, but this would not occur

<sup>1</sup>Wright and Larsen, 1909.

with the small grains found in pottery. Quartz has, therefore, been abandoned as a ceramic temperature indicator. All mineral inversions have not yet been exhaustively studied and it is possible that some may be found which will be useful to the ceramist, but it must be remembered that both low and high temperature forms may occur in nature and it is necessary to determine in some way the original state of the mineral—that in which it was introduced into the clay—before it can be used as a temperature indicator.

Hydrous minerals and the carbonates are the principal minerals whose composition is changed with moderate heating. Calcite is one of the commonest carbonates and has proved a useful temperature indicator. Fragments of calcite heated under certain conditions decompose and carbon dioxide is driven off, leaving calcium oxide which absorbs moisture to form calcium hydrate. The cycle may be completed if calcium hydrate unites with carbon dioxide of the atmosphere again to form calcium carbonate. But although the chemical composition of the calcite and this end product are identical, the two differ in appearance sufficiently to be easily distinguishable; calcite occurs in clear homogeneous fragments usually showing cleavages and acting as a unit optically, but after it has been calcined, hydrated and carbonated, it appears as aggregates of minute granules, lacking uniform orientation. Therefore, if particles of calcite are found in pottery, it is evident that the temperature at which calcination takes place was not reached in the original firing, but if there is free lime in the paste or if large calcined fragments occur, the temperature of calcination was exceeded. Calcination is sometimes shown by "popping" on the surface of the vessel. It is essential to record this condition since it is an important temperature indicator. The lime expands upon hydration and if the particle is large and near the surface of the vessel it will force off a flake. A little whitish material at the center of the rough and slightly conical area left by this fine spalling usually indicates the presence of lime, but in case there is any doubt the substance should be tested for calcium. If the calcite is in a fine state of division there will be no "popping" but minute whitish particles may sometimes be detected microscopically. These are so soft that they would have been disseminated when the clay was kneaded had they originally occurred in this state.<sup>1</sup>

<sup>1</sup>In the absence of visible particles which can be tested for calcium it is difficult to prove the presence of free lime in the paste. The determination of calcium hydroxide in the paste is based on an alkaline reaction with phenolphthalein followed by microchemical identification of lime as oxalate. If lime is found it may have been derived from calcium sulphate which has approximately the same solubility as calcium hydroxide and the pink color with phenolphthalein also is produced by other bases. The filtrate from the calcium oxalate should, therefore, be tested for sulphates. If sulphate is present in significant amount, it is necessary to make a quantitative determination of acids and bases in the water extract. Calcium bicarbonate is more soluble than calcium hydroxide but cannot occur with calcium hydroxide and an alkaline reaction with phenolphthalein shows its absence. Calcium carbonate gives a very faint alkaline reaction but only 0.0013 parts are taken in solution in cold water compared with 0.17 parts of calcium hydroxide.

If sherds are treated with hydrochloric acid when cleaned, the lime test is valueless. It may seem surprising that calcium should be present in the caustic state, but Mellor reports (1916, p. 332) that mortars in some ancient Roman buildings contain inner cores of calcium hydroxide after an exposure of 2000 years. Its existence in pottery is still to be proven. Some sherds showing clear evidence of "popping" gave no test for free lime, probably because the hydroxide had been reconverted to carbonate by exposure to the air.

The calcination of calcium carbonate does not commence and go to completion at a given temperature, as might be supposed from some published statements.<sup>1</sup> When calcium carbonate is heated the pressure of carbon dioxide in the atmosphere and in the kiln gases tends to counteract dissociation. Calcium carbonate is stable at ordinary temperatures because the pressure of the atmospheric carbon dioxide is greater than the dissociation pressure but they become equal at a temperature near 600° C. and at 898° C. the dissociation pressure equals the total atmospheric pressure.<sup>2</sup> If therefore, calcium carbonate is heated long enough at a temperature just above 600° C. all of the carbon dioxide will be liberated, while the change will be almost immediate at the "dissociation temperature." It has been found that impurities lower the dissociation temperature; 888° C. having been recorded for an impure limestone. In the present study, samples of Iceland spar, a very pure form of calcite, were heated in an electric resistance furnace with accurate temperature control to gain some idea of the rate of dissociation within the temperature range and with the rate of heat increase commonly obtained in primitive firing. The surface of crystals held at 700° C. for five minutes became milky from dissociation and films varying from 0.1 and 0.3 mm. in thickness were formed when this temperature was held for an hour; the same depth of calcination was obtained with ten minutes heating at 800° C.; heated for ten minutes at 850° C. the film was 0.4 mm. and for three minutes at 900° 0.6 mm. in thickness. It is evident that both time and temperature must be considered. A third factor which enters is the amount of carbon dioxide in the kiln atmosphere. The experiments with Iceland spar were made under normal atmospheric conditions, but in primitive firing, excess carbon dioxide from the combustion of fuel is present in the atmosphere surrounding the pots which retards the rate of calcination. Particles of calcite were fired both with dung and with wood fuel to compare the rate of decomposition with that obtained in the electric resistance furnace. The results indicated only a slight and scarcely measurable decrease in rate of calcination.

Therefore, instead of marking a specific temperature, calcite indicates a certain temperature range. If large fragments show no evidence of calcination and if undisturbed faces are fresh and clear, the firing temperature certainly could not have reached 800° C. and probably was not held at 700° C. for any length of time.<sup>3</sup> If, on the other hand, large fragments (1 mm. in diameter for example) have produced "popping," it is probable that the fire was held at 800° C. for at least half an hour, or that a temperature of 850° C. or more was attained with rapid heating. In the discussion of the Pecos material, the condition of the calcite has been mentioned specifically rather than the probable temperature indicated, and it will be convenient

<sup>1</sup>Speiser, 1933, p. 283: "...calcium carbonate does not begin to decompose into calcium oxide and carbon dioxide until a temperature of 1537° F. has been reached." (1537° F. = 836° C.).

<sup>2</sup>Wilson, 1927, pp. 154-155.

<sup>3</sup>Caution must be exercised in judging the degree of calcination from the appearance of fragments seen in a fresh break because the calcined layer tends to separate and break away from the uncalcined part of the crystal, and this is particularly likely to happen when the sherd is fractured. With thin sections and high magnification it should be possible to determine the extent of calcination from an examination of the contact zone of crystal and clay.

simply to remember that the presence of calcite shows that the heat treatment was low in terms of Pueblo firing and that definitely calcined material indicates a medium or high range, though it cannot be determined how far the temperature of calcination was exceeded.

The discussion of calcite as a thermal indicator is based largely on microscopic observation, but the same evidence has been studied by means of chemical analysis, the presence of calcium carbonate being inferred from carbon dioxide obtained in the analysis.<sup>1</sup> Carbon dioxide liberated upon digestion with hydrochloric acid would be derived from carbonates but that obtained from ignition of the sample might come from either the decomposition of calcium carbonate or the oxidation of carbon in the paste, and, as both reactions take place within the same temperature range, carbon dioxide from these two sources could not be distinguished. The chemical method used alone is of uncertain value because the condition and source of the carbonate of lime is not determined. Shards lying in the earth are sometimes impregnated with calcium carbonate from soil water and this fact would completely vitiate results of the chemical method. A secondary deposit is easily distinguishable from calcite with the petrographic microscope, and an additional advantage of the microscope, as compared with chemical analysis, is the fact that it shows the extent of decomposition, whereas with the chemical method the presence of a considerable amount of carbon dioxide may result either from a large amount of carbonate partially decomposed or from a smaller quantity unaffected in firing.

Other minerals which give promise of indicating firing temperatures may be briefly mentioned. Some varieties of chlorite, hydrous silicates of aluminum, magnesium and ferrous iron, change in color from green to brown when heated to 650° C. They resemble biotite superficially after firing. As there are a number of varieties of chlorite and closely related hydrous minerals additional experiments should be made. Muscovite, the potash mica, is also dehydrated upon heating and becomes gray and opaque. This change is familiar to everyone, for it takes place when the mica or isinglass windows of a range become opaque and somewhat opalescent. Repeated thermal experiments have shown that the temperature of dehydration of mica is somewhat variable, taking place between 900° and 950° C. with rapid firing—samples being brought to temperature in from thirty to forty minutes and held five minutes. Muscovite, therefore, furnishes another critical point in our ceramic thermometer. Small flakes of mica of uncertain composition, leached biotite for example, are not uncommon in pottery and, since they may not give as clear evidence of dehydration as muscovite, sherds should be reheated to the temperature in question and the condition of the mica then compared with the original. Thin sections are not generally necessary for this purpose because flakes can be picked out of the sherds with the aid of a binocular microscope and examined in refractive liquids. Evidence of dehydration of mica may sometimes be observed megascopically, for the expansion of plates just beneath the surface tends to force off thin flakes of clay, consequently mica which appears to be lying on the surface is seen upon careful inspection to be slightly depressed and the paste bounding it is irregular and

<sup>1</sup>Speiser, 1933, p. 283.

fractured. The change in chlorite and mica is due to dehydration, the rate of which is affected by time and temperature of firing but not by the character of the atmosphere.

The minerals discussed might all be found as natural inclusions or as part of the tempering material in pottery, since they are of common occurrence. But the clay minerals themselves of which the clay base is largely composed also undergo interesting and significant changes upon firing. The water of crystallization is first driven off and more complex changes, including the dissociation of the aluminum silicate, take place at higher temperatures. Optical properties are affected when the crystalline structure is broken down; the mineral ceases to be doubly refracting and acts upon light in the same way as an amorphous substance. Consequently, if the clay material is birefringent, and even though individual crystalline particles cannot be distinguished, it is known that the clay has not been heated high enough to destroy its normal molecular arrangement. The refractive index also changes upon heating, but instead of a single complete change, values vary with temperature but not uniformly or without interruption. Specific reference data for the use of clay minerals as temperature indicators could be given if the body clays were pure and unmixed with other substances and had the thermal behavior of the clay minerals been fully investigated. But practically all pottery clays are of mixed and uncertain composition and few studies of thermal changes have been made. Hence experiments must be made with each particular paste being investigated.<sup>1</sup> If the clay base of a sherd is isotropic, it will not be possible to tell whether this was its original condition or whether a crystalline structure has been broken down in the firing. But if the paste is birefringent, it is necessary only to make a few accurately controlled firings to determine at what temperature it becomes isotropic. This sets an upper limit above which it could not originally have been fired. The temperature at which this change occurs will vary greatly depending upon the particular clay mineral and impurities present. Studies made in connection with the Pecos investigation indicate that kaolinite in kaolin becomes isotropic at a considerably higher temperature than montmorillonite in bentonite, as might be expected from the difference in their relative refractoriness. Changes in the refractive indices of clay are less promising as temperature indicators than loss of birefringence because of their variability and complexity. If the raw clay from which a vessel was made is available, a study of its thermal behavior and comparison of refractive indices may offer some evidence. The rare discovery in excavations of potters' caches may establish the use of a particular clay.

Physical properties of the paste and its fusion point have sometimes been used as temperature indicators. The density of the paste is continually changing during firing; it decreases and the paste becomes more open when dehydrated but at some temperature above the point at which dehydration is completed, density commences to increase and this process continues until a condition of complete vitrification is

<sup>1</sup>For data on thermal behavior of clay see

Rhode, 1927, pp. 383-401, 414-415, 434-435, 452-454, 470-471.

Kraner, 1924, pp. 726-734.

reached. The accompanying change in volume can be measured as linear shrinkage, and porosity likewise indicates relative density. Therefore, after refiring a sherd to given temperatures these two properties can be measured and their values compared with the original. A distinct difference may be shown if the firing temperature has been exceeded, but in some pastes only slight changes occur over a considerable temperature range. The presence of unoxidized substances, such as carbon in the paste, will introduce an error. The softening and fusing point of clay or its pyrometric cone equivalent is determined by forming small tetrahedrons of clay corresponding in size and shape to the pyrometric cones of commercial practice (7 mm. along the edge of the base and 30 mm. high).<sup>1</sup> These are set in a base at an angle of 82° to the horizontal and fired. The softening point is the temperature at which the tip commences to bend and the fusion point the temperature at which it touches the base. This test not only shows fusion point but also, by the time required for the cone to bend, records the temperature range between initial and complete vitrification. In other words, it serves to distinguish between clays which vitrify suddenly and are subject to distortion if the vitrification point is reached and those which vitrify more slowly and so may safely be carried to this point. The fusion point of the paste of a sherd has been used to determine an upper limit which must exceed the original firing temperature if the sherd shows no sign of vitrification.<sup>2</sup> The value of the test is doubtful because texture as well as composition affect vitrification. The fusion point of two clays having the same chemical composition will differ with grain size for vitrification is promoted by fineness of grain and the close contact of particles. A consideration of this fact will show that such a test cannot be a reliable indicator of the fusion point of the paste, for when the sherd is ground the clay substance probably will not be brought to its original fineness, whereas medium or coarse temper, if present, will be reduced to a much finer condition, and two unknowns are thus introduced to vitiate results.

Considering all factors, therefore, changes in minerals detected optically are the most reliable temperature indicators. These mineral indicators may be compared to the pyrometric cone because they are affected by length of heating as well as temperature and reflect total heat treatment but do not specifically record maximum temperature. Even with these limitations they furnish important evidence and are especially valuable if two or more can be found in the same specimen.

#### DESCRIPTION OF PHYSICAL PROPERTIES

The adequate description of certain ceramic properties is difficult because we lack accepted standards of comparison and methods of measurement. Consequently, there is a current belief among archaeologists that many of the characteristics of pottery cannot satisfactorily be defined or described, although they are recognized with certainty by the experienced individual. Forms are accurately recorded by specified measurements, illustration, and the calculation of certain ratios; a satisfactory nomenclature of vessel forms is becoming established. Design

<sup>1</sup>Journ. Am. Ceram. Soc., Vol. XI, No. 6, p. 452.

<sup>2</sup>Speiser, 1933, pp. 282-3.

likewise has been treated analytically. But properties such as color, texture, hardness, density and porosity, which are also significant, are described in relative terms and with reference to subjective standards; such descriptions are of limited value or even confusing. The statement that a paste is gray, fine, hard, well kneaded or levigated means very little unless one is familiar with the range of pastes which form the basis of judgment. Such terms as well kneaded or levigated are particularly objectionable, since they designate processes in the preparation of clay which cannot be proven from observation of the paste. The physical properties of the vessel are important because they affect its appearance, durability and usefulness; and since they are determined by the materials used and the method of firing, they throw light on composition and technique. The principal physical properties of pottery have been defined, and standards of description together with methods of measurement have been adopted in the field of commercial ceramics.<sup>1</sup> Many of these can be adapted to archaeological purposes and a few, which measure properties of particular significance, have been tested and applied in the present study as well as certain standards which have found acceptance in other fields.

*Color*, being one of the most striking properties of pottery, has received considerable attention in published descriptions and has been much used as a classificational criterion. The color of clays when fired influences the aesthetic value of pottery, and since color is determined by the composition of the clay, together with firing temperature and atmosphere, it records evidence of these factors. Like the patterns of finger prints, its variations are infinite, but its value in recording distinctions is proportional to the accuracy of color designation. The vagueness and limitations of the color vocabulary of the average individual are so well recognized, that it hardly seems necessary to urge the need of a standard color scale and nomenclature. But it may be argued that the range of color variations of a single clay fired under different conditions is so great that exact color description is impracticable, and such general terms as red, brown, gray, buff, etc. are sufficient for the needs of the archaeologist. This objection simply raises the question whether we shall take advantage of the innumerable and often subtle variations in pottery to build up a body of significant data, or allow ourselves to become confused and discouraged in the attempt to understand the evidence before us. A standard for color description is essential both in comparative studies of pottery types and for analysis of the color range of clays, pigments, and glazes with varying firing conditions.

Colors are most easily defined by comparison with a recognized standard color scale. A number of these have been published, but *Color Standards and Color Nomenclature* by Robert Ridgway<sup>2</sup> is the most widely used by scientists. It has been the standard of reference for zoologists and botanists for over two decades and more recently has been used for ceramic descriptions both in archaeological studies and in commercial work.<sup>3</sup> In the present investigation it has proved entirely satisfactory in range, distribution, grading and arrangement of colors, and a copy used in this

<sup>1</sup>See *Journ. Am. Ceram. Soc.*, Vol. XI, No. 6, for standard definitions and tests adopted by the American Ceramic Society.

<sup>2</sup>Ridgway, 1912.

<sup>3</sup>Bradfield, 1931, pp. 30-39. Dietrich, 1928, pp. 248-252.

work for six years shows no fading or change in colors. The fact that it has become a well established standard through its general acceptance by scientists is also in its favor.

Ridgway's arrangement of color is logical and convenient. The key to the system is the series of thirty-six pure colors—the spectrum colors and intermediate hues—which are arranged horizontally across the center of a series of twelve plates. In the column above each color are three of its tints, made by adding given percentages of white to the pure color, and below are three shades formed by the addition of black. Five succeeding sets of plates repeat the colors of the first twelve with increasing amounts of neutral gray. The hues are designated by odd numerals, tints by the letters *b*, *d* and *f*, shades by the letters *i*, *k* and *m* and the five series of grayed colors or values by the symbols ' to '''. The use of odd numbers and alternate letters permits the designation of intermediate colors and so increases their number within the scale. The three color variables, indicated by number, letter and prime in the Ridgway system, express fundamental properties of color. Hue or position of the color in the spectrum scale is determined by the wave length of light; the intensity of color, by which light colors are distinguished from dark or tints from shades, is dependent upon the amplitude of the light wave, and the grayed colors or values are a measure of the relative purity of one wave length as separated from all others. Familiarity with this system enables one to tell at once from the number-letter-prime symbol, the position of a color in the spectrum scale, whether it is a tint or a shade and the degree to which it has been grayed. For example, 9'i is orange red-orange (20% red and 80% orange) with 45% black and the whole modified by 32% neutral gray. Outside of the grays the colors of fired clays fall principally between Ridgway's 5 (orange orange-red) and 23 (yellow), and unmodified colors occur only in the glazes. In the common use of color names, Ridgway's 1 to 5 would be red, 9 to 15 orange, and 17 to 23, yellow; the *f* tones are very light or pale, and the *k* tones in the series of hues from 7 to 17 would be classed as browns, the *m* tones as dark browns. The brightest or clearest clay colors are one prime; three primes are dull and the five primes are grays. Ridgway's names, as well as the symbols, have been used in the present study, but it is believed that the symbols will prove more satisfactory, once the system is known. In this report color names not capitalized are used in a general sense, as in reference to a color range, and the Ridgway system has seldom been applied to colors observed microscopically because of the difficulty of making accurate readings.

Some experience and certain precautions are required for accurate color reading, and at the start the exactness of one's color matching should be checked by individuals with experience and training in this line. It is important to hold the object being matched in the same plane as the color plate; the angle at which light strikes the plate and is reflected to the eye should be approximately equal. A north light is preferable, and readings should never be made in direct sunlight. The object being matched should be held as close to the standard color as possible, and in matching the paste color of sherds it will be found convenient to break off a small flake which can be held against the plate. When making a reading it is also advisable to block all colors on the plate except the one being compared and if a polychrome

sherd or one combining distinct colors is being matched, a mask should also be used on the specimen. Frequent mottling of the surface, as well as differences in texture and luster may be confusing and increase the difficulty of matching. It is sometimes helpful to regard the colors at arm's length or with partly closed lids. Colors not matched in the Ridgway standard can always be accurately classified by the system and thus satisfactorily designated.<sup>1</sup>

<sup>1</sup>Since the above was written the desirability of a standard of color description has been ably discussed by March (1934, pp. 23-30). March has used *A Dictionary of Color* by A. Maerz and M. Rea Paul in preference to Ridgway's Standard and gives three reasons for his choice, namely, that the number of colors given by Ridgway is relatively small (1,115 as compared with 7,000 in the *Dictionary of Color*), that the Ridgway plates are more subject to light and must be handled with care, and finally that Ridgway's nomenclature is faulty. March tested both works in matching the colors of Chinese porcelains. A comparison of the two systems was subsequently made in the study of the Pecos material, and since a wide range of clays, subjected to the varying temperatures and atmospheres obtaining in direct firing, are included in this material, it may be considered reasonably representative of primitive pottery in general. In these tests, Ridgway was found to be more useful as a standard and the objections pointed out by March proved no serious detriment.

The value of a color scale cannot be judged simply by the number of colors given, we are concerned also with the completeness and uniformity with which the entire color range is represented; a large number of colors may simply mean that fine variations are given in certain ranges only and wide gaps left in others. In respect to range and uniformity of distribution Ridgway has been found more satisfactory than the *Dictionary of Color*. The change from hue to hue and tint to tint in the latter is very slight, actually much closer than is required by the student of primitive ceramics, for a number of colors would have to be named in most designations because of the slight variations which generally occur. It is even questionable whether the majority of individuals would always match to the same color in certain ranges of this system. On the other hand, the difference between values and in some cases between tints and hues is much greater. Ridgway's colors are more evenly graded and cover the total color range more completely. The limitations of *A Dictionary of Color* are noticed particularly when matching the deep browns. Shades in the range of Ridgway's 5'm to 17'm are not represented. These colors are important to the student of primitive ceramics. The grays in the *Dictionary of Color* are generally less neutral than Ridgway's and the plates of grays in the latter greatly facilitate matching. In using Ridgway one is not actually limited to the colors illustrated, since allowance is made in the system for the designation of colors intermediate in hue or intensity, and there is never any question as to the position of a given color; it can be accurately defined by reference to the colors illustrated. Interpolations are not as easily made in the *Dictionary of Color* because of an entirely different and unusual system of arrangement.

The publishers of Ridgway's Standard warn against unnecessary exposure of the plates to light. However, permanence of the colors is best tested by comparing volumes which have received long and constant use with new ones. Such comparisons have shown that Ridgway is reliable in this respect.

The criticism of Ridgway's nomenclature is not without foundation; however, the fact that some of the adjectives are confusing, that priority was not invariably recognized and that commercial names are included does not seriously impair the value of the standard. Symbols are here used in preference to names, since hue, value and intensity of the color are definitely indicated by the symbol, which is a decided advantage. In *A Dictionary of Color* the plate number, file letter and rank number designate the color but bear no logical relation to its position in the color scale and reference must, therefore, always be made to the work to visualize the color.

There are two principal advantages in the Ridgway system as compared with that of Maerz and Paul which fully justify its retention as the standard of comparison in ceramic studies. The composition of colors is fully defined and the range is uniformly represented. The Maerz and Paul volume, on the other hand, is, as its name indicates, a dictionary; it includes the largest number of colors available in any work of this kind, but the colors are not defined nor uniformly distributed. In the second place Ridgway's arrangement and designation of color is logical and convenient and automatically trains the user in color reading, while the only guide in matching colors in the *Dictionary of Color* is spectral arrangement.

*Hardness* has been defined as resistance to abrasion. Its importance to the potter is well illustrated by differences in slips. In a random lot of sherds there will be some which are as smooth surfaced and fine as when first made, and others having slips which are rough and, in places, completely worn away. The hardness of pottery is affected principally by two factors, refractoriness of clay and firing treatment, although paste texture also influences vitrification point and consequent hardness. Therefore, conclusions regarding either firing temperature or quality of the paste cannot be drawn from the determination of this property alone. The hardness of pottery is difficult to measure, particularly since pastes are non-homogeneous. The bond is most often determined by this test. Estimates of hardness are sometimes made by scratching the surface with a steel point or fracturing the sherd with pliers. In the American Ceramic Society's discussion of standards it is suggested that this property be tested by "noting the relative hardness of trials as compared with steel."<sup>1</sup> Since comparatively few wares in the archaeological field are as hard as or harder than steel, and estimates of the relative ease of scratching will vary, such a test does not meet the archaeologist's requirements. In order to eliminate personal judgment as far as possible, a number of standards of reference within the range represented by pottery is necessary and such a series is supplied by the minerals of Mohs' scale of hardness, which is commonly used by geologists. A high degree of accuracy cannot be claimed for this method and the scale is not evenly divided. However, absolute accuracy in the determination of hardness is not required by the archaeologist, but rather a standard reference by which four or five degrees of hardness within the ceramic range can uniformly and consistently be recorded. This requirement is met by Mohs' scale. The minerals most used are calcite, fluorite, apatite, orthoclase and quartz, which number three to seven in the scale.

A paste which is scratched by one mineral but scratches the one next lower in the scale is recorded as plus or minus the number of the nearer mineral, or if it is approximately midway between two minerals, it is indicated by adding half to the number of the softer mineral. As hard inclusions in the paste influence judgment, the coarsely tempered, friable pastes of culinary wares will be found most difficult to test. A surface which has been compacted by smoothing and polishing will be harder than the paste; determination of the latter should, therefore, be made on an unpolished surface or on a fractured edge which has been smoothed. A good point should be kept on the mineral, a relatively uniform pressure applied and care exercised to distinguish a scratch from the streak left by a mineral rubbed on a harder surface. If one proceeds from the harder to the softer minerals in testing, unnecessary wear of the soft minerals will be avoided.<sup>2</sup>

<sup>1</sup>Journ. Am. Ceram. Soc., Vol. XI, No. 6, p. 457.

<sup>2</sup>Since the above was written, the adoption of Mohs' scale in ceramic studies has been recommended by March (1934, pp. 17-22). He has also suggested the introduction of additional minerals to form half steps in Mohs' scale. These have not been used in the Pecos study as the limitations in the accuracy of the methods do not seem to justify small subdivisions of the scale. The reliability of chabazite to measure a hardness of 4.5 is particularly questionable, since its hardness varies from 4 to 5 (Dana, 1892, p. 590). March states (p. 21) that minerals from 2 to 4.5 inclusive are ". . . adequate to meet the needs of archaeologists working in the American field, for extensive experiments in the Ceramic Repository in the Museum of Anthropology have revealed nothing harder than 4.5." Pastes harder than 4.5 however, have been found among Pueblo types, and the archaeologist should be supplied with the minerals of Mohs' scale up to and including quartz.

*Strength.* The difference in thickness of sherds and their curvature have been obstacles in measuring the strength of pottery. Moreover, the significance of the data has been questioned because of the considerable variation in this property which naturally results from the uncertainty of primitive methods; overlapping of types is to be expected, and possibly only slight differences will be found in the average strength of the majority of types. But this supposition should be put to test, and, furthermore, if we are to understand the materials with which we deal, the strength of clays must be determined and the effect of various kinds and amounts of tempering materials studied.

Different methods of measuring transverse breaking strength have been tested by applying them both to sherds and to specially prepared test pieces. Experiments were first made with a fracture machine employing a lever, but an apparatus in which weight is applied directly was found more accurate and reliable. Sherds are cut with a carborundum wheel  $\frac{5}{32}$  of an inch in thickness and 7 inches in diameter having a speed of 3500 revolutions per minute. The pieces, approximately  $\frac{1}{2}$  inch wide by  $1\frac{1}{2}$  inches long, rest on two knife edges set 1 inch apart. Pressure is applied through an upper knife edge by turning, at a uniform rate, the wheel below the dynamometer. The breaking weight is recorded directly on the dial of the dynamometer. To calculate the transverse breaking strength of the sherd in pounds per square inch the formula for modulus of rupture is used:

$$R = \frac{3Pl}{2bd^2}$$

In which:

R = modulus of rupture in pounds per square inch

P = breaking load in pounds

l = distance between supporting knife edges in inches

b = breadth of test piece in inches

d = depth or thickness of test piece in inches

Since the distance between the supporting knife edges is constant and unity, the numerator of the formula is simplified to  $3P$ , and if the test sherd is cut  $\frac{1}{2}$  inch in width the denominator is reduced to  $d^2$ ; it is then only necessary to record the breaking load and take a micrometer measurement of the thickness of the piece.<sup>1</sup> The American Ceramic Society, in describing this test, specifies that a minimum of ten specimens of each type be broken, any varying more than 15% from the average discarded and if more than two are discarded the clay retested.<sup>2</sup> This applies to clay tests prepared and fired under identical conditions. Sherds containing a variable amount and grade of temper and having been fired to different temperatures will differ more than 15% from the average. But these normal variations must be dis-

<sup>1</sup>It was necessary to follow the English system in building the fracture machine because the dynamometer reads in pounds. But it has been deemed advisable to adhere consistently to the metric system throughout this report and modulus of rupture calculated in pounds per square inch has therefore been converted to kilograms per square centimeter by using the factor 0.07.

<sup>2</sup>Journ. Am. Ceram. Soc., Vol. XI, No. 6; Tentative test methods, p. 461.

tinguished from those caused by flaws, therefore, in the Pecos study ten sherds of a type were tested and those which varied more than 15% from the average retested and the results included only when the breaking load was consistent.

The two most obvious factors which might vitiate the results of such a test when applied to pottery are curvature and differences in thickness, the latter factor being considered because surfaces compacted by polishing bear a different ratio to the normal paste in thick sherds than in thin sherds. Experiments were, therefore, made to test the applicability of the method to sherds, over a hundred test pieces being prepared for the purpose. In studying the effect of variation in thickness five sets of test pieces, ranging from 3.8 to 8.9 mm. in thickness, with differences of 1.25 mm. between sets, were used. This practically covers the range found in vessel walls. The test pieces were identical in composition, highly polished on one side and heated to temperatures obtaining in Pueblo firing. When fractured, the average of each set was found to vary less than 15% from the average of all five sets, and the character of variations showed that the factor of thickness is negligible in effect. To determine the error due to curvature, test pieces were formed with a curve 7.6 cm. in radius, which is greater than need ever be used in testing sherds, since the majority of bowls exceed 15.0 cm. in diameter, and the curvature at the base is frequently less than on the sides. The curved test pieces were divided into two groups, one of which was fractured with concave side up and the other with concave side down. These were compared with flat test pieces, all three sets having been made under accurately controlled conditions and differing only in shape. The curved pieces differed in strength by 5% from the flat pieces. The fact that the curved test pieces did not show the increased strength which would be expected is perhaps explained by the manner in which they are supported, since the strength of an arch results when it is supported at the ends. In any event the error introduced by curvature is so slight that it may be disregarded.

Flaws, often so small as to be unnoticed, are sometimes a more important cause of variation than either of the factors discussed. They are, of course, more common in sherds than in prepared test pieces and fractured surfaces should always be examined for evidences of lamination. The error introduced by flaws is usually corrected when sherds which vary more than 15% from the average and do not give a consistent second test are discarded. It is also important for the test pieces to rest evenly and squarely on the supporting knife edges. The distance between supports influences the accuracy of the test, and the American Ceramic Society recommends a 12.5 cm. span for a test piece having a 2.5 cm. square cross section.<sup>1</sup> A span of 2.54 cm. for test pieces which average 0.8 sq. cm. in cross section has given consistent results and it is desirable to reduce the size of the test piece as much as possible without sacrificing accuracy.

The strength of pastes can be compared by means of this determination of modulus of rupture, because the breaking load for a section one centimeter square is always calculated. It is also interesting to know the strength of types with their given thickness of wall; to learn, for example, whether thicker walls were made to

<sup>1</sup>Journ. Am. Ceram. Soc., Vol. XI, No. 6, p. 460.

compensate for weaker pastes. This test is very simply made with the same fracture machine by merely cutting from sherds pieces of uniform width and measuring the breaking load. In the present study 2.5 cm. proved a convenient width and the average of ten pieces was considered representative.

The Pecos study illustrates the differences in strength and modulus of rupture found in a group of primitive wares, though very much stronger types are found in other parts of the Pueblo area. The range in strength of a paste is, as might be expected, often greater than the difference between the averages of types; nevertheless, some significant results were obtained and the method has been particularly useful in the study of clays and the effect of temper.

*Porosity* is an important property of pottery, for it determines its degree of permeability to liquids and influences its strength. An accurate determination of porosity furnishes the most satisfactory basis for comparing the density of pastes and gives some indication of the degree of vitrification which has taken place. It has sometimes been judged in the field by noting the length of time required for a drop of water to soak into the sherd. This is not only a very rough test but may actually be misleading, for the rate of absorption is not controlled by the amount of pore space alone. The size and shape of the pores which determine the capillarity, and the relative compactness of the surface produced when the vessel was smoothed or polished are both important factors. Experiments with sherds, whose porosity had been accurately determined, have shown that the more porous sherds sometimes absorb water more slowly than the less porous. Consequently, the rate of absorption cannot be considered a test of porosity and this property is best determined in the laboratory. The method which has been used in the present study is based on that adopted by the American Ceramic Society.<sup>1</sup> Types of Mimbres pottery have been tested by this method.<sup>2</sup> Porosity, reported as percentage, is calculated from the amount of water absorbed considered in terms of exterior volume, the following formula being used:

$$P = \frac{Sf - Wf}{Vf} \times 100$$

in which:

P = per cent apparent porosity

Sf = weight of saturated test piece in grams

Wf = weight of dry test piece in grams

Vf = volume of test piece in cubic centimeters

Sherds are dried to constant weight at 110° C. and cooled in a dessicator before taking the dry weight. They are boiled in distilled water for three hours and cooled in water to obtain complete saturation. A damp sponge takes off excess moisture without drawing it from the pores and the weighing is made as rapidly as possible to avoid loss of water from evaporation. The volume is determined in an overflow volumeter of Schurecht's design.<sup>3</sup> It is, of course, important to clean sherds thor-

<sup>1</sup>Journ. Am. Ceram. Soc., Vol. XI, No. 6, p. 456.

<sup>2</sup>Bradfield, 1931, pp. 34-38.

<sup>3</sup>Journ. Am. Ceram. Soc., Vol. XI, No. 6, p. 493.

oughly before testing and first to remove loose or projecting particles which might be rubbed off during the test. It is advisable to place a screen in the bottom of the vessel in which the sherds are boiled to avoid unnecessary agitation from the formation of bubbles beneath them. Some soluble salts may be lost in boiling but not in amount sufficient to affect seriously the accuracy of the test.

This test measures only partial porosity referred to as *apparent porosity*, because water does not penetrate the sealed pores and only the volume of the open pores is calculated; however, determinations of both apparent and total porosity have shown that in low-fired pottery, sealed pores either do not occur or form a very small percentage of the total pore space. For our purpose, therefore, apparent porosity closely approximates true or total porosity.

If a volumeter is not available absorption can be reported instead of porosity; that is the water absorbed is considered in terms of the dry weight of the specimen instead of its volume.<sup>1</sup>

While it may be found that the porosity of many types of Pueblo pottery averages between 20 and 30% and that sherds of a single paste may differ from 5 to 10%, types which fall below or above the average are none the less interesting and significant and the test is fully justified.

#### STANDARDS OF POTTERY DESCRIPTION FOR THE FIELD WORKER

Field workers have been accustomed to describe technological features of pottery, as well as to classify and name types, on the basis of megascopic examination alone. It should not be the part of the ceramic specialist to discourage these observations, but rather to lend whatever assistance is within his power. The advantages of exact methods of analysis and the significance of technological data have conclusively been demonstrated, but the amount of material which will yearly be studied and reported upon far exceeds the facilities for microscopic examination. It is important therefore clearly to distinguish between those aspects of the subject which must be left to the specialist and the tests and observations which it is practicable for the general archaeologist, without special equipment or analytical experience, to undertake. The necessity for specific, impersonal standards of description which can be applied by the field worker is generally recognized, but if megascopic classification is accurately to record facts there must be at the start a candid acknowledgment of the limitations of megascopic identification.

Many archaeologists have demonstrated a reliable pottery sense, that is they recognize at once and without conscious analysis the likenesses and differences between types, but too often the basis of judgment is not scrutinized and as a result the idea that many ceramic properties can readily be recognized but cannot be described has taken deep root. Insistence upon adequate description will of necessity require more analytical and systematic examination than has hitherto been customary. Reviewing the features of pottery—paste, surface treatment, form, and decoration—usually selected for purposes of classification, it hardly need be pointed out that form and decoration simply require systematic, accurate observation and

<sup>1</sup>Journ. Am. Ceram. Soc., Vol. XI, No. 6, p. 457.

measurement, while paste and technological features in general can only be described superficially or incompletely by visual inspection alone. It is only logical therefore that design and form should be emphasized in megascopic work and should form the primary criteria for classification. But as long as paste, surface finish, and nature of the pigment contribute to the impression upon which the field worker bases his classification, they must be described. A few suggestions are accordingly made here in the hope that they may contribute to the general effort to systematize methods of description and classification.

*The paste* is difficult to describe both because of its fineness and the invisibility of important features and because of the continuous intergradation of properties. The differentiations which can be made do not depend alone upon the power of the hand lens used, because the keenness of vision, training and knowledge of the observer play no small part in what he sees. Therefore due allowance must be made when it is said that this or that can or cannot be recognized. The characteristics of the paste which can profitably be considered by the field archaeologist are color, nature of inclusions, texture and hardness.

Color should be defined by reference to a standard (see p. 430). It is important that the description include the typical color, the color range and exceptional colors. The relative uniformity of color from surface to surface of a paste as viewed in freshly fractured section should also be recorded. The width of cores in relation to margins and the thickness of the inner as compared with the outer margin may sometimes be characteristic.

The field worker frequently attempts to identify temper or inclusions with the aid of a hand lens, but a review of southwestern archaeological literature proves that many of these identifications are incorrect. The folly of guesswork is realized when one stops to consider that some of these classifications were made by men whose vision was keener and knowledge and training broader than those of the majority of workers. The writer, who has exceptionally good vision, has during the last four years, constantly checked megascopic identification by petrographic examination with the resultant conviction that it is generally inadvisable to attempt to identify temper megascopically or with a low power hand lens. It is far better to describe in specific terms the appearance of the inclusions than to add to the accumulated fallacies of the past and their resultant confusion by uncertain identification. At best only the coarser inclusions can be seen and there are many possibilities for error in the identification of these; for example, lumps of clay in a carelessly prepared paste may look like sherd temper, fractures of feldspathic rock are often indistinguishable from fragments of whitish paste sherd, black sherd fragments may be confused with shale, and finally when temper is too fine for megascopic identification the paste may erroneously be classed as sand tempered on the basis of stray coarse grains which are merely accidental inclusions. In describing the appearance of inclusions the following characteristics should be noted: color, luster, degree of transparency, and shape—whether granular or platy, angular, rounded, or irregular. Even accidental inclusions may be characteristic of a paste, as lumps of unmixed clay or dull black rings surrounding pores which are caused by carbonaceous matter.

Our visual impression of texture is influenced principally by the grain size and amount of temper. This conclusion has been reached only after comparing specimens which were prepared in the laboratory with known differences in size, amount, shape and kind of temper. It was found that samples containing the same amount of aeolian sand, ground potsherd, ground rock and ground mica schist, all of which has been screened to obtain identical grain size, were indistinguishable except for the sand which appeared slightly finer and less ragged in texture; but even this difference was barely noticeable and would not ordinarily be recognized. Grinding mica schist did not effectively separate the plates and consequently the distinctive laminated structure was not produced. When grain size only was varied, using the standards suggested (see p. 410), the grades from fine to very coarse were distinguishable with the unaided eye and seen clearly with a 10-power lens. Likewise specimens with 10, 25 and 40% of temper of the same grading are very distinct in texture. These samples were prepared with red clay and sand temper, materials having poor contrast, and therefore demonstrate the possibility of recognizing differences of this magnitude in the majority of clay and temper combinations found in actual pastes. They seem to offer a feasible means of describing by reference to a standard, not absolute grain size or true volume of temper, but rather textural appearance, provided certain precautions are observed. The standards should be made of clay and temper having approximately the same color or degree of contrast as that of the paste being judged for it has been demonstrated experimentally that color contrast has an important effect upon both apparent size and abundance of inclusions. Grain size will often include several grades and only the range can be described. Actual volume of temper cannot be estimated because of the fine material which is invisible, and the terms sparse, moderate, heavy, when used by the field worker would have to be understood as describing the appearance as influenced by the proportion of medium to very coarse grains. A fractured surface gives the best standard for comparison, since relief, the pattern of light and shadow is usually observed in the paste and grinding the fracture to a plane diminishes the apparent difference in textures, reducing it to two dimensions instead of three. Photographic standards could not be used since the standard and unknown should be observed in the same light and with the same magnification. It would be possible to substitute for the prepared standards, sherds in which the grain size and volume of temper of megascopic proportions had been determined micrometrically. The experience of a number of workers should, of course, be compared before methods and standards are finally established. Present lack of standardization renders most textural description nearly meaningless. Some such method as that proposed would serve as a common denominator to bring the observations to comparable terms without unduly increasing the time required for description, especially as the standards would be prepared in a technological laboratory.

Properties of the clay, though not as important as grain size, grading, and amount of inclusions, also influence paste texture. The mechanical composition of a clay, together with its relative refractoriness determines whether the clay base will be compact and dense or loose and porous in texture. Visual impression of clay texture should be supplemented by observation of the way in which the paste breaks; if it

chips it may be described as dense or compact, if it crumbles it is friable. It is hardly practicable to distinguish between the factors of porosity and mechanical composition as affecting relative density. Although in extreme cases the rate of absorption of a drop of water will distinguish between a porous and a compact clay, in the middle range such a test is of little value and it is not a sufficiently direct or accurate measurement of porosity to justify timing the absorption of a drop.

The manner in which a paste breaks is affected by its texture and hardness. Coarse inclusions will tend to produce a ragged fracture, fine inclusions a smooth fracture. If the paste is hard and dense large grains may cause an irregular break, whereas the line of fracture in a soft friable paste is more easily controlled by direction of pressure. A fine, soft, friable paste has a square smooth break and a coarsely tempered dense paste, the most irregular and jagged one.

In judging the nature of fracture a uniform method of breaking the sherd should be followed. Direct pressure applied with the end of a triangular file will usually show whether the paste chips or crumbles but does not give a long enough break to show the character of the fracture. When pliers are used just sufficient pressure should be exerted to hold the sherd and the break made by leverage, the push always being made squarely and in the same direction. The fracture may vary in different directions of the vessel and it is therefore well to note the orientation of the sherd and habitually make either a horizontal or vertical break.

Mohs' scale of hardness (see p. 433) can be used by the field worker as well as by the technologist and if this property is defined it should be by reference to a standard. It may be found that the majority of types of a period or area do not differ appreciably in hardness but the exceptional ones are none the less significant for this reason, nor is there less necessity for an impersonal standard definition.

*Surface Finish.* Standards for the terms rough, smooth and polished as applied to surface texture have been proposed by March.<sup>1</sup> He calls attention to the factors of paste texture and workmanship, but emphasizes the uncertainty of speculation upon methods of workmanship. Mere theory of technique has, indeed, no place in description, which should admittedly be purely objective, but a study of finishing processes reveals characteristics, the recognition of which is no more subjective than is color reading. Observations of the methods of modern primitive potters and well planned experiments bring out the multiplicity of conditions influencing the appearance of the finished surface and prove the impossibility of giving accurate or satisfactory descriptions with a few simple textural terms.

The principal factors which affect surface appearance are color, hardness, and texture of the paste or slip clay, method of evening the vessel surface, and final finishing process. The texture of the paste, particularly the amount and grain size of the temper, will obviously affect the surface texture, but this effect may be largely offset by the method of evening the vessel. The importance of the finishing technique is most evident when a coarse-textured paste is used. There are three general methods of evening the vessel surface when it is in a plastic condition or immediately after moulding, namely: scraping with an edge held nearly normal to the surface,

<sup>1</sup>1934, pp. 35-37.

rubbing with a smooth, hard tool generally having a convex face, and rubbing with a soft or yielding tool. If a coarse paste is scraped the particles of temper will be caught by the tool and dragged along leaving characteristic pits and striations. Rubbing with a resistant convex surface, on the other hand, tends to imbed the temper and if thoroughly done may leave the surface as smooth and even as that of a fine-textured paste. A water-worn pebble, a piece of gourd rind, or a smooth sherd may be used for the purpose with no marked difference in the effect. If the finger instead of a hard tool is used it will yield to protruding inclusions, only partially imbedding and leveling them and a characteristic roughness will result. A surface which has been smoothed with the fingers generally carries unmistakable markings, fine striations produced by the ridges of the skin and by fine inclusions which adhere to the fingers. These striations are distinguished from tool striations by shallowness, uniformity of depth and spacing.

A surface may be evened immediately after moulding, when it is leather hard, or after it is completely dried. The surface which was evened when dry can often be distinguished from that which was worked over with a tool immediately after moulding. If the moist clay surface is evened with a rubbing tool it is practically impossible to avoid slight depressions and undulations of surface, but if the vessel is scraped with a straight-edge when leather hard or if it is dried and subsequently rubbed with a piece of fine sandstone, or a similar abrading tool, a far truer plane is obtained. It may not always be possible to distinguish a carelessly sanded or scraped from a carefully rubbed surface, but an undulated surface is usually indicative of finishing in the plastic state. Evening when the clay is in either a leather hard or dry state is most practicable with a fine-textured paste since coarse inclusions are unavoidably caught and dragged from the paste, leaving a pitted surface.

Non-culinary vessels having a well smoothed surface may be either slipped or unslipped. In some cases it is difficult to tell whether a ware was slipped, particularly if the coat was very thin or if it was similar in color to the paste. But ordinarily the slip, if present, can be observed by examining with a hand lens a carefully fractured section through the vessel wall. The edges of that portion of a break which come under the pliers are likely to be crushed by pressure so that they do not give clear evidence of the surface finish. Peeling or abrasion may sometimes indicate the presence of a slip, but crazing, although often caused by unequal contraction of slip and paste, may occur on unslipped as well as slipped surfaces.

An exceptionally well smoothed but unslipped surface has sometimes been designated by the term "floated" on the assumption that this texture was produced after sundrying by working over the moistened surface in such a manner as to bring up or float the finer particles of the clay, thus covering the coarser material in much the same manner as is done in cement work. Either the finger, a cloth, a piece of fur, or even a polishing tool can be used in this process, but the surface must be quite wet and worked very lightly. Such a method obviously never results in either a very smooth or a highly lustrous surface, nor does it resemble the kind of finish usually designated by the term floated. This method may have been used to even the surface before applying a slip and is in fact so used by certain modern Pueblo potters. But experiment and careful observation prove that the very smooth, lus-

trous, unslipped surfaces do not differ in finishing technique from polished slipped surfaces. In other words the surface was compacted by rubbing with a smooth, hard tool; the process usually designated as polishing. The present usage of the term floated should, therefore, be discontinued and well smoothed, fine-textured, often lustrous unslipped surfaces should be designated by the term compacted, polished or simply well-smoothed, all of which are accurate and legitimate descriptions, whereas the term floated if taken literally gives an entirely false impression of both technique and appearance.

The principal characteristics of the slip which should be recorded are color, hardness, texture, and luster. The description of color and hardness have been discussed under paste and requires no further comment other than that the relation between hardness and wear should be noted. Textural differences are not as obvious as those of paste, since slip clays were very rarely tempered and fineness of grain was one consideration in their selection. Important differences do exist, however, the most marked of which is that between the clay with high and that with low colloidal content. The clay which is exceptionally fine and of nearly uniform grain size cannot be pebble-polished when damp, but is easily smoothed with a cloth or piece of buckskin, and when entirely dry it can be given some luster by polishing, whereas the more granular clay will take a high polish when damp but is marred by further polishing when dry. The explanation of these facts is simple; if the grains are graded in size they will pack or nest more closely than grains of uniform size and the closely packed surface reflects light more completely than the loose, open one. The Rio Grande Pueblo potters have recognized empirically the relation between texture and smoothing technique, for they seldom attempt to polish the highly colloidal Santo Domingo slip, but instead smooth it with a cloth. These facts are of interest to the archaeologist primarily because they suggest caution in estimating the amount of mechanical polish which a slip has received by its degree of luster alone.

The terms smoothed, lustrous, and polished should be clearly distinguished. Smooth is a textural term and is judged by feel more than by appearance. Luster refers to the degree to which the surface reflects light and should be judged by the degree of gloss or shininess observed when the specimen is held in such a position that its surface forms approximately the same angle with the source of light as with the line of vision. Polish and luster are often used synonymously, but polish suggests technique and luster more correctly describes a property which is affected by other factors in addition to workmanship, for a surface well worked with a polishing stone may actually be completely dull or matte in appearance, although it will always feel smooth unless subject to some defect such as abrasion or crazing. The effect of clay texture upon luster has been discussed. A high firing temperature may also modify polish. This fact is best understood from a consideration of the nature of a lustrous surface. Rays of light falling on a rough surface are reflected at all angles and this diffusion produces an appearance of dullness; whereas light rays falling on a perfect plane are reflected at the same angle, thus producing a brilliant gloss. The luster of a clay surface is proportional to its smoothness, evenness, and compactness. If, therefore, a well polished surface is heated sufficiently high to cause noticeable firing shrinkage the arrangement of clay particles will be disturbed and the surface,

though still even and smooth to the touch, will lose its high gloss. The primitive potter would naturally discover this fact by experience and probably wares which were fired sufficiently highly to cause shrinkage were not often given a high mechanical polish.

In describing a lustrous surface, the uniformity, as well as the degree of luster, should be noted. Dull streaks on a lustrous surface may be due either to indifferent polishing or to an ineffectual method of evening the surface before slipping, for if the surface is pitted or ridged it cannot be given a uniform luster no matter how faithfully the polishing stone is used.

*Paint.* Certain physical properties are characteristic of particular kinds of paint and thus aid in megascopic classification after the composition of the paint has been determined by test. The following characteristics should be recorded: color, luster, relief, hardness, evenness, spreading; and such defects as abrasion, crazing, and peeling. Mineral and vegetal pigments can, as a rule, be distinguished by the oxidation test (see p. 412) which being non-technical can be applied by the general archaeologist. Certain characteristics which usually distinguish the vegetal from the mineral pigment of Southwestern Black-on-white pottery may also be mentioned. The vegetal pigment lacks relief entirely and has approximately the same texture and luster as the clay surface upon which it is applied. This is because the pigment is in solution and penetrates the clay without noticeably disturbing the arrangement of surface particles. Any coating of organic matter which originally covered the surface is removed during firing by oxidation leaving the clay colored by that which has penetrated. The mineral pigments, on the other hand, are insoluble, being applied as suspensions. They form a coating upon the clay surface, consequently they often have distinct relief. Their texture is due to their physical condition, treatment (smoothing or polishing) which they may receive after application, and changes such as vitrification which take place in firing. Frequently the greatest contrast between an organic and a mineral paint is in luster, the latter being entirely matte or dull in contrast to the smooth glossy surface of the former when applied on a well polished slip, but mineral paints are sometimes polished after application and if vitrified they become lustrous, though in this case the surface is seldom smooth and there is distinct relief. Mineral pigments are often rough and granular in texture and they may be thick and caked in patches. The hardness of an organic pigment usually varies but slightly from that of the clay surface upon which it is applied, whereas the hardness of a mineral pigment bears no relation to that of the clay, if unsintered it may be noticeably softer, if vitrified it will probably be considerably harder. The mineral paints are also more often affected by wear than are the organic paints. The normal grays or black of organic and mineral pigments may be indistinguishable but when oxidized these paints exhibit distinct ranges which can best be studied from refired specimens.

This brief review of the megascopic observations to be made in the description of pottery suggests no new terms or striking innovations in method. From the standpoint of the technologist the essentials are accurate, systematic examination, reference to impersonal standards, and strict definition of terms. Some of the observations which have been suggested may seem unnecessarily detailed or even

trivial, but any of these characteristics may be distinctive of a type and so go to make up the archaeologist's impression of its appearance; while failure consciously to recognize and record just such minute details may in some measure explain the difficulty experienced in giving a description which will actually differentiate the type recognized.

For convenience and clarity the suggestions made are summarized in outline:

#### *Paste*

*Color*—range, typical and exceptional colors, uniformity in color, and relative width of color zones described by reference to a standard color scale.

*Inclusions*—identified only when coarse and diagnostic features are unmistakable. Appearance described by color, luster, degree of transparency, and shape.

*Texture*—proportion and grading of visible grains estimated by reference to prepared standards made in accordance with the following definitions:

*Sparingly-tempered*—visible inclusions make up less than 15% of the volume of the paste.

*Moderately-tempered*—visible inclusions make up from 15 to 30% of the volume of the paste.

*Heavily-tempered*—visible inclusions make up over 30% of the volume of the paste.

*Fine*—inclusions under 0.25 mm. in diameter.

*Medium*—inclusions from 0.25 to 0.50 mm. in diameter.

*Coarse*—inclusions from 0.50 mm. to 1.0 mm. in diameter.

*Very Coarse*—inclusions over 1.0 mm. in diameter.

The texture as affected by the shape of inclusions described as *granular* or *laminated*.

The texture as affected by the character of the clay is described as:

*Dense*—fine, compact, chips rather than crumbles when broken, leaving a smooth fracture.

*Friable*—finely granular, crumbles when broken and the fractured surface is earthen.<sup>1</sup>

*Fracture*—the way in which the paste breaks is influenced by texture. It should be observed whether the direction of break is straight or irregular; whether it is at right angles or oblique to the vessel surface; and whether the fractured surface is smooth and fine, or rough and granular.

*Hardness*—is defined by reference to Mohs' scale.

#### *Surface Features*

*Color*—described by reference to a standard color scale.

*Hardness*—determined with minerals of Mohs' scale.

<sup>1</sup>This limits the term *friable* to instances in which the entire body of the paste has a weak bond and crumbles to a fine powder. Used in this sense the term is not applicable to those pastes which have a hard compact clay base even though they are weakened by coarse temper and so easily broken.

*Evenness*—surfaces may be designated as even or uneven according to the presence or absence of the irregular undulations which mark the imperfectly planed surface. If present record should also be made of: *a*—fine parallel ridges such as are produced by using the rubbing stone on the plastic clay; *b*—broad, shallow, depressions on the vessel's interior such as are indicative of the paddle and anvil technique.

*Texture*—the property resulting from texture of paste together with final finishing process may be described as:

*Smooth*—slick to the touch.

*Rough*—gritty to the touch.<sup>1</sup>

*Granular*—characterized by protruding inclusions. The term may be modified by the words medium, coarse, etc., depending upon the size of the inclusions. Such features as fine striations or pits should also be noted.

*Luster*—according to the amount of light which it reflects, a surface may be described as dull, lustrous, or highly lustrous. Uniformity of luster and presence or absence of marks of the polishing tool should be recorded.

*Slip*—recognized as a surface layer seen in fractured cross section through the vessel wall. *Thick* if visible to the unaided eye. *Thin* if seen only with a 10- or higher-power lens.

*Defects* may be significant marks of properties of the slip or paste and should be recorded.

*Abrasion*—rubbing away of a soft slip by wear.

*Peeling*—cracking and loosening of a slip which has a poor bond with the paste.

*Crazing*—the formation of a network of fine, irregular cracks by contraction.

*Spalling*—the deep flaking of the surface caused by the expansion during firing of accidental inclusions, or of steam.

#### *Paint*

*Composition*—organic distinguished from inorganic pigment by the oxidation test.

*Properties* to be recorded: color, luster, relief, hardness, evenness, and defects.

<sup>1</sup>The term rough is frequently used loosely to cover a variety of surface textures produced both by distinctive finishing processes and by paste texture. It is here proposed to limit the term to the textural characteristic of clay which has not been compacted in the finishing process and to define or describe specifically textural features resulting from inclusions in the paste and from particular finishing techniques.