DEPARTMENT OF THE INTERIOR

U. S. GEOLOGICAL SURVEY

The Contribution of Marble Characteristics to the Failure of Column Capital Volutes at the Jefferson Memorial, Washington, D.C.

by

Elaine S. McGee

U.S. Geological Survey, Mail Stop 959, Reston, VA 22092

Open-File Report 91-432

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards.

1991

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Project Summary

After one piece of a column capital fell and another was accidently knocked off during preliminary examination, six similarly cracked pieces were intentionally removed from the Jefferson Memorial in Washington, DC. Elaine S. McGee of the U.S. Geological Survey (USGS) was asked by the National Park Service to examine the eight pieces of marble column capital volutes that had been removed from the Jefferson Memorial. The main purpose of this study was to determine if there was a mineralogical cause for the failure of these pieces.

The pieces are made of Vermont Marble from Danby, Vermont; a marble used in many buildings of historic value. Marble from the same locality was described by Elaine McGee prior to its use in stone exposure studies sponsored by the National Acid Precipitation Assessment Program. The marble is mostly white calcite with a few noticeable gray streaks of dolomite inclusions and some less obvious linear inclusion streaks of mica with minor pyrite. Of primary interest in this study was whether an inherent characteristic of the marble, such as mineral inclusions present along the fracture plane, may have caused the failure of these pieces.

The samples in this study are from four columns around the outer colonnade and four columns on the inner part of the memorial. The samples came from each of the sides of the memorial, so their failure does not correlate with position of the columns around the memorial. Each of the pieces fractured along a plane that was horizontal and parallel to the ground, however the heights (from lower edge to center of the volute) of the pieces range from nearly 3 inches to 7 3/4 inches so they did not all break at the same point on the volute. This examination concentrated on features of the fracture plane on each sample, but the outer and inner faces of each piece were also examined to see if any clues to features found on the fracture face could be seen. Primary phases present on the fracture surface are minerals that are part of the original marble and these include calcite, micas, feldspar, and pyrite. Secondary phases were formed or deposited on the fracture surface after the crack formed, and include organic material, gypsum crystals, dirt, and pollutant particles. Calcite is the predominant phase on all samples except one. The calcite characteristically occurs as either blocky, almost square stepped ledges, or in broad, more planar steps. Mica is a minor phase in some samples and occurs as scattered individual grains that are mostly co-planar with the calcite. In one sample, mica is the dominant primary phase, but only very faint thin traces of similar inclusions of mica are visible on the inner face of the sample. The more obvious gray inclusion streaks visible on the inner face of another sample are unrelated to the fracturing, and the dolomite that composes the streaks does not appear on any fracture face as a dominant phase. Because of their low abundance and mode of occurrence, inclusion phases do not seem to be an important factor in the fracturing of these pieces. Secondary phases are minor and randomly distributed; they are clearly surficial because the dominant feature, even in areas of accumulation of dirt and organic material, is the blocky and stepped habit of calcite. Although gypsum crystals have formed in some places, they are very small, recently formed crystals, and it is highly unlikely that they contributed to the development of the fracture. The most striking feature of the fracture surfaces

is the blocky, stepped appearance of the surface that resembles slickenside surfaces in geologic faults, where gradual slipping occurs along shear zones. As a metamorphic rock, marble may have a foliated (planar) texture that arises from the elongation of mineral grains or from the formation and healing of shear planes during formation of the marble. Zones of weakly healed shear planes that are a part of the marble's texture may be susceptible to weakening from external influences.

It is likely that no single factor contributed to the failure of these volutes. Although inclusions are present in the marble pieces, with one exception they are insignificant in the location of the fracture. External influences probably took advantage of physical characteristics of the stone such as the breaking habit of calcite, the fortuitous presence of inclusions, or a zone of weakness in the original stone, and developed the fracture where the stone was weakest. A systematic examination of the remaining volutes at the memorial would be useful to give some indication of the abundance, distribution, and appearance of similar cracks. Likely external influences that may have contributed to the failure of the volutes, such as vibration or water penetration resulting from storms or from washing, should also be investigated further.

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by
Elaine S. McGee

Introduction

The lower portion of a volute from an Ionic column capital at the Jefferson Memorial in Washington, DC fell during the night of May 21, 1990. During subsequent examination of the memorial, another volute was accidently knocked off. Six other pieces were found to be badly cracked and it was deemed necessary to remove them to avoid having them fail catastrophically, as had happened with the first two. To determine whether mineralogical factors may have contributed to the failure of the capital pieces, the samples were made available for visual, optical, and limited sampling study. Of primary interest was to determine if these pieces of marble possessed inherent characteristics, such as a vein of inclusions along a potential fracture plane, that caused weaknesses in the stone and led to its failure.

The Jefferson Memorial is made of marble from Danby, Vermont; the same type of marble as that used in stone weathering studies conducted by the National Acid Precipitation Assessment Program (NAPAP) (McGee, 1989). The marble is predominantly composed of calcite (calcium carbonate) grains that are 0.3-0.9 mm in size and form a tightly interlocked fabric. Inclusions of dolomite, phlogopite, muscovite, chlorite, feldspar, pyrite, rutile, and apatite are present in fresh samples of Vermont marble (McGee, 1989). The most obvious inclusions in the marble typically occur as randomly distributed gray streaks that contain dolomite + phlogopite ± pyrite ± rutile. Less noticeable light colored linear streaks tend to weather as grooves relative to the surrounding calcite and typically contain muscovite, phlogopite, chlorite, and pyrite. Marble that is exposed to washing by rain typically weathers (deteriorates) by sugaring or dissolution of the calcite around the edges of grains causing the stone surface to become rough as grains loosen and fall off. Where inclusions are present in the marble, preferential weathering is frequently observed; the inclusions remain resistant to weathering relative to the surrounding calcite, or the inclusions are loosened and fall out leaving a depression or groove in the stone surface that may contain traces of the inclusion phases. Thus, identification of the abundance and type of inclusions in the marble of the volutes is important, because inclusions could have contributed to the failure of the volutes by their tendency to weather differently from surrounding areas of calcite in the marble.

The colonnade at the Jefferson Memorial consists of an outer circle and row of columns across the front entrance, and sets of four columns that stand in the doorways around the inner statue chamber. The columns are numbered following the plan in Fig. 1. The four volutes on each capital are identified by the letters A-D which indicate if the volute faces inward toward the center of the building (A & D), or outward (B & C). Four of the samples in this study are from the inner doorways and four are from the outer colonnade (Fig. 1). It should be emphasized that these samples were either fortuitously available or were removed because of a perceived danger. Thus, these samples do not necessarily represent either the distribution of stones at risk, or the overall condition of the stones in the building at this time. They are a small sample of some of the column volutes, that have experienced significant deterioration.

The Samples

Although each of the samples came from the lower portion of the Ionic volute (Fig. 2), the pieces vary in size. This suggests that although the hanging portion may be susceptible to fracture, something in addition to the design of the capital (perhaps a characteristic of the marble) must also contribute to its failure, because different proportions of the volutes have broken. Each of the pieces was weighed, measured, and photographed (Table 1) to document the range of physical dimensions of the samples. The largest sample (15A) is the one that fell off and was found after it had fallen. The piece is not as complete as the others, as it fragmented when it fell, and those fragments were not considered in determining the dimensions. The smallest sample (25C) is also the only sample that faced outward on the outer colonnade (Fig. 1). On average, the pieces are 18x8x5 inches in size and weigh 21 pounds; sample 45D is closest to the average in size.

For the purposes of this study, three faces on each sample were defined: the inner, outer, and fracture faces. The inner face is the smooth part that would be closest to the column when the piece is in position. The outer face is the curved and grooved face that faces away from the column and is most readily visible to an observer. The fracture face is the plane along which the piece broke when it fell or was removed from the capital. The focus of most of the observations in this study has been on details of the fracture face, but observations were also made on the inner and outer faces, to see if there were features that might provide clues to the location of the fracture.

Outer faces. One of the most marked features of the samples, particularly on the outer faces, is the surficial blackening. The blackened surface is smooth and retains the carved features of the stone, but none of the original mineral characteristics of the stone surface are visible where the blackened crust has accumulated. Such crusts typically develop on areas of marble buildings that are exposed to urban pollutants and are not regularly washed by rain (Camuffo, 1986). The crusts consist of a mat of gypsum ($CaSO_4 \cdot 2H_2O$) crystals that have trapped dirt and pollutant particles and, although they apparently preserve the original stone details, the stone underneath may become severely disaggregated with time (McGee, 1989a). Four of the samples have outer surfaces that appear very blackened compared to the others (samples 38A, 43B, 40A, and 26D), but there is no obvious correlation between the sample position around the building and amount of surficial blackening on the stones (Table 3). The surficial blackening is unrelated to the fracture and catastrophic loss of the volutes that prompted this study; however on one sample (38A) some bits of black crust from the outer face-inner face edge came off during handling of the sample, revealing loosely aggregated marble under the black crust. This may be a matter of concern in the long-term preservation of the stone in the memorial.

One sample, 25C, has a very badly sugared outer surface, with loose individual calcite grains that come off easily when the surface is touched. This is typical of marble that has experienced dissolution from exposure to regular washing by rain, and this deterioration conforms with the sample's bold exposure, facing outward on the outer colonnade. Calcite dissolves in weak acids, and carbon dioxide that is present in the air makes rain water slightly acidic, thus causing exposed marble to dissolve slightly when it is washed by rain water. Pollutants in urban air can make the rainfall slightly more acidic and thus accelerate dissolution of calcite grains. NAPAP studies on the dissolution of flat marble and limestone test samples (Baedecker et al, 1990) found that only a small (15 - 20 percent) contribution to carbonate stone dissolution could be attributed to acid deposition; the natural acidity of rain accounts for the remainder of the observed carbonate stone dissolution. However, studies of dissolution from sculpted marble surfaces suggest that the 15 - 20% figure obtained by Baedecker et al (1990) may represent a minimum contribution; dissolution over carved surfaces may be 3-5 times greater than on flat, vertical surfaces (Sherwood and Chase, 1991). Furthermore, as with the surficial blackening discussed above, these effects are surficial and may not be applicable to the catastrophic failure of these volutes.

Inner faces. All of the inner faces of the samples are somewhat darkened compared to fresh marble surfaces, but the differences between the samples are not as pronounced on these faces as they are on the outer faces. Two forms of inclusion traces are visible on the inner faces of the samples: diffuse light gray bands appear as streaks that are just below the surface, and thin lines of micas appear at the surface. Easily visible inclusion streaks (dark streaks in the white marble) are notable on one sample (51D) and are suggested on two others (43B and 25C), however these streaks do not trend parallel to the fracture edge.

Fracture faces. The fracture faces of the samples are all roughly planar and most have only small areas that appear freshly fractured. Dirt and organic material have widely accumulated on many of the fracture surfaces, indicating that cracks may have been open for extended periods of time prior to catastrophic failure or removal. The pattern and appearance of dirt accumulation on the fracture faces suggests that the opening and development of the fractures may have been gradual. Freshly fractured parts of the marble appear very white and irregular compared to the rest of the fracture surface. Dirt has accumulated mostly near edges of the fracture faces (Appendix 1), and it appears that dirt accumulation on the fracture surface may be greatest near the outer face edge. The direction that cracks opened, to eventually form the fracture plane, might be inferred from trends on the fracture face between the areas of greatest dirt accumulation and the areas of apparently recent fracture. However, although many of the cracks on these samples probably first appeared on the outer face, the samples show no apparent pattern in these trends (Appendix 1). The nature of the fracture surfaces were looked at in more detail after examination was made of each of the individual pieces.

Individual Sample Examination

Each of the eight samples was examined visually, optically (with a hand lens and a microscope), and was sampled for further optical and scanning electron microscope examination. The samples were evaluated for overall characteristics and appearance, and were examined for variations that might give clues as to why the samples fractured. Emphasis was placed on the various mineral inclusions that are present in addition to the calcite and that may have contributed to the fracture development, and on discerning features of the calcite in the marble that might also provide clues. A summary of each of the samples is given below; sketches of the fracture faces of each sample are in Appendix 1.

Sample 15A. The fracture surface is mostly white, with some areas of minor dirt accumulation. Most of the fracture face is characterized by a layered "stair step" surface. The calcite is white with a dull luster to its surface; there are no other mineral phases readily visible, visually or optically on the surface. Calcite grains are angular to sub-rounded, mostly 0.2 - 0.4 mm size, and some are up to 1.5 mm. Very small inclusions of pyrite (0.05mm) and rutile (0.1mm) were observed on some of the samples taken from the fracture face.

The outer face is mostly yellowed with surficial dirt accumulation and there are very faint suggestions of light gray inclusion streaks just below the surface. On the inner face there are light gray lines, suggestive of inclusion streaks of dolomite or muscovite, that trend somewhat parallel to the fracture edge.

Sample 25C. The central portion of the fracture surface has a lot of dirt accumulation; the two ends appear sugary and freshly broken. On one end of the fracture face there is an area of bright yellow-green accumulation that appears organic in origin, possibly algae. The calcite underneath the dirt that accumulated in the central area has a jagged, blocky fracture. Loose calcite grains, especially abundant because the outer surface of the sample is pervasively sugared in texture, are angular in shape and cloudy-white colored. Grains are commonly 0.5 to 1.3 mm size. The accumulations of dirt and organic material on this sample are especially notable, suggesting that the crack may have been present for quite some time, and open to extensive penetration by water and dirt.

The outer surface of this sample is very sugared; grains come off readily when the sample is touched or handled. There is one streak, on the rim of the outer surface, where some slightly more resistant phase (perhaps dolomite or feldspar) is raised relative to the surrounding loose calcite grains. On the inner face, a hint of diffuse inclusion streaks are present but difficult to distinguish because of the rough surface.

Sample 26D. Most of the fracture surface is darkened in appearance due primarily to flakes of phlogopite that lie flat along the fracture surface. There are a few areas of accumulation of dirt particles and on one end of the sample the fracture surface is white and appears freshly fractured. Except in the freshly fractured area, the surface is dominantly covered by phlogopite plus calcite with some pyrite. The phlogopite and calcite grains are intergrown, and form layers that give the surface a stair-step, shingled appearance. The calcite is clear and shiny and commonly 0.2 to 0.5 mm in size.

The outer face of the sample is very dirty, so it is difficult to tell whether there are any clues to the presence of the phlogopite-rich region that forms the fracture plane. The inner face is less darkened, and there are faint mica-rich lines that follow a trend parallel to the fracture edge.

Sample 38A. Unlike all the other samples, the fracture face of this sample does not form a single plane; most of the surface is flat but there is a break near the right end of the sample and about one sixth of the face forms a lower plane. There is an area of distinctive stair-step fracture along the left edge of the fracture face and in the center of the sample, the stone surface forms a massive, irregular hill. However, there is no apparent change in texture or mineralogy where the fracture face changes from almost regular stair-steps to a more massive fracture. Very fine dirt has accumulated in the area of stair-stepped fracture. Calcite grains are angular and cloudy white with a dull luster or clear with a shiny luster. The grains are mostly 0.3-0.5 mm in size, but some are 0.8-1 mm size.

The outer face is darkened by accumulated surficial dirt that obscures features of the original stone. On the inner face of this sample, traces of light colored platy inclusions and a few grains of pyrite are present. The linear clusters of platy grains (probably mica) are scattered and randomly distributed; they do not trend parallel to the fracture edge.

Sample 40A. Two features are most notable about the fracture surface on this sample: it is covered by shreds of light beige, papery, stringy material and there are two small (0.5 cm) holes just right and left of the center, about 14 cm apart. Notes from the preliminary stone survey (Hartman Cox Architects, 1990) indicate that this piece was once re-attached with two aluminum pins and some (undefined) adhesive. There is no information given about why the piece had required repair, when it was done, or where the pins are now. Some areas of the fracture face show pronounced accumulation of dirt; no area appears freshly fractured, so it may have been suspended by the pins prior to its recent removal. There is some indication of stair-step like fracture on the surface, but the adhesive remnants obscure much of the surface. Where calcite grains are visible they appear frosted rather than clear or shiny; they are angular to subangular and 0.5-1 mm size.

The outer and inner faces of this sample are evenly and uniformly blackened, so no details of the stone can be seen.

Sample 43B. This sample is in two pieces because it broke when it fell, after being accidently knocked during placement of the preliminary scaffolding. The fracture surface is slightly uneven, with a shingled texture over most of the surface. In a few areas, where some dirt has accumulated, the fracturing appears to have a more blocky, stair-stepped pattern. Overall the surface is yellowish-white in color with one area, to the left of center, that is slightly tan or yellow compared with the rest. Calcite grains are angular, have a shiny luster, and some are nearly clear; they are about 0.5 mm size.

The outer face is nearly all dark gray to black with accumulated surficial dirt. There is a thin inclusion streak on the inner face, near and more or less along the right fracture edge and there are several diffuse gray bands of inclusions just below the surface and also nearly parallel to the edges.

Sample 45D. The fracture face is uneven and irregular, and it has areas of white, gray, yellow-white, and some green coloration. The surface has a shingled fracture pattern and there are no obvious areas of recent (fresh) fracture. Three areas of green accumulation consist of fine, soft, round green (apparently) organic particles that are concentrated between grains or along surface irregularities. In some areas, white translucent to opaque calcite grains are intermingled with plates and flakes of white or clear mica. The mica is in small flakes that lie parallel to each other and to the surface, giving some pieces a linear, foliated appearance. Angular calcite grains are either about 0.5 mm or nearly 1-2 mm in size.

On the outer face there are several faint linear traces of micas on edge near the center of the piece; there are no visible inclusion traces along the fracture edge, however. There are similar linear traces on the inner face, near the top, that also run horizontal and do not parallel the fracture edge.

Sample 51D. Most of the fracture face is white with some yellowing and a slight dirt concentration near the outer edge. There is a light blue-green streak along the fracture face - inner face edge on the left end of the sample. The light blue-green streak consists of very fine organic "particles" that are concentrated along grain edges and cracks. The fracture surface is uneven and has some shingling, but it has no regular "stair step" pattern. Calcite grains are angular to sub-angular, white, with a shiny luster and are 0.5-1 mm size. Some small pyrite grains and flakes of phlogopite and white mica are also present in the sample.

The outer face has a slight diffuse gray band of inclusions that lie just below the surface and trend at an angle to the fracture edge. Thin traces of micas that form lines at the surface occur with some of these diffuse inclusion streaks. Dark inclusion streaks are clearly visible on the inner face. The dark gray bands trend across the back of the sample (with no particular relation to the fracture edge) and resemble the dolomite + mica rich bands seen in the Vermont marble samples used in the NAPAP exposure site studies (McGee, 1989).

Patterns of Fracturing Visible on the Fracture Surface

All of the fracture surfaces are approximately planar, but they also show distinctive fracture features that are readily visible upon examination. Three forms of fracture were identified to characterize the appearance on the surface, and the approximate area covered by the forms of fracture on each of the samples was estimated. **Stepping** fracture is regular, blocky, and resembles the cleavage breaks of calcite (Fig 3A). Stepped areas typically have a striated (fine, parallel scratches) surface; the areas are most readily visible where dirt has accumulated to highlight the edges and ridges of the break pattern. Sample 38A has an area that is a particularly good example of stepping fracture. **Massive** fracture is irregular, without a planar or blocky trend and the surface is uneven with no distinctive features about it (Fig 3B). Freshly fractured areas (where the grains are still white and more highly lustrous) are typically characterized by massive fracture. Sample 25C has good examples of massive fractures on either end of its fracture face. **Planar** fracture is in planar sheets, somewhat similar to stepping fracture but the edges of the breaks are wavy and irregular compared to the more square edges in stepped areas (Fig 3C). Sample 26D, that has abundant phlogopite lying on the fracture plane, is a good example of planar fracture.

Each of the samples was sketched and areas were defined for the fracture forms visible on the surface (Appendix 1). From the sketches and fracture identification, estimates were made of the percentage surface area covered by stepped, massive, and planar fracture (Table 2). In some areas the fracture form appeared to be transitional (eg. planar-massive) so they were identified as such in the sketches but totaled only using the first descriptor to estimate the percentages of areal coverage.

The fracture surfaces are dominated by the planar and stepped forms of fracture. In only two cases was more than half of the fracture area characterized by massive fracture (51D & 25C) and in sample 51D 80% of the area had notable planar features ("massive-planar"). Planar fracture is slightly more common than stepped fracture, but it should be noted that these two forms of fracture are similar. Both the "planar" and "stepped" fracture patterns observed on the fracture faces of the samples may reflect a similar phenomenon in the way that calcite in marble breaks. The "stepped" areas also closely resemble the appearance of a slickenside ("A polished and smoothly striated surface that results from friction along a fault plane." Bates and Jackson, 1987; e.g. see Plate 2 in Paterson, 1958.). This similarity in appearance suggests that there has been movement along the fracture surface similar to movement that occurs along geologic faults.

Scanning Electron Microscope Observation of Samples

Small samples of a few grains or clusters of grains were pried from the fracture face of the samples for optical examination. Some of those samples were then mounted for examination with the scanning electron microscope to further identify mineral phases and to identify characteristics on a surficial scale that may have led to the fracture and subsequent failure of the pieces. Mineral phases were identified using qualitative energy dispersive X-ray analysis that gives spectra with peaks for detected elements that have atomic numbers greater than 10. Mineral phases are either primary (part of the original marble) or secondary (formed or deposited on the marble surface, after the crack formed). Primary phases found in these samples include: calcite, muscovite, chlorite, phlogopite, pyrite, rutile, feldspar, and possibly quartz (it is more commonly a secondary phase). Secondary features observed on the samples include: organic growth (most likely algae), gypsum crystals, dirt (quartz, clay, and a mixture of mineral fragments) and pollutant particles. Calcite is the only or dominant phase in most of the samples (Table 4). The calcite characteristically occurs either as blocky, almost square stepped ledges (Fig. 4), or as more planar features (Fig. 5) with slightly curved edges and smaller steps than exist in the blocky form. The blocky and stepped fracture habit of the calcite is observed at very fine scales (Fig. 6), suggesting that it is an inherent and important characteristic of the fracture surface. Sheet silicates, while present, are mostly minor phases that occur either randomly as individual grains (Fig. 7) or in clusters of grains that are co-planar with the calcite (Fig. 8), with the exception of sample 26D, where sheet silicates dominate over calcite (Fig. 9). Because of their low abundance, and mode of occurrence, the sheet silicates do not seem to be a dominant factor contributing to the nature of the fracture surface, except in the case of sample 26D. Secondary phases are randomly distributed and minor in amount. They are clearly surficial, as the calcite underneath (with its typical breaking habit), is often visible (Fig. 10, 11). Where present, gypsum crystals are very small and appear as if they formed recently (Fig. 12); it is highly unlikely that they contributed to the development of the fracture.

A brief summary of observations made for each of the samples using the scanning electron microscope is given below. Mineral phases identified on the fracture face of each sample are listed in Table 4, and Appendix 2 contains photos with typical features observed for each sample.

<u>Sample 15A.</u> Calcite is the main phase found in this sample. It has a stepped habit that forms orderly, repeating rectangular edges, probably controlled by the cleavage habit of calcite. Some loose grains of dirt (eg. quartz, and organic particles) were observed scattered on the surface of some of the calcite.

<u>Sample 25C.</u> The calcite forms broad, planar steps and stepped blocky edges. Minor primary muscovite is present. Organic material and a wide variety of dirt and pollutant particles are abundant on some of the samples. In some areas, the original stone is obscured by the accumulation of secondary material.

<u>Sample 26D.</u> The fracture surface primarily consists of sheet silicates (phlogopite and chlorite) with minor pyrite and very minor apatite. The sheet silicate minerals form irregular, nearly flat layers and are intermingled. The form of the fracture surface is controlled by the habit and appearance of the sheet silicates. Calcite is only rarely visible on this sample.

<u>Sample 38A.</u> Calcite is the only primary phase observed on this sample. The calcite

forms blocky steps and broad, flat lying planes; in some areas there are miscellaneous secondary grains and pollutant particles on the calcite. Small gypsum crystals are present in some areas, but they appear to have formed after the crack that formed the fracture opened.

Sample 40A. The surface of this sample is covered by particles and small grains that resemble the blackened crusts that typically develop on sheltered areas of marble buildings. The crust is a mixture of dirt particles, adhesive remnants, and pollutant particles. Most of the underlying calcite is obscured by this crust, that resulted in part because the piece was reattached some years ago. In a few areas calcite with a blocky, stepped habit is visible under a sparse accumulation of dirt and particles. In another area of the sample, although the surface is covered by very small (2 μm) crystals of calcite, the general surface topography is suggestive of a thin layer of crystals covering an original surface with stepped features. It appears that the original fracture plane was dominated by calcite.

Sample 43B. The calcite has a very regular stepped appearance that persists even to a very fine scale. Other primary phases include muscovite, feldspar, and rutile but they are minor in abundance compared to the calcite. Some of the samples examined had accumulations of dirt and some gypsum that formed as a secondary phase. Even in areas of fairly great accumulations of dirt, the stepped habit of the calcite underneath can be discerned.

Sample 45D. Chlorite and muscovite occur with calcite as primary phases; they are intergrown, and form ledges and steps. Where calcite is more abundant, the fracture habit is blocky and rectangular; where chlorite is the main phase, it forms thin shelves and planes. Muscovite is randomly scattered as individual grains. Some gypsum is present as a secondary phase on the calcite, and in some areas dirt (quartz, clays?) has accumulated.

Sample 51D. Blocky steps of calcite are the dominant feature with fairly abundant muscovite that occurs as books and grains with rounded edges that are scattered and usually coplanar with the calcite. Sphene is also present as a rare primary phase. Small gypsum crystals were observed in three forms on calcite surfaces as a secondary phase.

Conclusions

The focus of this study has been to determine if there was a reason for the failure of the column capital volutes that arose from some characteristic of the marble in the volutes. Several important points about the scope of this study should be kept in mind when considering this report in relation to the current state of the Memorial. Compared to the number of capital volutes at the memorial, this study was made on only a small number: 8 out of 216 possible. The samples were available because they had fallen, they were perceived to pose a risk for failure, and they were accessible for examination during the preliminary survey that was made at the memorial. Thus, as samples of the whole, they may not be representative of the overall condition of the volutes at the memorial. A second caveat is that for this study, only the pieces of marble removed from the building were examined. No examination was made of the parts that remained on the building, nor was an examination of this sort made on the samples prior to removal. However, observations from this study suggest that several factors may have contributed to the failure of these pieces.

Design of the volutes. The design of the volutes may contribute to their failure. All of the pieces are from the lower portion (thinnest area) of the volute and the fractures are nearly all planar and horizontal (parallel to the ground). However, the pieces did not all break at the same point on the volute and they do not all have the most recent fractures (last place to hold) at the same point. This suggests that although the volute may be a weak design, something else must contribute to the failure of the piece.

If the design of the capital contributed to its failure, one would expect to find other examples of Ionic columns with similar fractures or failures. Some photographs of Ionic columns in Greece that have fractured similarly to those in the Jefferson Memorial are shown in Appendix D of the preliminary stone survey report prepared for the National Park Service by Hartman Cox Architects (1990). Although this provides evidence of similar fractures, it is not convincing that the design alone has led to the failure of the volutes at the Jefferson Memorial. A number of buildings in Washington, DC of varied stone types and ages, have Ionic Columns (Table 5). It might be more convincing and relevant to survey some of these buildings (even of various stone types) to see how common a problem this is for the volutes.

Stone characteristics. Physical and chemical characteristics of marble can influence its durability and resistance to weathering. The nature and identity of inclusions in the marble, the physical and chemical characteristics of calcite, and the structural fabric of the marble all may have contributed to the failure of the volutes at the Memorial.

Marble is a metamorphic rock, with a crystalline texture, predominantly composed of calcite with some inclusions of mica, feldspar, quartz, and pyrite. As a metamorphic rock, the grains in a marble are not held together by any cement; instead, the irregularly shaped grains interlock like pieces in a jigsaw puzzle. Where non-calcite inclusions are present, the "pieces" of the rock may not fit together as well as calcite grains alone, so these areas may present a weakness. Also, the slightly different physical and chemical properties of calcite and inclusion minerals may lead to a weakness in the stone around the inclusions. Mineral inclusions are common in marble, and are visible as streaks of contrasting color in the stone. Being a different material (Appendix 3), these inclusion streaks are likely to behave differently (weaker, or more resistant) from the surrounding calcite. They may also serve as pathways to carry water into the stone, since the calcite-inclusion grain boundaries may not be as tightly interlocked as are calcite-calcite boundaries. On the columns at the Jefferson Memorial, inclusion streaks have weathered out creating grooves that trend approximately vertically (McGee, 1989; McGee, 1990). However, similar grooves were not found on the volutes in this study, probably due to the exposure and orientation of the inclusion streaks in the volutes. On the volutes, the most visible inclusions are diffuse, black to gray streaks of dolomite that is similar in grain size and habit to the calcite and shows no sign of preferential weathering compared to the calcite. In contrast, the mica rich inclusions that may aid in the development of the fracture, form thin, light colored traces that appear in small isolated segments that are not visually obvious. It is possible that water may have penetrated along the planes of these inclusions, and along with physical processes (freeze-thaw?) have contributed to the failure of the stone. Only one of the samples examined in this study has significant mica inclusions on the fracture plane. In that case phlogopite and chlorite, as the dominant mineral phases on the fracture face, form a planar surface that is dominated by the sheet-type habit of these minerals. Although the opposite side of the fracture plane has not been examined for mineral inclusion phases, it seems likely that if there were significant inclusions on the fracture faces, they would have been evenly divided between the two sides of the fracture. Similar inclusions of micas are present in minor amounts in only three other samples, and in these samples the dominant feature of the fracture plane is the stepped habit of the calcite. This suggests that the inclusions may have had little or no role in the failure of the piece.

Because it is predominantly composed of calcite, the physical and chemical properties of calcite are likely to have a significant impact on the durability of marble. Properties of calcite such as its breaking pattern (cleavage), its tendency to glide along certain crystal directions under stress, its thermal expansion and contraction properties, and its reactivity to acids, could have contributed to the failure of the marble (Appendix 3). However, because of the location of the fractures on the volutes, the appearance of the fracture face surfaces, and the distribution of the failed volutes around the Memorial, it seems unlikely that chemical reaction, translation gliding, or thermal expansion of the calcite were significant contributors to the failure of the volutes. The column capitals are mostly sheltered by the dome and porch of the Memorial and four of the volutes that failed came from the inner colonnade, thus dissolution of the calcite by rain water would be a minimal factor for these samples. Also, the surfaces of the fracture planes do not have an appearance that is typical of calcite dissolution surfaces. Although water used to clean the Memorial might have a dissolving effect that is similar to rain water, water used to clean the Memorial rarely reaches many of the volutes as evidenced by the blackened appearance of most of the outer and inner faces of the volutes (from accumulated dirt plus surficial gypsum, that is very soluble in water). The volutes that fractured hang from the column capitals, so stress from structural design in the building is unlikely on these pieces, suggesting that translation gliding of the calcite would have little impact on the failure of these pieces. Although thermal expansion and contraction of calcite has been suggested as a factor in marble failure in some instances (Zezza et al., 1985; Sage, 1988) the volutes in this study are mostly sheltered from direct sunlight and are distributed around the Memorial, so they would experience varying influences from solar radiation, suggesting that the thermal characteristics of calcite are also an unlikely explanation for the failure studied here.

The most striking feature on the majority of the fracture surfaces is the blocky, stepped habit of the calcite. This feature is visible both macroscopically and microscopically on the samples, and it seems likely that the cleavage and breaking habit of calcite has controlled the form of the fracturing observed on the fracture plane. The calcite surface appears frosted, and forms steps and ledges that, highlighted by the minor dirt that has accumulated, look as though it could have been the site of slight sliding or slipping movement back and forth along what became the fracture plane. The great similarity between the stepped appearance of the fracture faces and the appearance of fault surfaces strongly suggests that movement on the fracture plane has been similar to the gradual slipping that occurs on geologic faults and along shear zones in metamorphic rocks.

The structural fabric and texture of the marble could also have contributed to the failure of these volutes. Marble is a metamorphic rock; it was formed when a sedimentary rock was subjected to heat and pressure, resulting in recrystallization of the minerals in the stone. Metamorphic rocks no longer have the bedding planes that characterize sedimentary rocks but they do have a foliation, or planar arrangement of textural or structural features. The foliation in a metamorphic rock may be seen as an elongation of its mineral grains, or as a series of shear planes that formed and healed (or recrystallized) during and following metamorphism. Shear planes develop in marble as the stone is squeezed and folded during metamorphism, and the shears tend to form in clusters that are parallel to each other. Such zones of structural weakness in the stone partly control the sizes of blocks that can be extracted during quarrying of the marble, and the blocks may intersect partially recrystallized shears at various locations. It is possible that some of the stone pieces used for the column capitals at the Jefferson Memorial, intersect a weakly healed shear plane. The selection of pieces of similar size and orientation after the stone was removed from the quarry, might explain the consistent horizontal orientation of the fracture plane in the volutes, and also the variation in heights of the failed pieces. The pieces for these capitals may have come from slightly staggered adjacent locations intersecting the same shear plane, or they may come from an area with a series of subparallel weak shear planes. When the pieces were carved, the planes were probably either not noticeable or were not considered a risk for the soundness of the pieces. However, upon exposure and with time, these areas of weakly healed shear planes would be the most susceptible to external influences such as penetration by fluids or physical weakening, resulting in failure of the piece along the shear planes.

External influences. The accumulation of dirt, organic particles, and secondary mineral phases on the fracture surface indicates that all of the fractures were open to penetrating moisture, dirt, and pollutants for some time prior to failure. Since the volutes and cracks were not monitored prior to their failure or removal, it is not known whether the pieces fractured gradually or suddenly, but the spread of dirt and the appearance of the fracture face suggests a gradual opening. Although moisture, dirt, organic material and gypsum on the fracture face may have contributed to the eventual failure of the pieces, it is unlikely that they were the sole reason the pieces broke where and how they did. The gypsum that is present as a secondary phase on the fracture surface is mostly small, newly formed crystals that are unlikely to have contributed significantly to the development of the crack. Likewise, the organic material that is present on some of the fracture surfaces forms small clusters that have developed in protected locations and are not pervasive over the entire fracture surface.

Examination of these samples suggests that two external influences, water and vibration, may have contributed to the failure of the volutes. Evidence of water penetration along the fracture plane is seen in the presence of organic material, the presence of some gypsum crystals, and is possibly reflected by the distribution of fine dirt particulates. The slickenside like appearance of the fracture surface suggests that there may have been small gradual movement along the fracture plane. The pieces that failed hang from the capitals in a position that might pick up and amplify small vibrations, thus vibration might be a likely external source contributing to their failure.

Further study. Based on this study, "inherent vice" of the marble from the presence of mineral inclusion phases is not the sole cause of the failure of the volutes. It seems most likely that no single factor caused the failure of the capital pieces. External influences, in conjunction with characteristic features of the marble such as a weakness in the fabric of the stone, probably caused the fracturing to develop. Where and how water might penetrate into small cracks in the volutes should be investigated to see what contribution water movement and possibly freeze-thaw cycles may have made towards widening microfractures. Movements of the volutes from vibration should also be investigated to see if such movements may have built up stress and (or) played on weak points in the stone.

The design of the capital, nature of the stone, and the influence of water and vibration are all likely to have been important contributors to the failure of the volutes. To more clearly identify what led to the fracturing of these pieces, it may be important to consider all (or a more representative sampling) of the volutes. Such a study would permit examination of early stages of cracks on the pieces, of the other side of the fracture plane on the capital, and of slight traces around all sides of cracked pieces.

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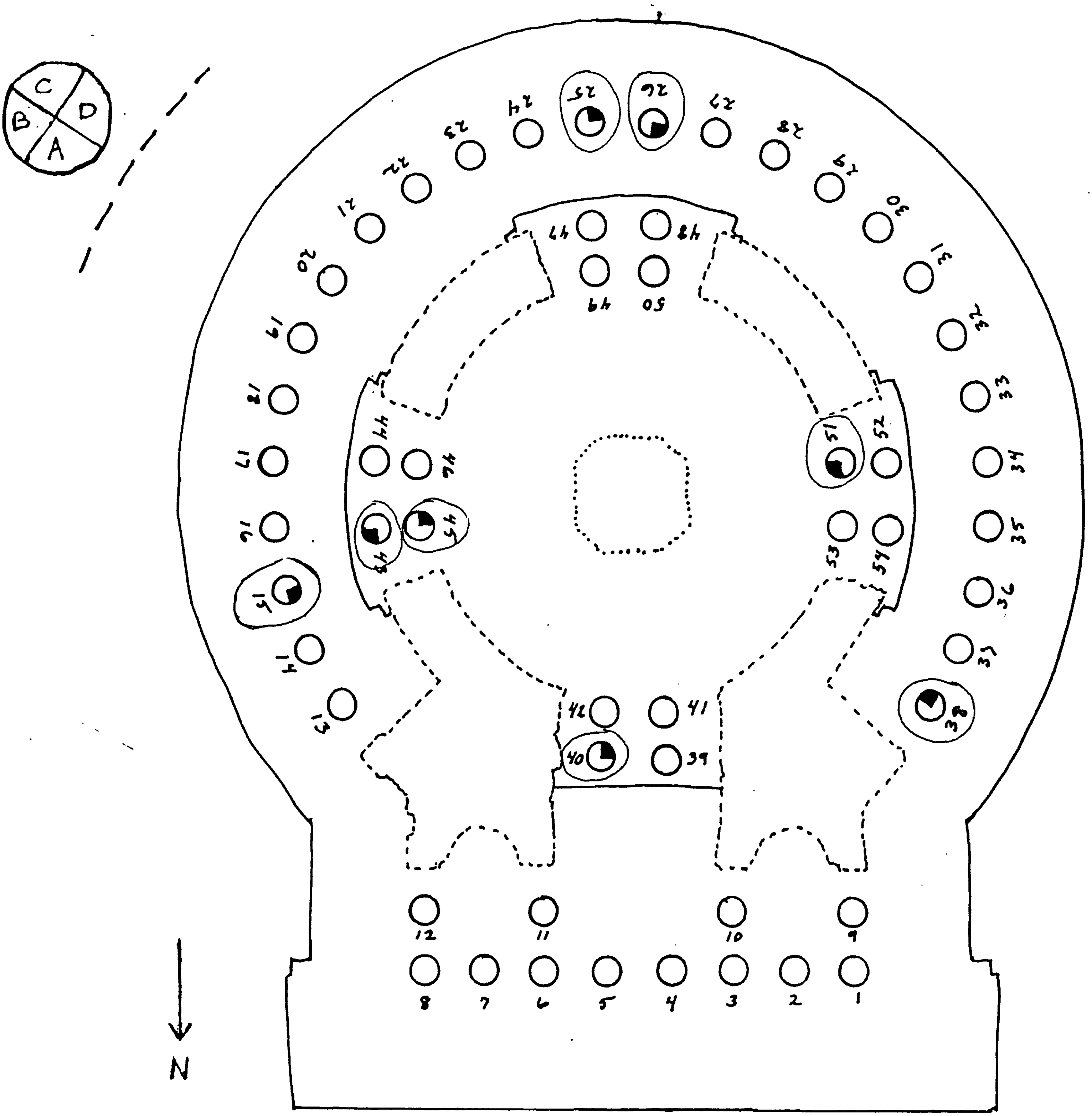


Figure 1. Sketch of Memorial plan, showing column numbers and locations; columns where volutes have been removed are shown with the appropriate quadrant marked in black.

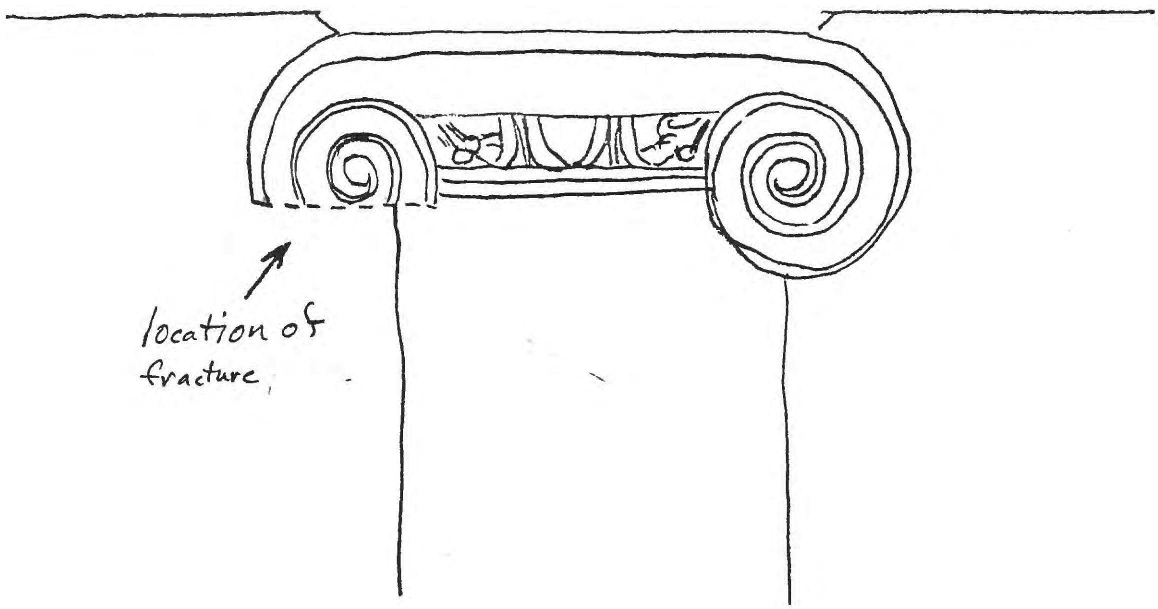


Figure 2. Sketch of a column capital, to show the location of a typical missing portion of a volute.

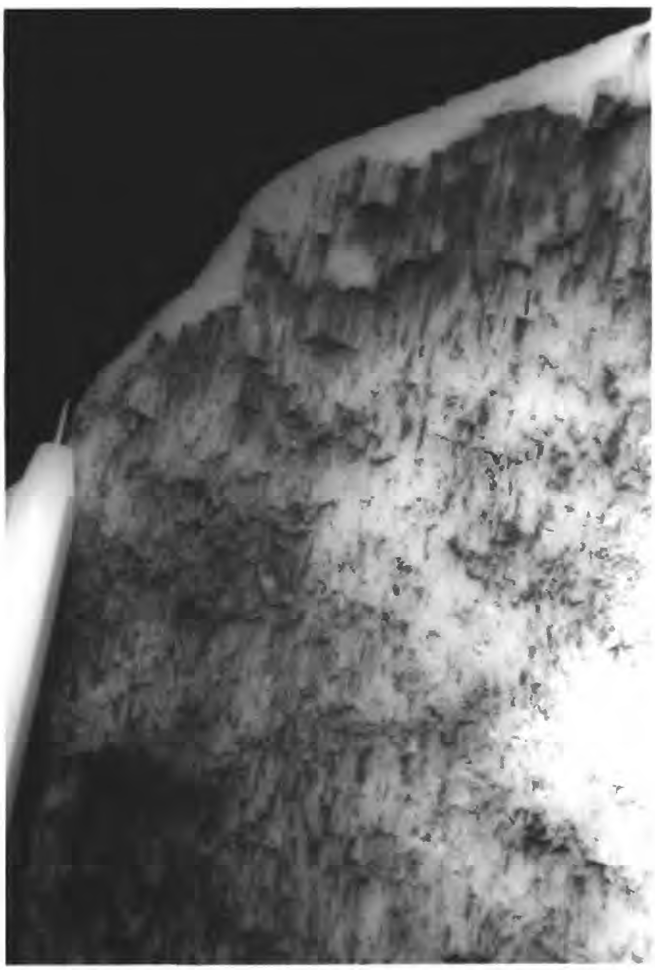


Figure 3A. Example of fracture form: Stepping fracture.

Figure 3B. Example of fracture form: Massive fracture.

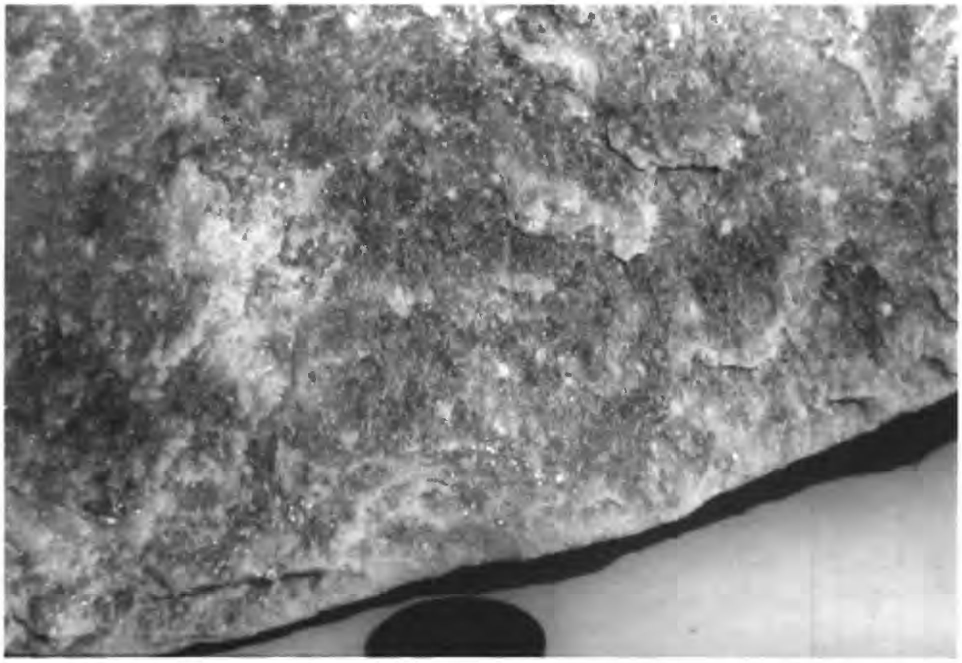


Figure 3C. Example of fracture form: Planar fracture. Penny (lower center) for scale.

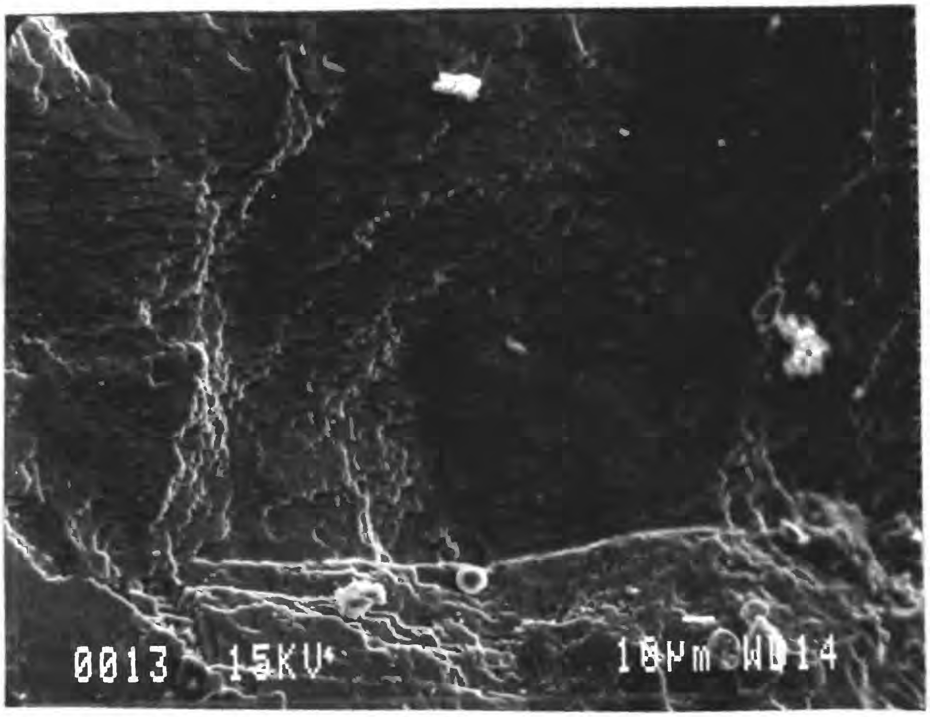


Figure 4. Blocky, stepped calcite seen with scanning electron microscopy, sample 15A. See also photos for samples: 15A, 38A, 43B, 45D, 51D.

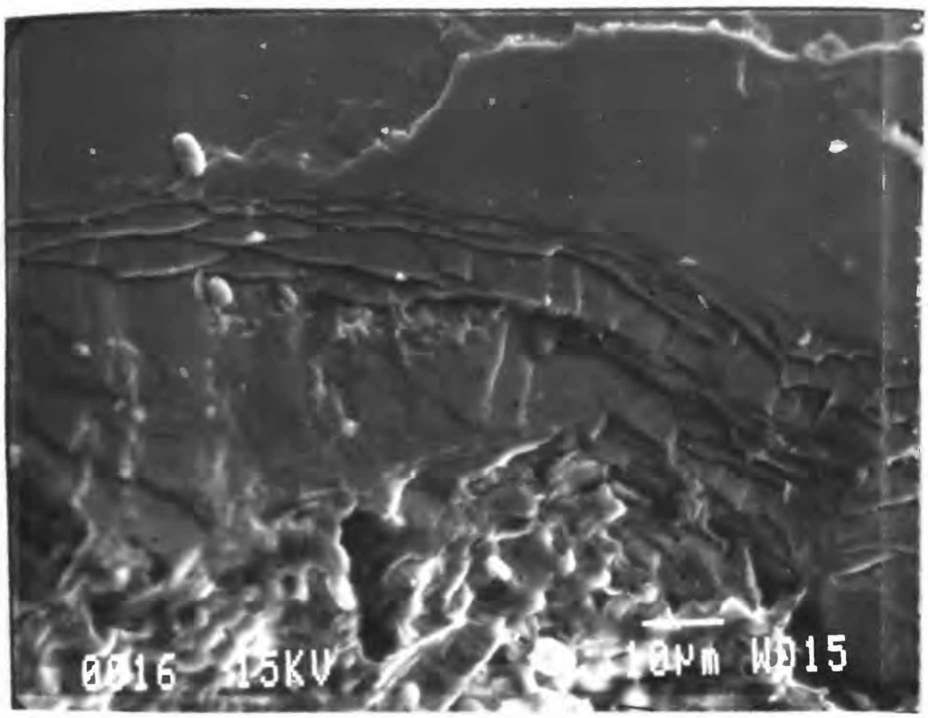


Figure 5. Planar habit of calcite seen with scanning electron microscopy, sample 25C. See also photos for samples: 38A, 45D, 51D.

A.

B.

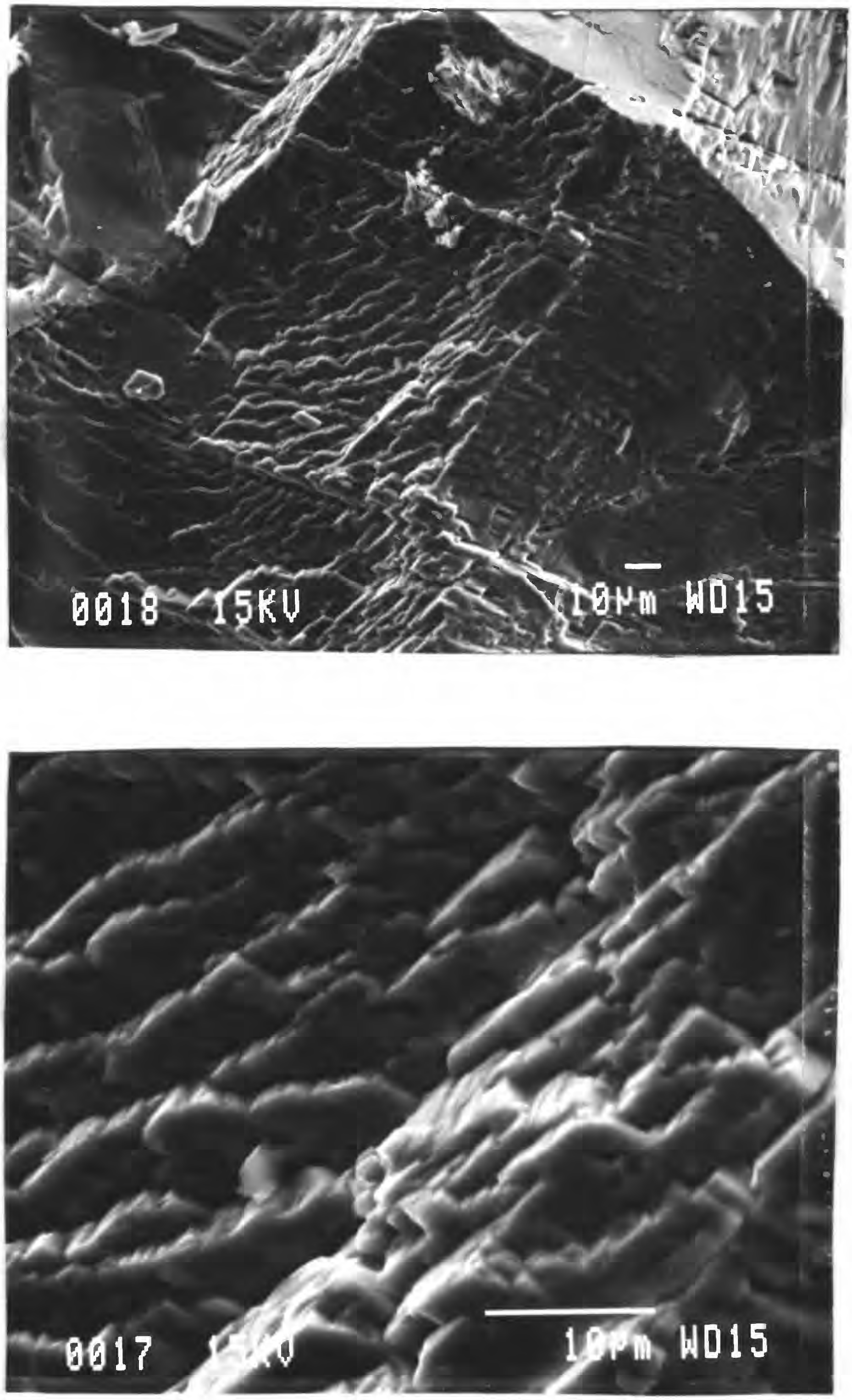


Figure 6. Stepped habit of calcite carries to even very fine scales, sample 51D; A. area of steps, and B. close-up view of center area shown in A.

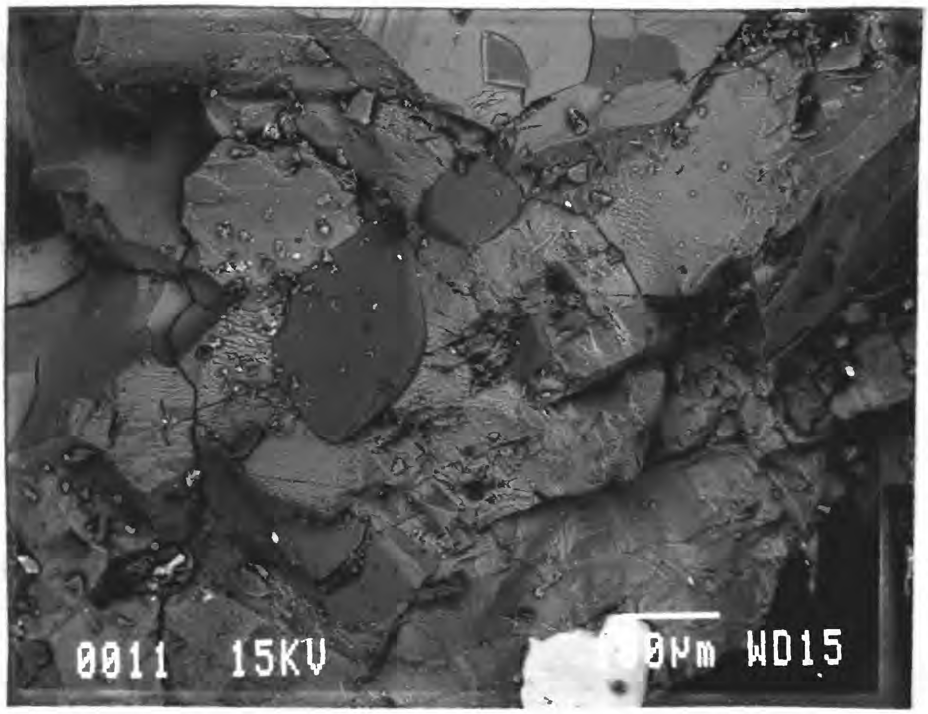


Figure 7. Sheet silicate inclusions are random, individual grains; sample 51D (backscattered electron image), mica grains are smooth darker gray grains with slightly rounded edges. See also photos for samples: 45D, 51D.

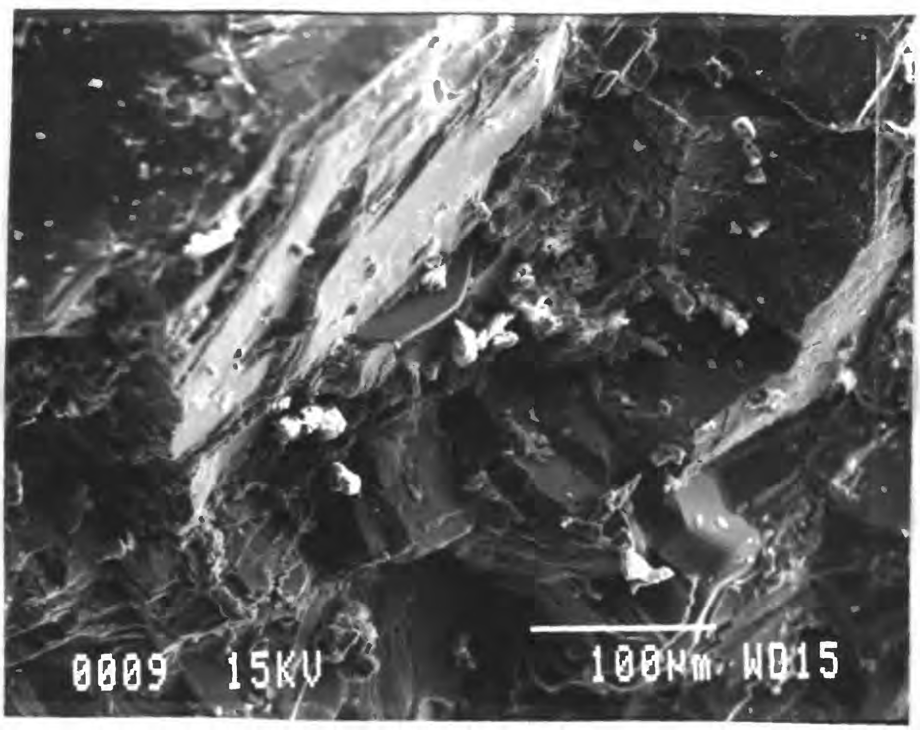


Figure 8. Inclusions in clusters that are co-planar with the calcite, sample 51D. Mica grains at the center and lower right corner of the photograph protrude from the calcite ledges and have smooth surfaces and hexagonal edges.

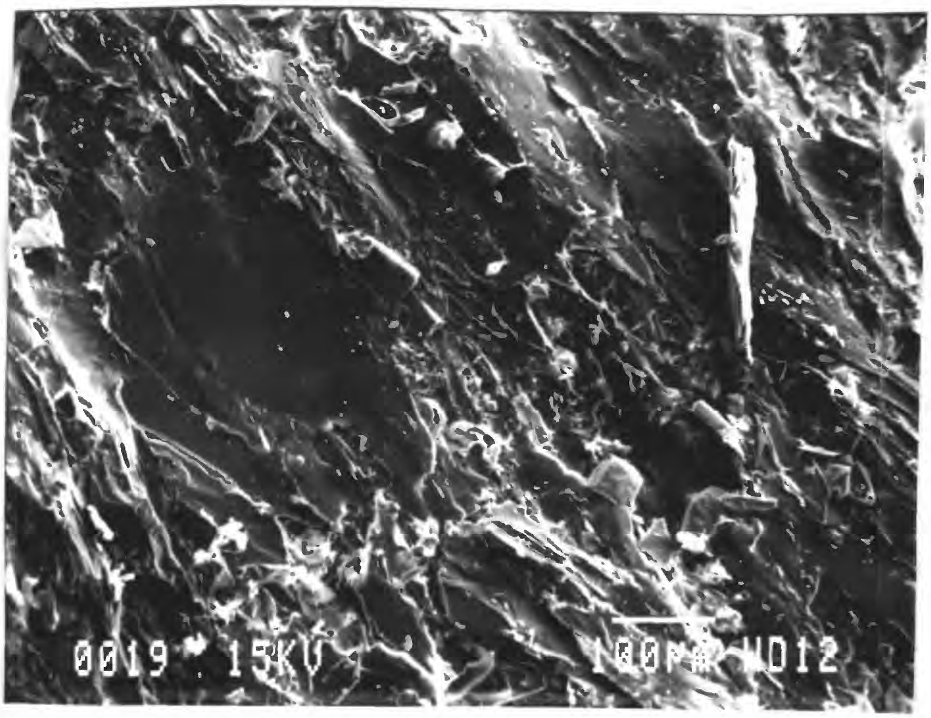


Figure 9. Mica predominant surface texture is in sheaves of grains that are not blocky; sample 26D; compare with blocky calcite photos in figure 4. See also a localized area of mica-rich inclusions in photos of sample 45D.

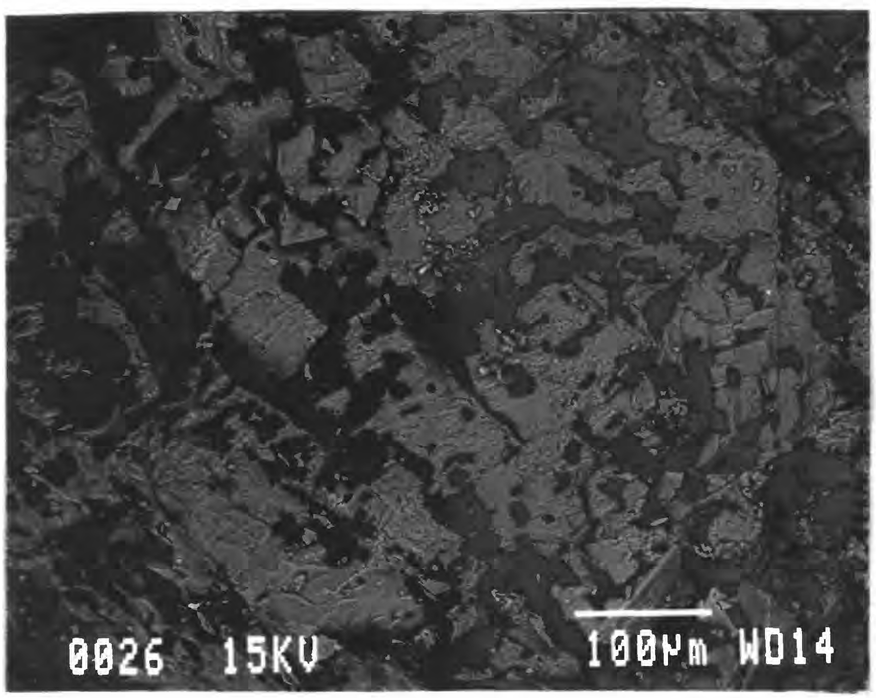


Figure 10. Organic accumulation appears black in a backscattered electron image of sample 25C, but does not hide the dominant surface feature of blocky, stepped calcite. See other photos for 25C.

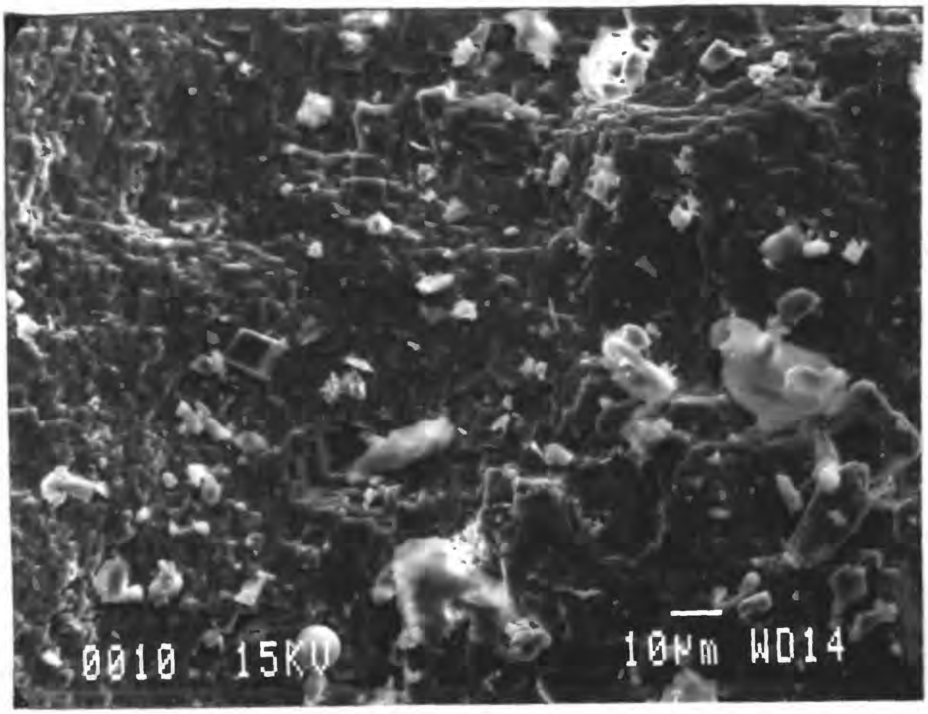


Figure 11. Dirt and particulate accumulation appears as surficial litter on the stepped calcite surface underneath, sample 15A. See also photos for 25C, 45D.

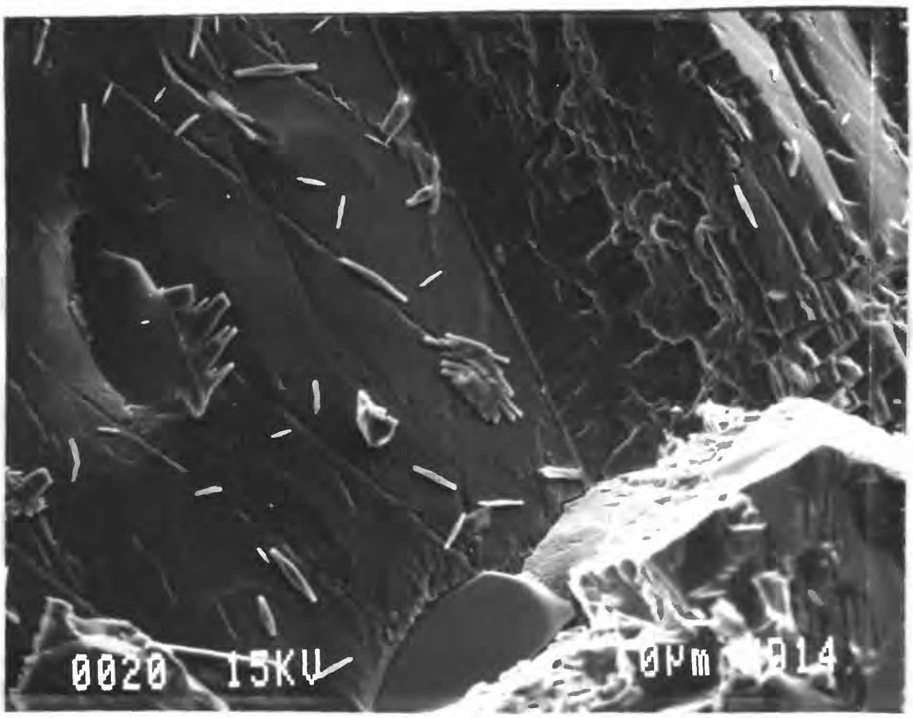


Figure 12. Gypsum crystals appear as small needles on the calcite surface; some of the needles have begun to form small clusters but all are small and the dominant surface feature is the habit of the calcite; sample 51D. See also photos for 43B, 51D.

Table 1. Dimensions of the eight column pieces.

Sample #	length (in.)	depth (in.)	height (in.)	weight (lbs)
15A	18.75	10.0	7.75	34
25C	14.62	3.25	2.87	6
26D	19.5	6.75	5.0	17
38A	20.5	8.37	6.56	30.75
40A	19.12	5.37	4.75	15.25
43B	20.0	7.5	6.44	27
45D	19.37	8.12	5.75	22.25
51D	18.75	5.5	4.88	16.5

Length, depth, and height measurements are in inches and were made perpendicular to one another. Length is measured from side to side over the fracture face, depth is from front to back across the fracture face, and height is measured across the outer face perpendicular to the lower edge and toward the center of the volute (thus, forming a portion of the volute radius). Weight is measured in pounds; the weight for 43B includes both pieces but for 15A only the single large piece was weighed.

Table 2. Estimate of surface area covered by fracture type.

Sample #	% Stepped	% Planar	% Massive
15A	10	80	10
25C	40	0	60
26D	0	90	10
38A	35	60	5
40A	50	30	20
43B	20	70	10
45D	40	50	10
51D	0	0	100*

* This figure may be somewhat misleading; 80% of the area has some planar character and was identified as "massive-planar".

Table 3. Visual Hierarchy of Blackening on Each Face

	Outer Face	Inner Face	Fracture Face
Darkest	38A	40A	26D
	43B	26D	40A
	40A	43B	25C
	26D	15A	38A
	51D & 45D	45D	45D
		38A	43B
Whitest	15A	51D	15A
	25C	25C	51D

The estimate of darkest reflects a combination of the most area and most pronounced accumulation of dirt. Sample 25C has a coarse and roughened surface so it doesn't really fit into the scheme of darkened surface. The inner faces of all the samples have some darkened areas, but none are as uniformly dark as the outer faces. There may be a broader similarity in the darkening on the inner faces compared with the outer faces, because the inner faces are sheltered by the column and may have received a more similar exposure than the outer faces.

Table 4. Mineral Phases Identified On Each Fracture Face

SAMPLE #	MINERAL PHASES FOUND major	minor	rare
15A	calcite		rutile, albite, dolomite
25C	calcite	muscovite	
26D	phlogopite, chlorite	pyrite	calcite, apatite
38A	calcite		
40A	calcite		
43B	calcite		muscovite, albite, rutile
45D	calcite	chlorite, phlogopite	rutile
51D	calcite	muscovite	sphene

Major mineral phases are the predominant mineral present on the sample; minor phases are observed in several places and are perhaps 5% of the sample; rare phases are those where one or two grains were found in examining the sample, they probably constitute less than 1% of the phases present on the fracture surface.

These phases were identified with qualitative energy dispersive X-ray spectra. These phases are not alteration phases but are part of the original stone. Only in sample 26D is a phase other than calcite the most abundant; in all the other samples, calcite is by far predominant, while all other phases occur as random grains or in localized clusters.

Quartz was commonly observed as part of the "dirt" present as loose grains on the calcite surface. Gypsum was found as small, individual crystals growing on the surface of calcite grains or as small clusters in protected cracks of the calcite. The gypsum most likely formed on the fracture surface after the crack had opened, while it accumulated moisture, dirt, and pollutants; it is unlikely that it contributed to the growth of the cracks. Gypsum was identified on the following samples: 25C, 38A, 43B, 45D, 51D.

Table 5. Buildings in Washington, DC with Ionic Columns

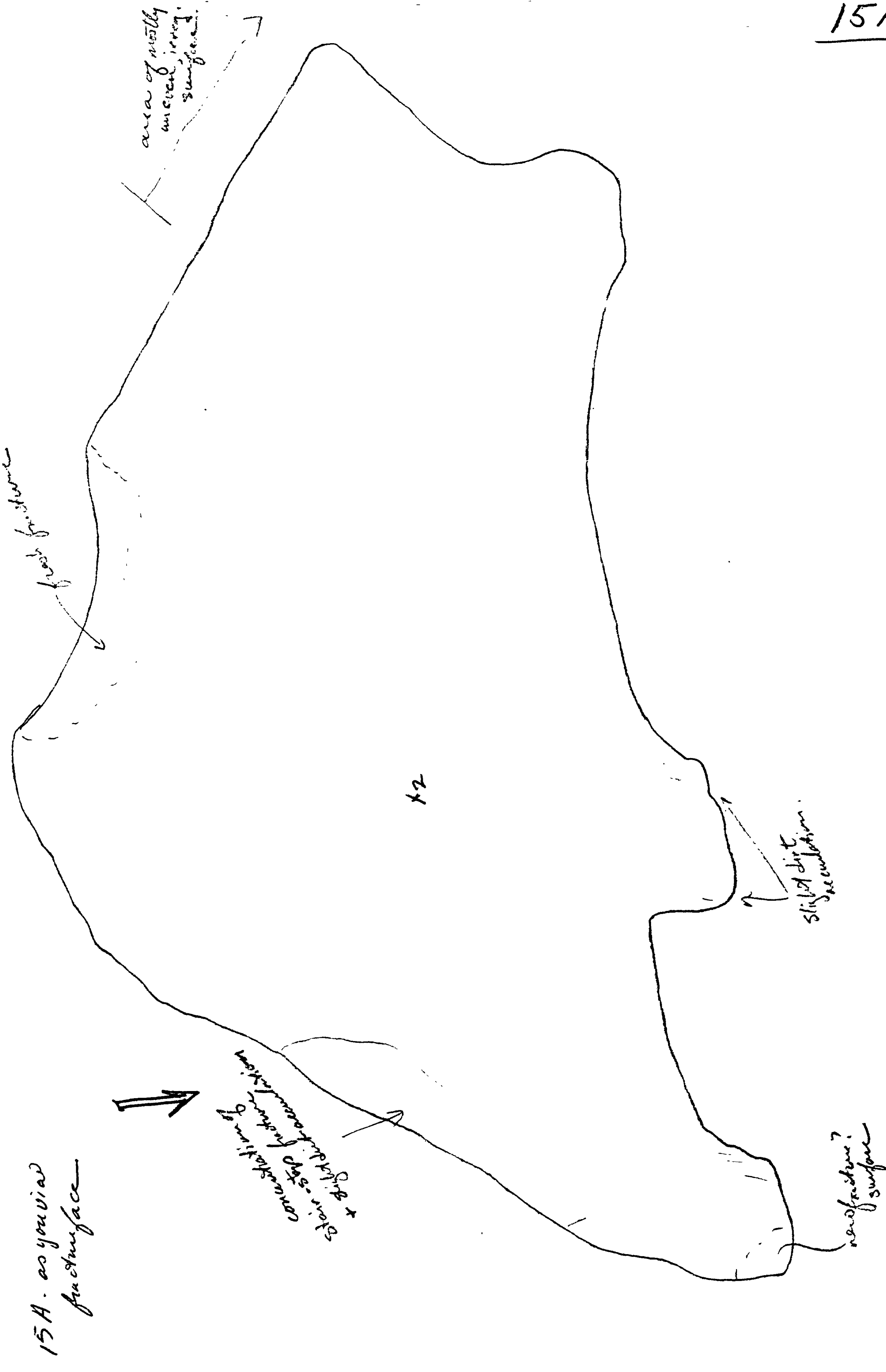
Building	Year Built	Stone
White House	1814	sandstone/marble
Treasury Building	1839/1869	sandstone/granite
Memorial Continental Hall	1909	marble
Constitution Hall	circa 1930	limestone
Apex Building	1937	limestone
National Gallery of Art	1941	marble
Rayburn Building	1965	marble
Union Station	??	granite(?)

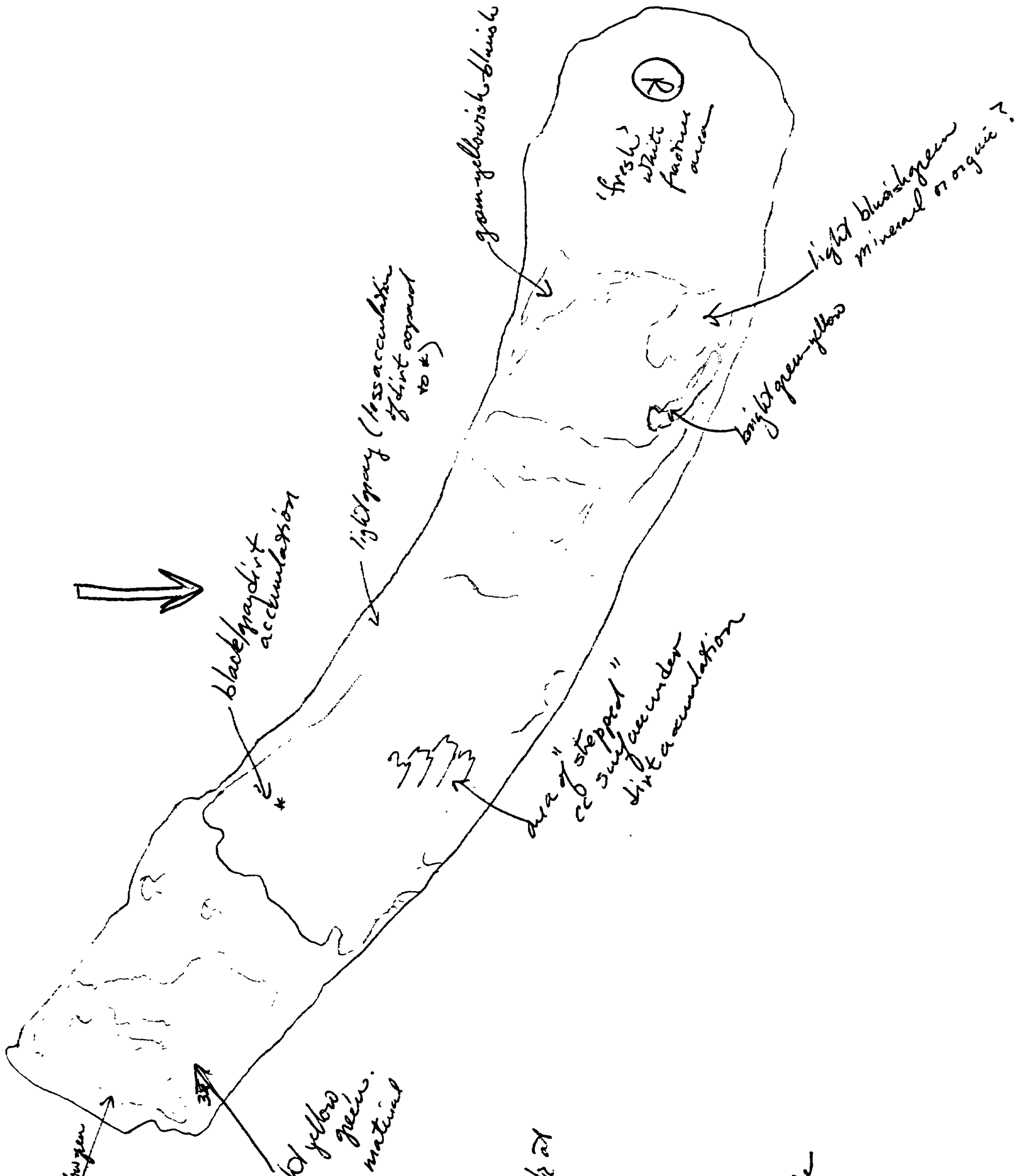
Appendix 1. Sketches of Fracture Faces of the Samples

Traces were made of each face of each sample by laying the face on paper and drawing around the edge; the traces were then sent to the National Park Service for their files. Copies of the fracture face traces were reduced by 50% and are included in this appendix.

One set of reduced traces was used to sketch features observed on the samples and to note locations where small samples were removed for optical and SEM examination. Large arrows outside of the traces indicate the area and direction in which it appears that the fracture first opened, allowing subsequent penetration of water and dirt. Areas where it appears the most recent fracture occurred (i.e. where the sample broke as it fell or was removed) are indicated by an encircled uppercase R.

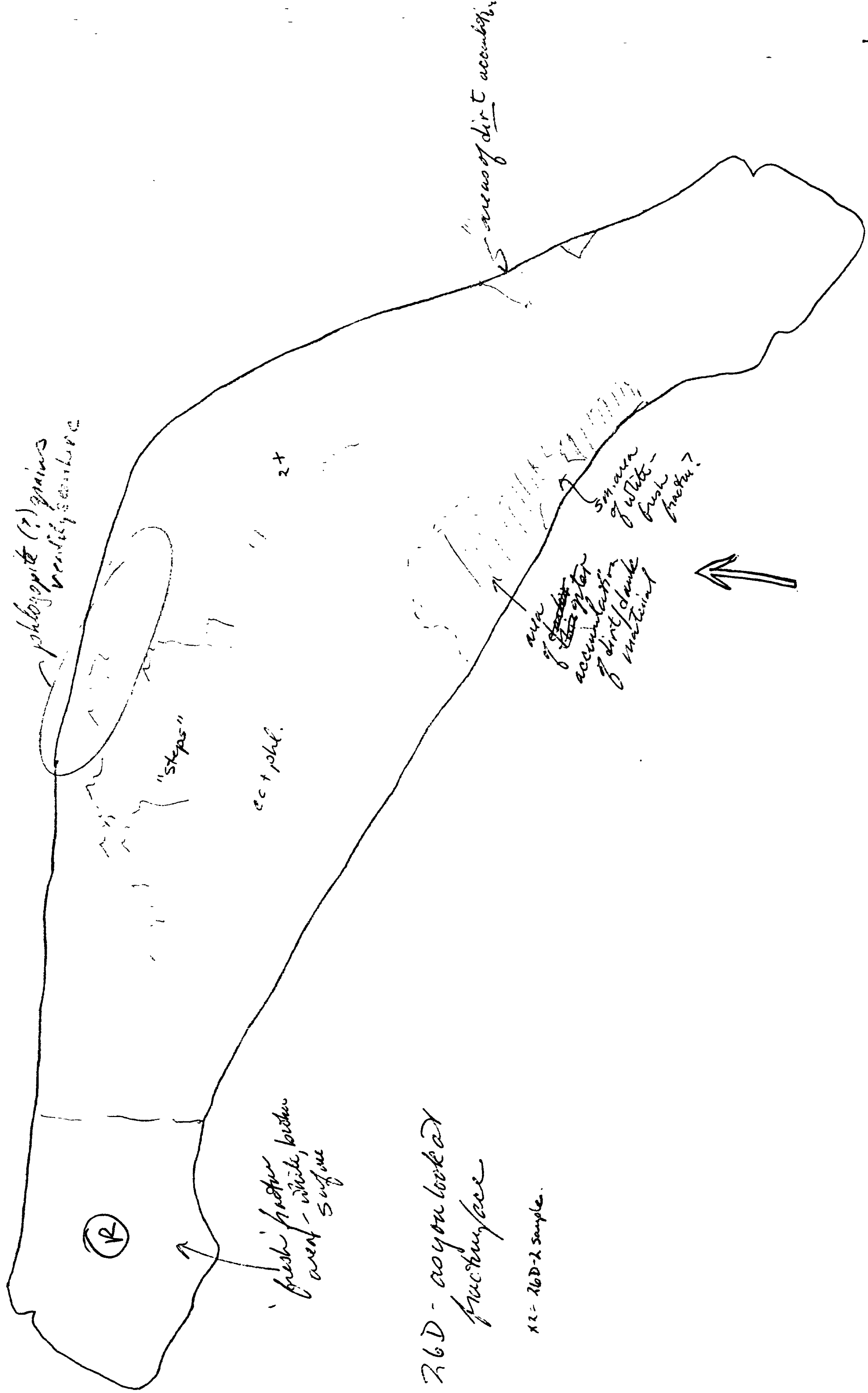
A second set of traces was used to designate areas on the samples with the mode of fracturing (stepping, planar, massive) present. Estimates of the approximate area covered by each type of fracture on the samples were made using the sketches in this appendix and tabulated in Table 2.

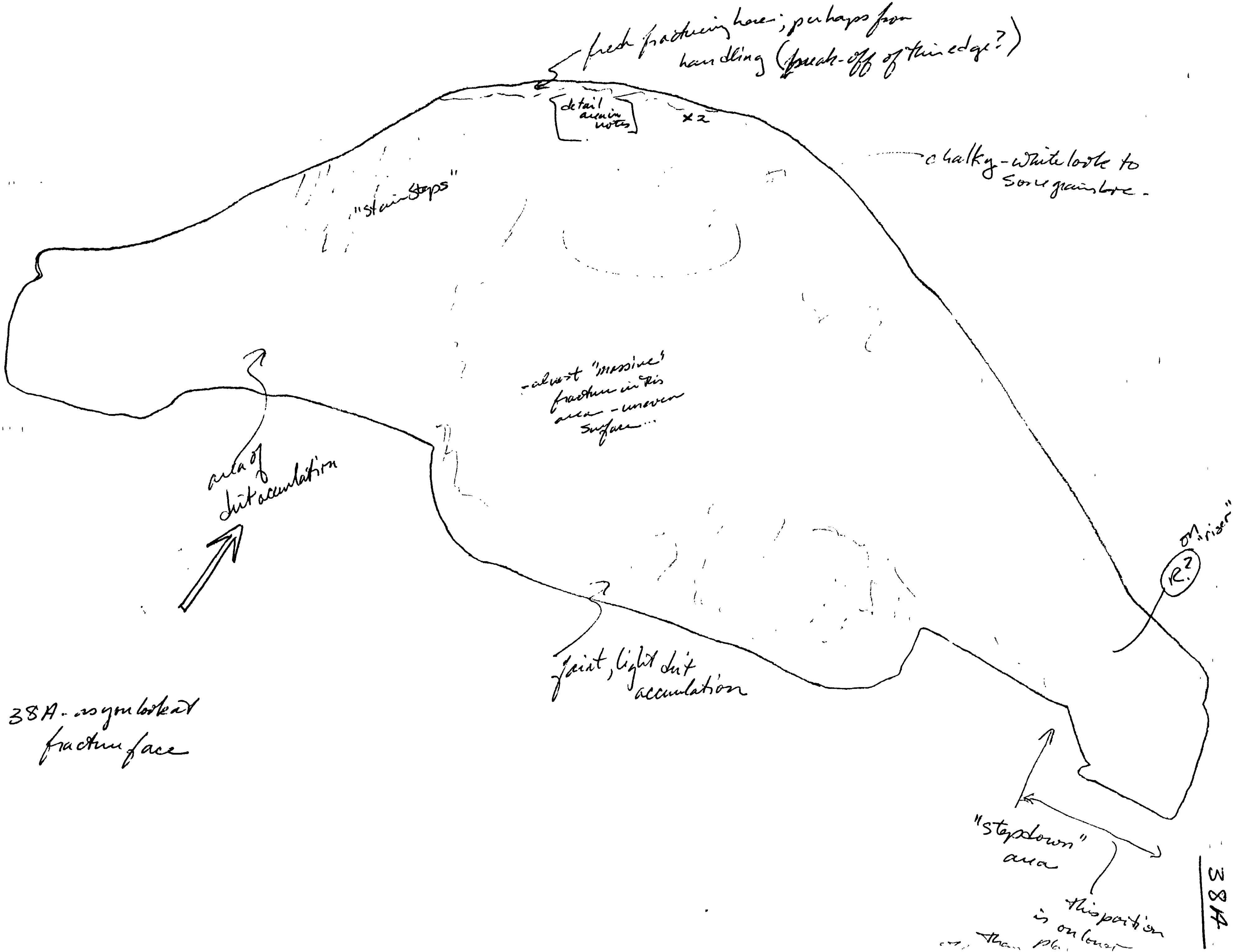

15A. as you view fracture face
fresh fracture
area of mostly uneven, irreg. surface
slight dirt accumulation
new fracture? surface
x2

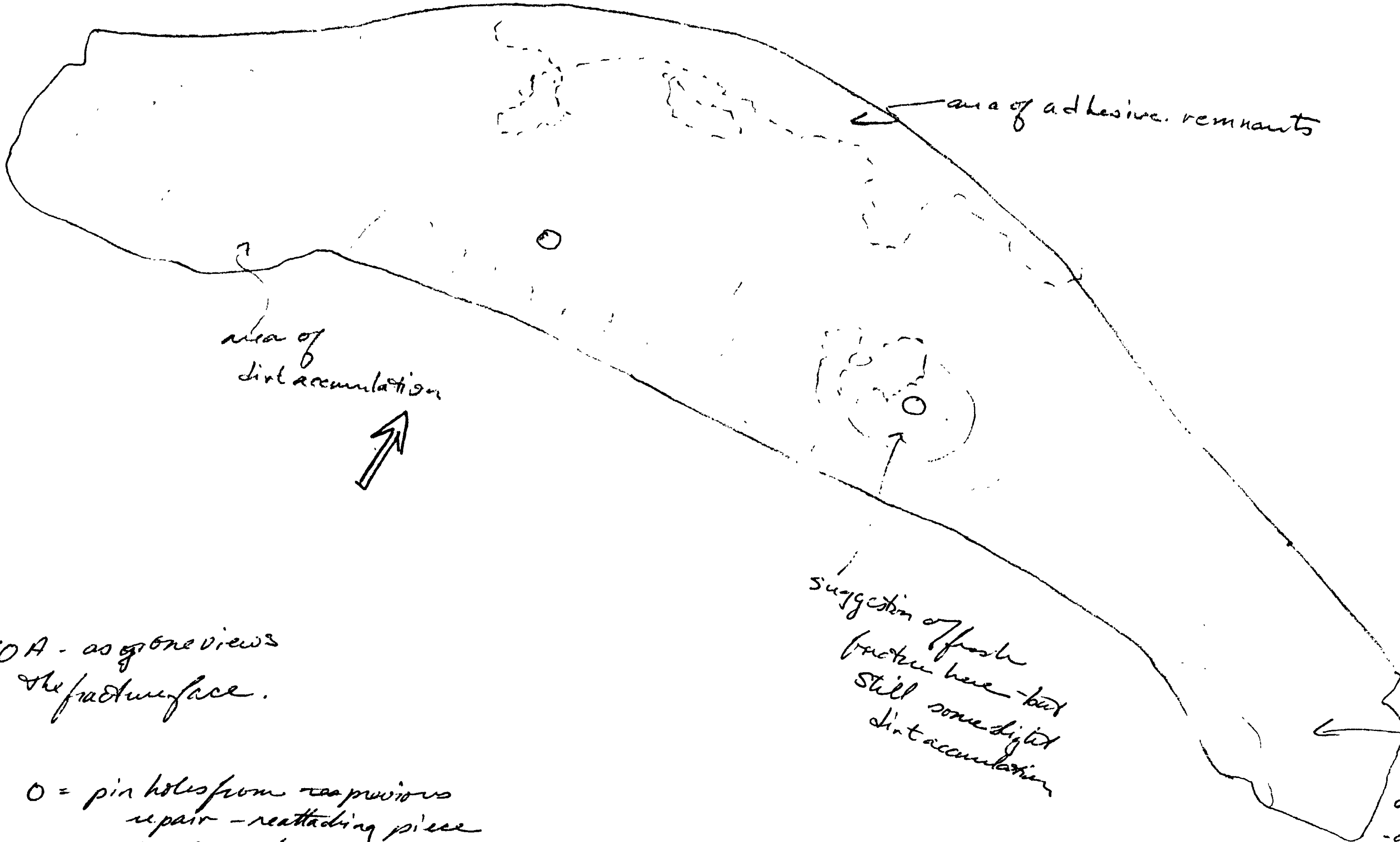


25C - as you look at fracture face

3X - 25C-3 sample

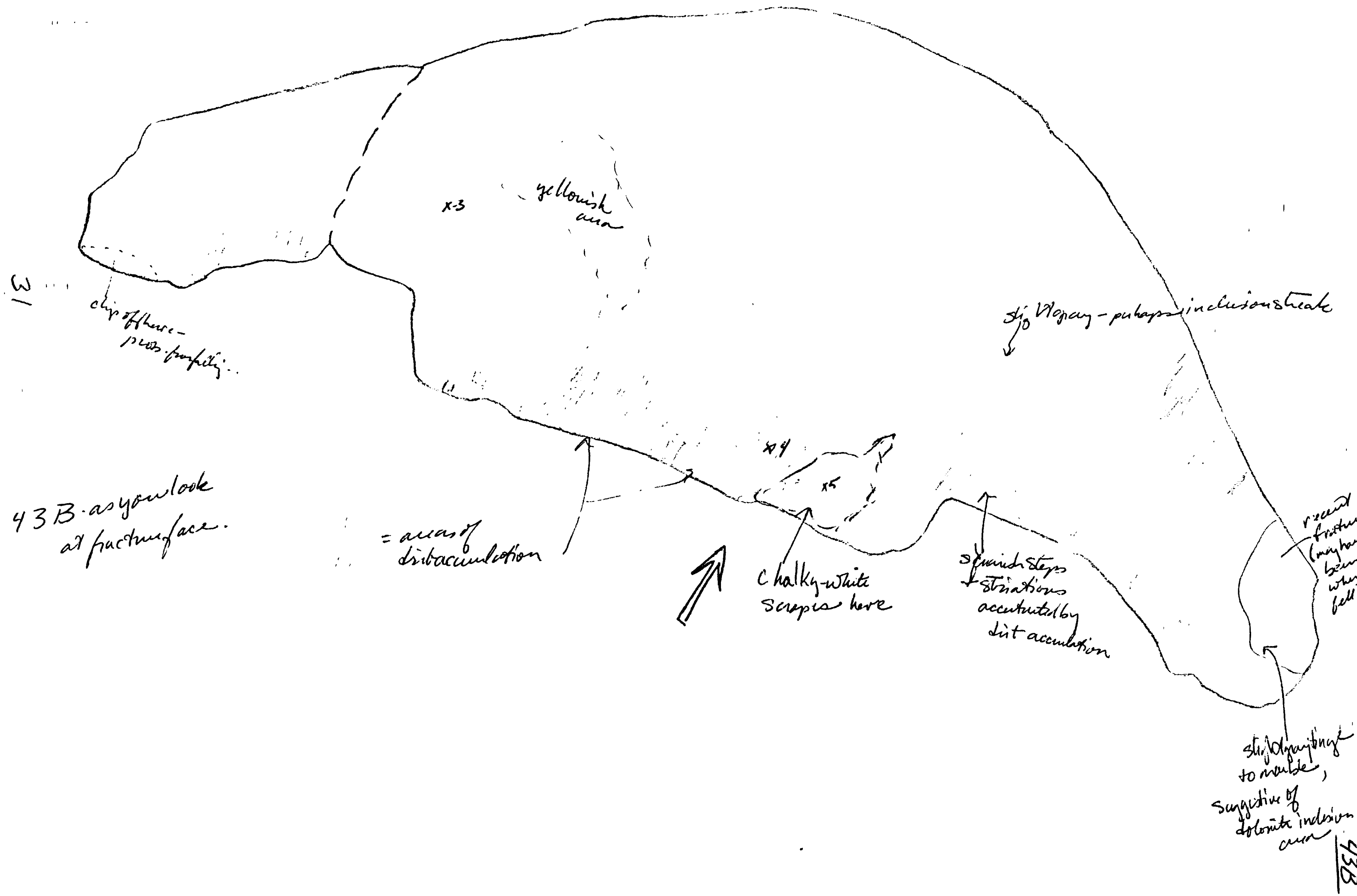

areas of dirt accum
"steps"
cc + phl.
R
x2 = 26D-2 sample.


fresh fracturing here; perhaps from handling (break-off of thin edge?)
detail area in notes
x2
chalky-white look to some grains here.
"stairsteps"
-almost "massive" fracture in this area - uneven surface...
area of dirt accumulation
faint, light dirt accumulation
on "riser"
R.²
"stepdown" area
this portion is on lower
38A - as you look at fracture face

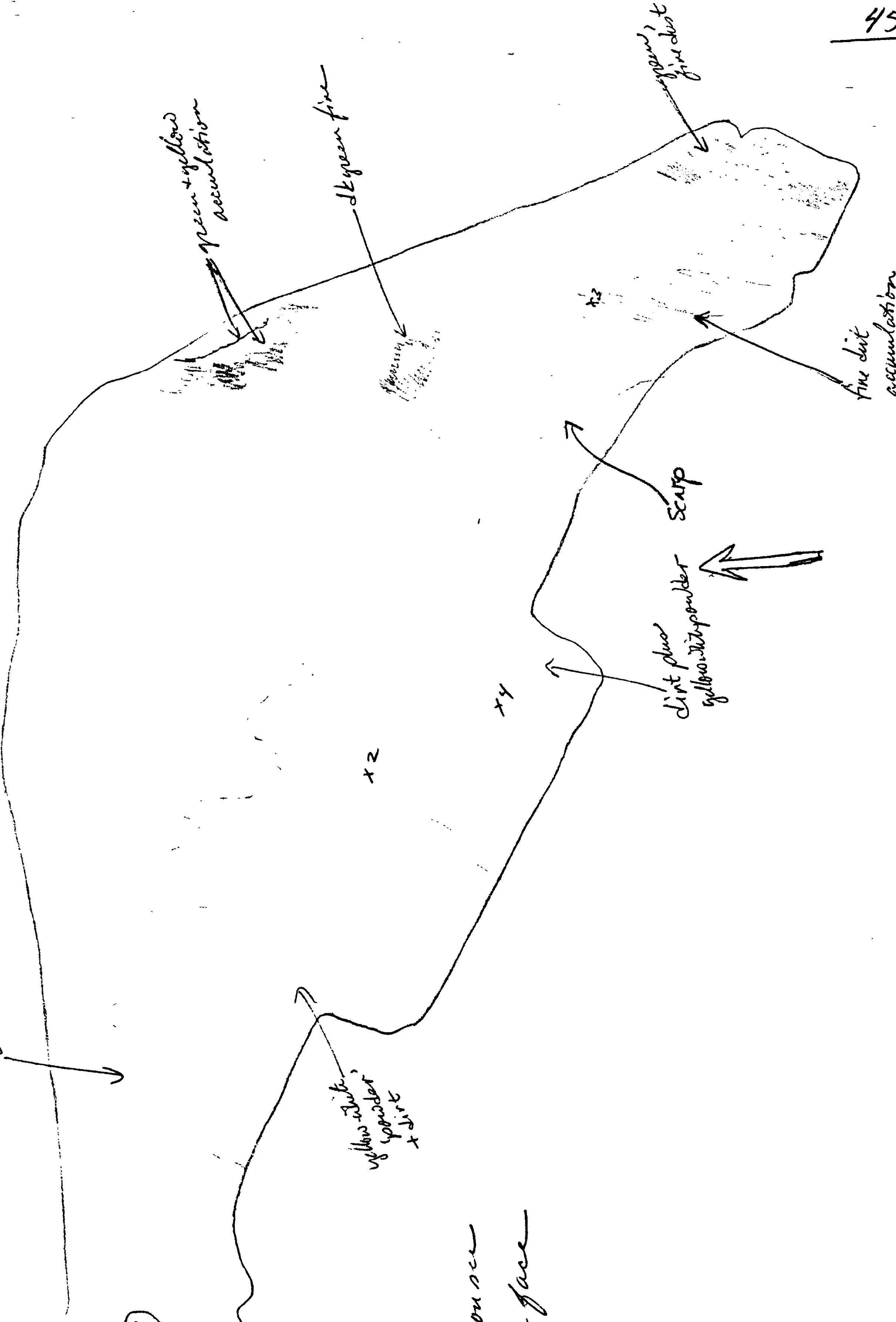


40A - as one views the fracture face.

O = pin holes from ~~the~~ previous repair - reattaching piece to column (see prelim. stone survey comments).

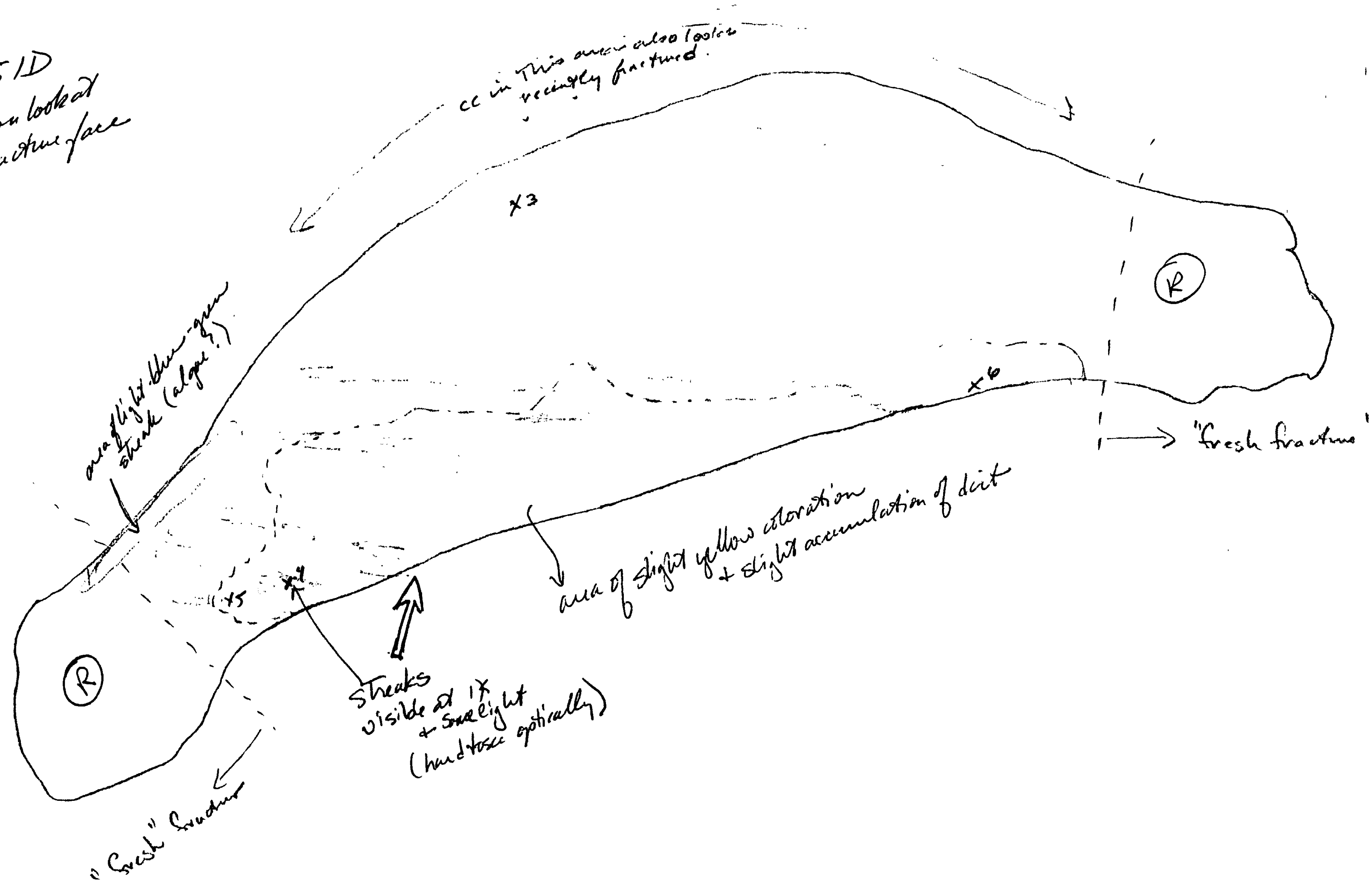


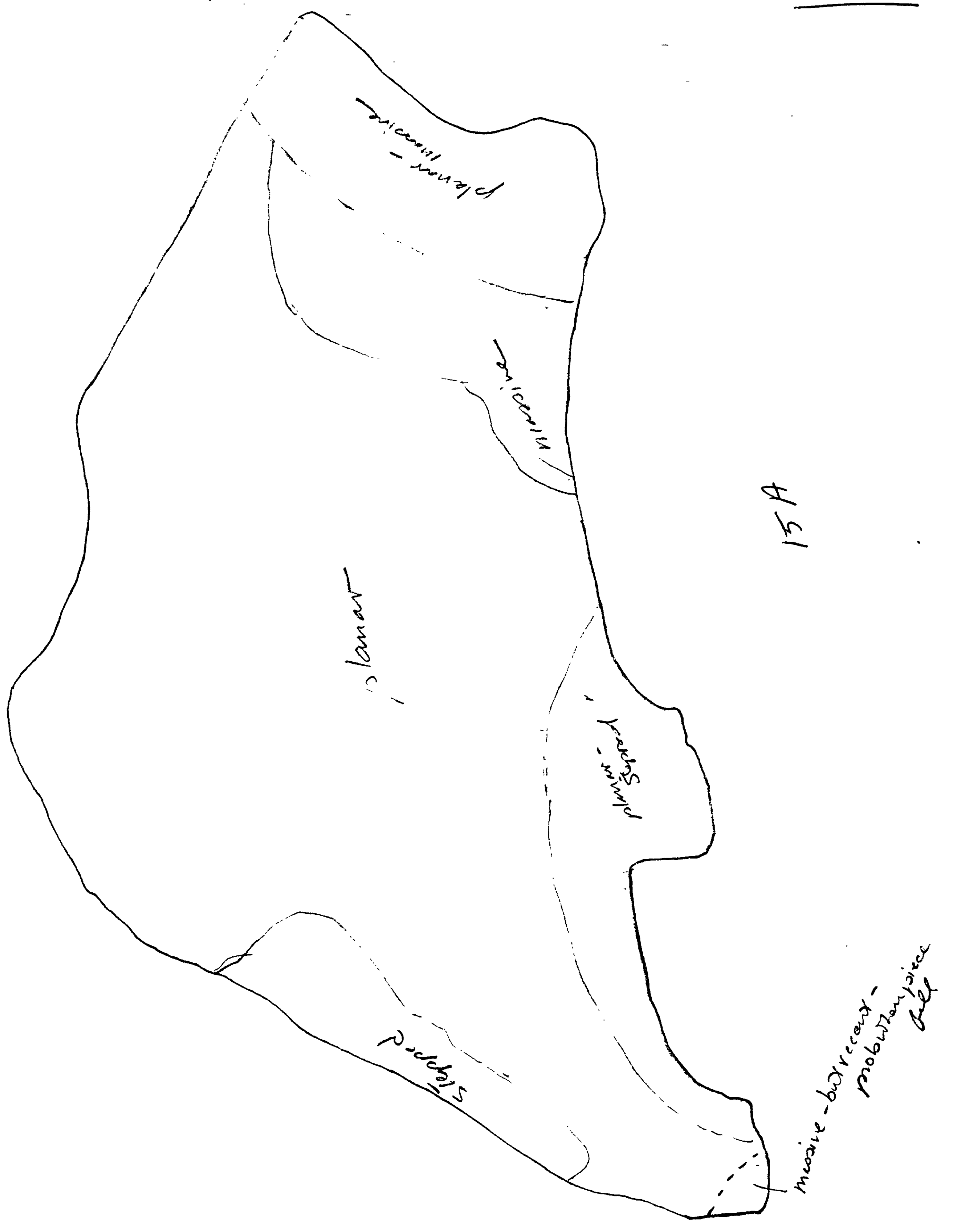
43B as you look at fracture face.

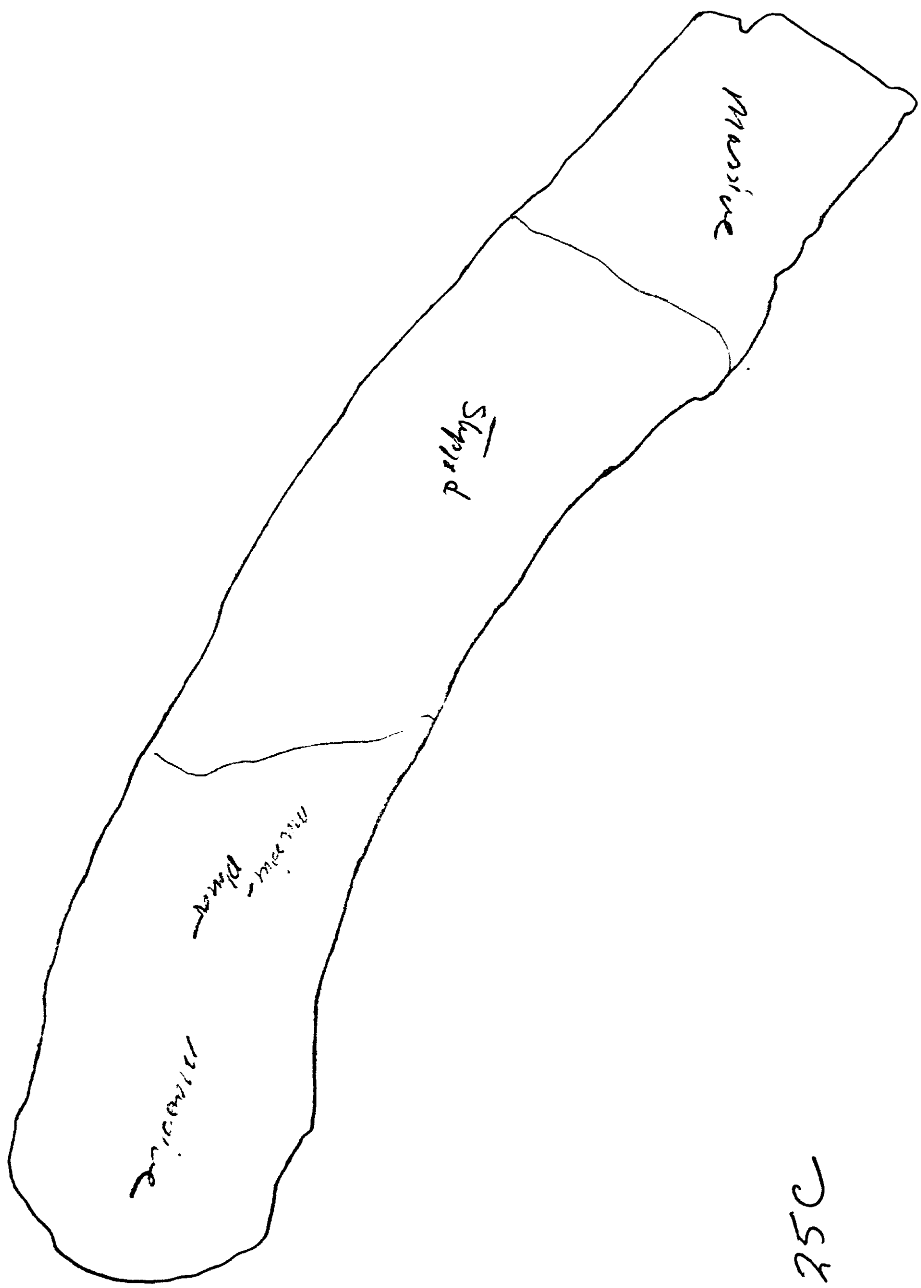


45D as you see fracture face

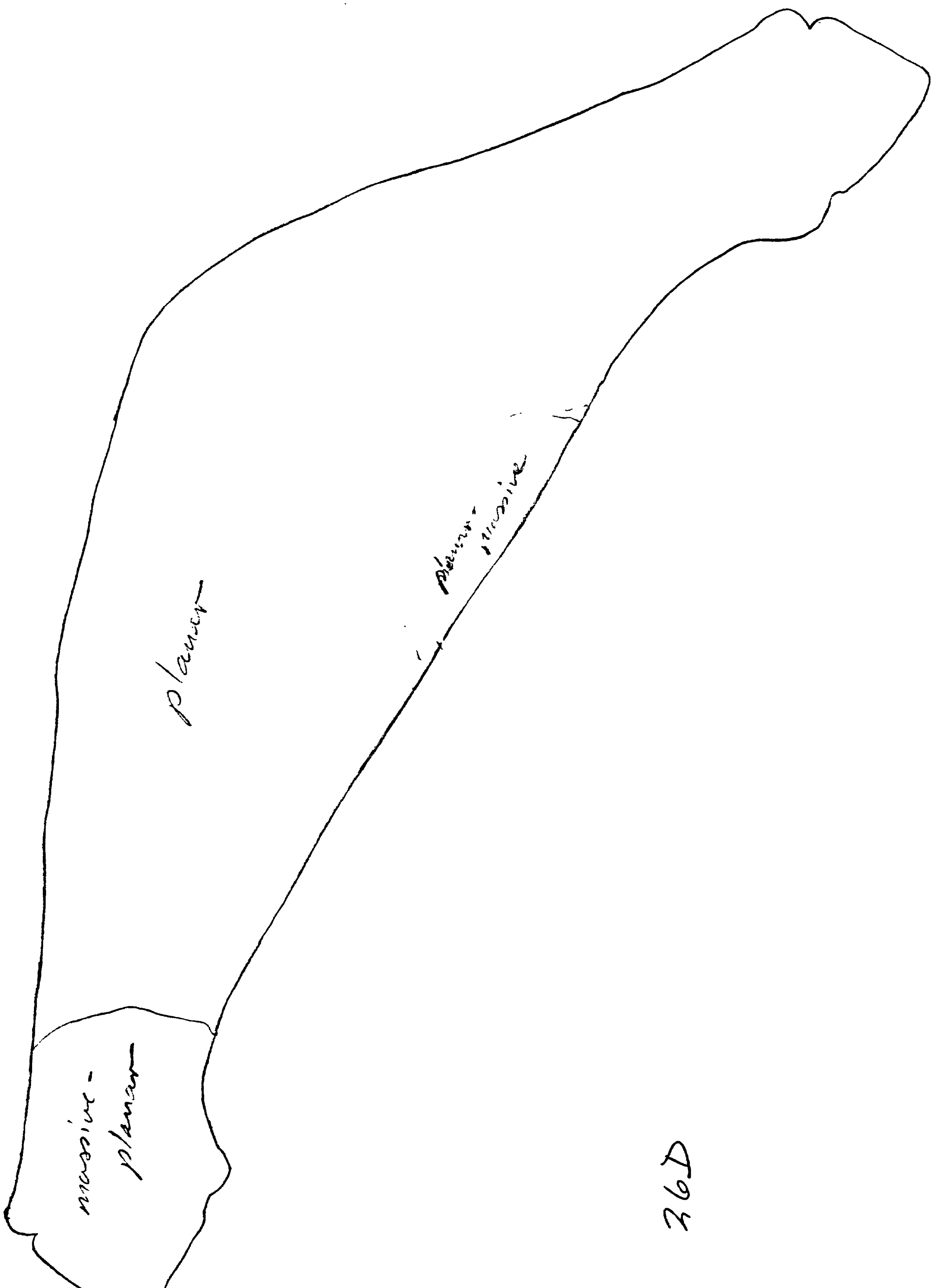
51D
as you look at fracture face



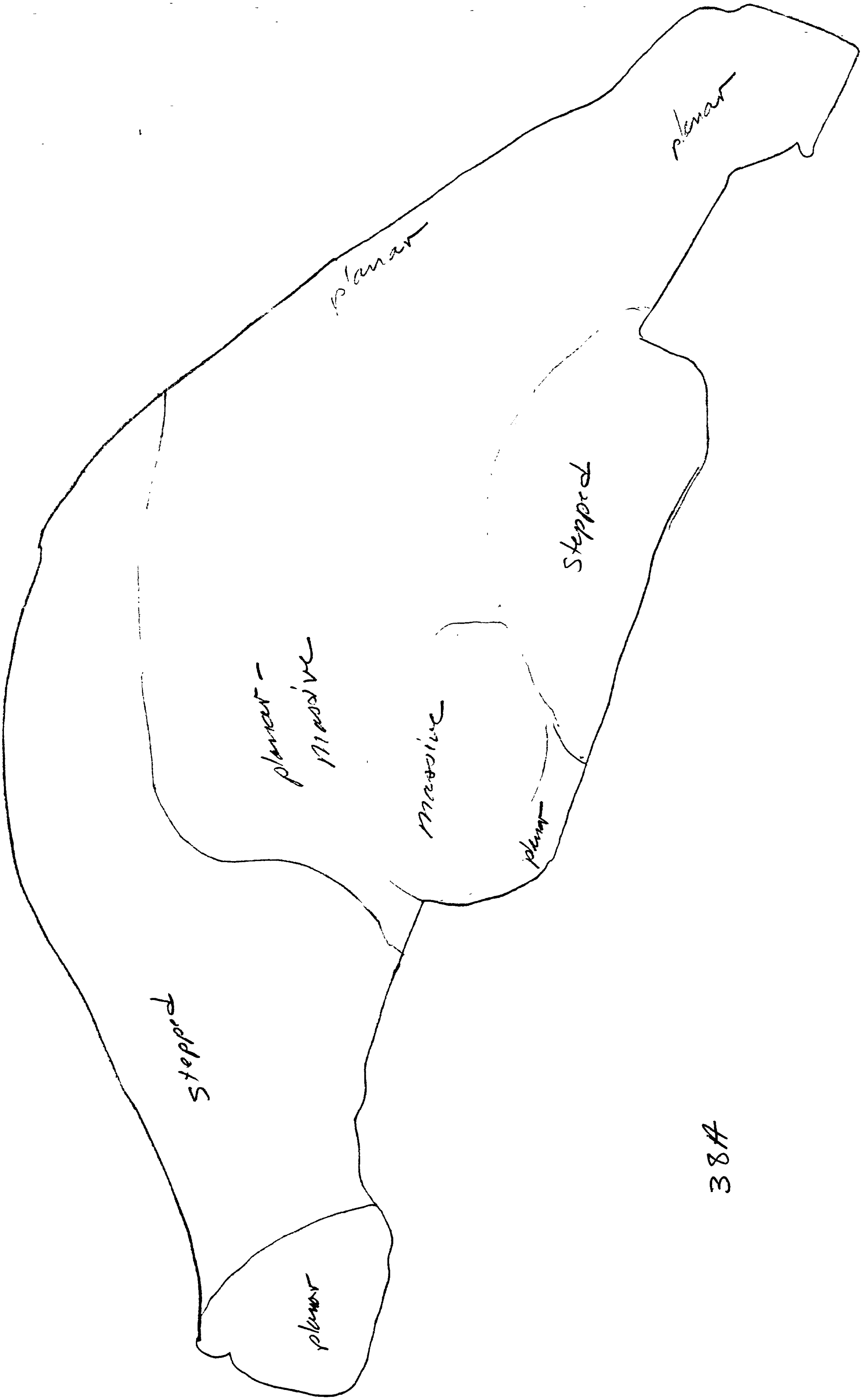

15A
planar
stepped
planar - stepped
massive - but recent - probably new piece fall



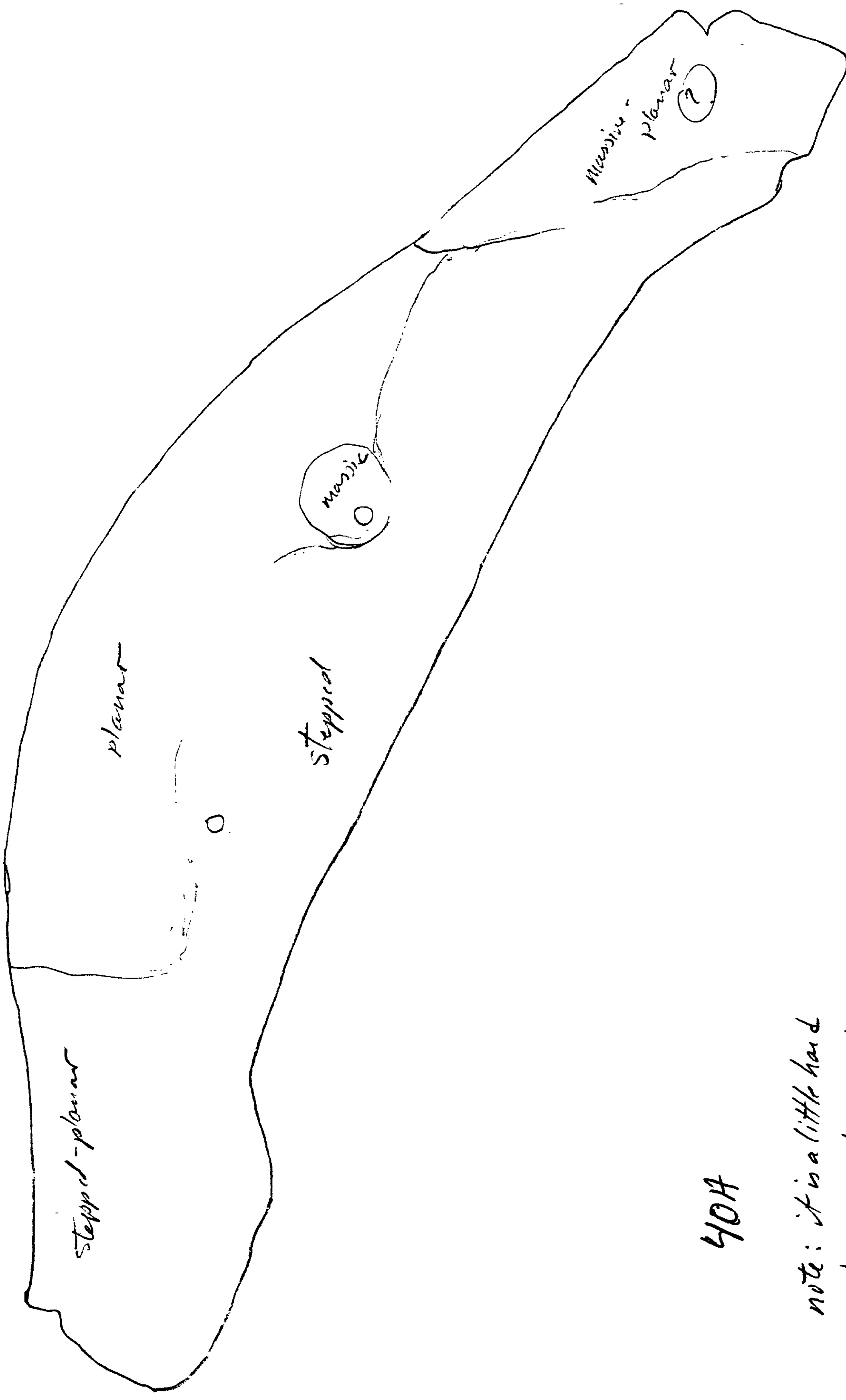
75C



36D

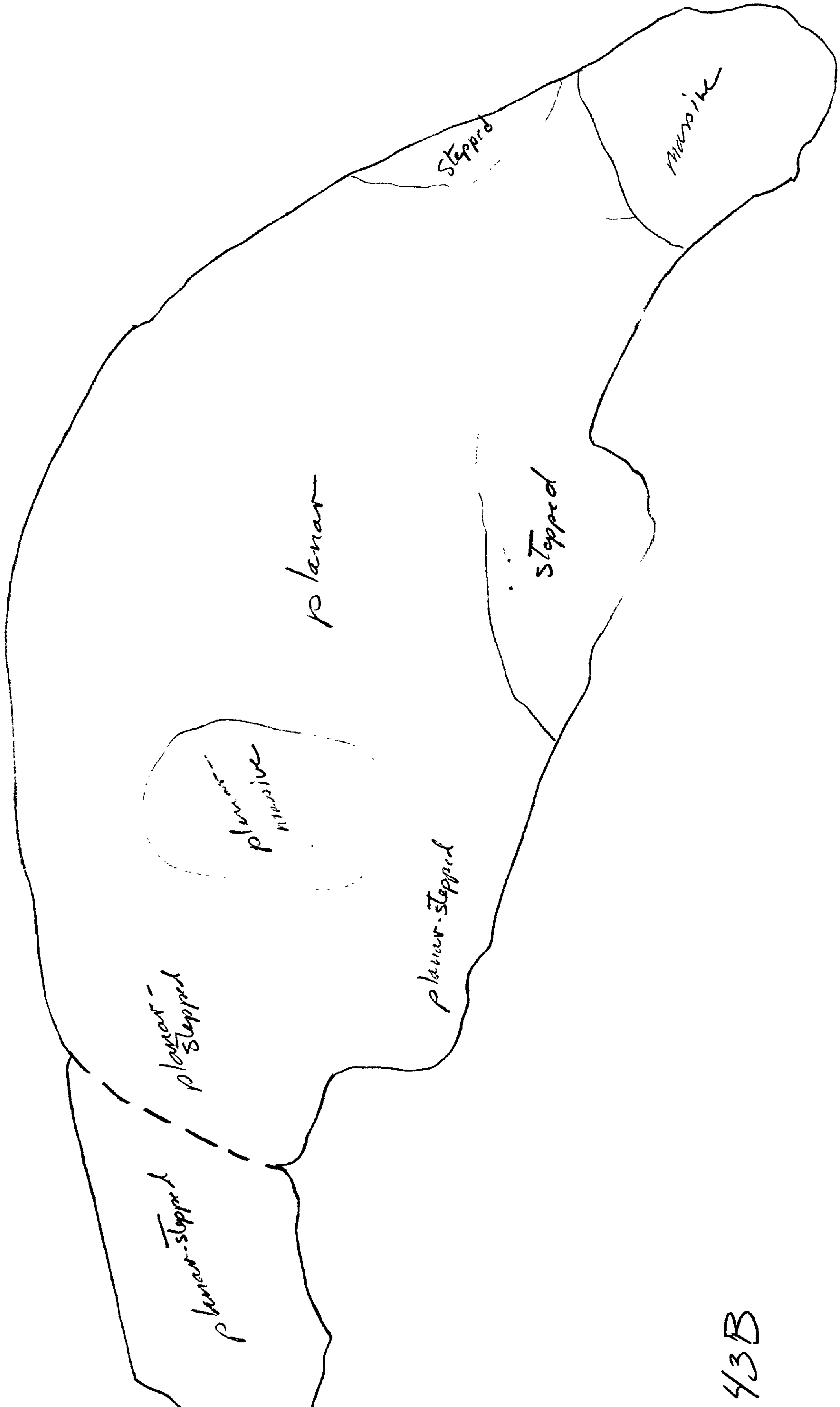

planar
planar
stepped
planar-
massive
massive
planar
stepped
planar

38A

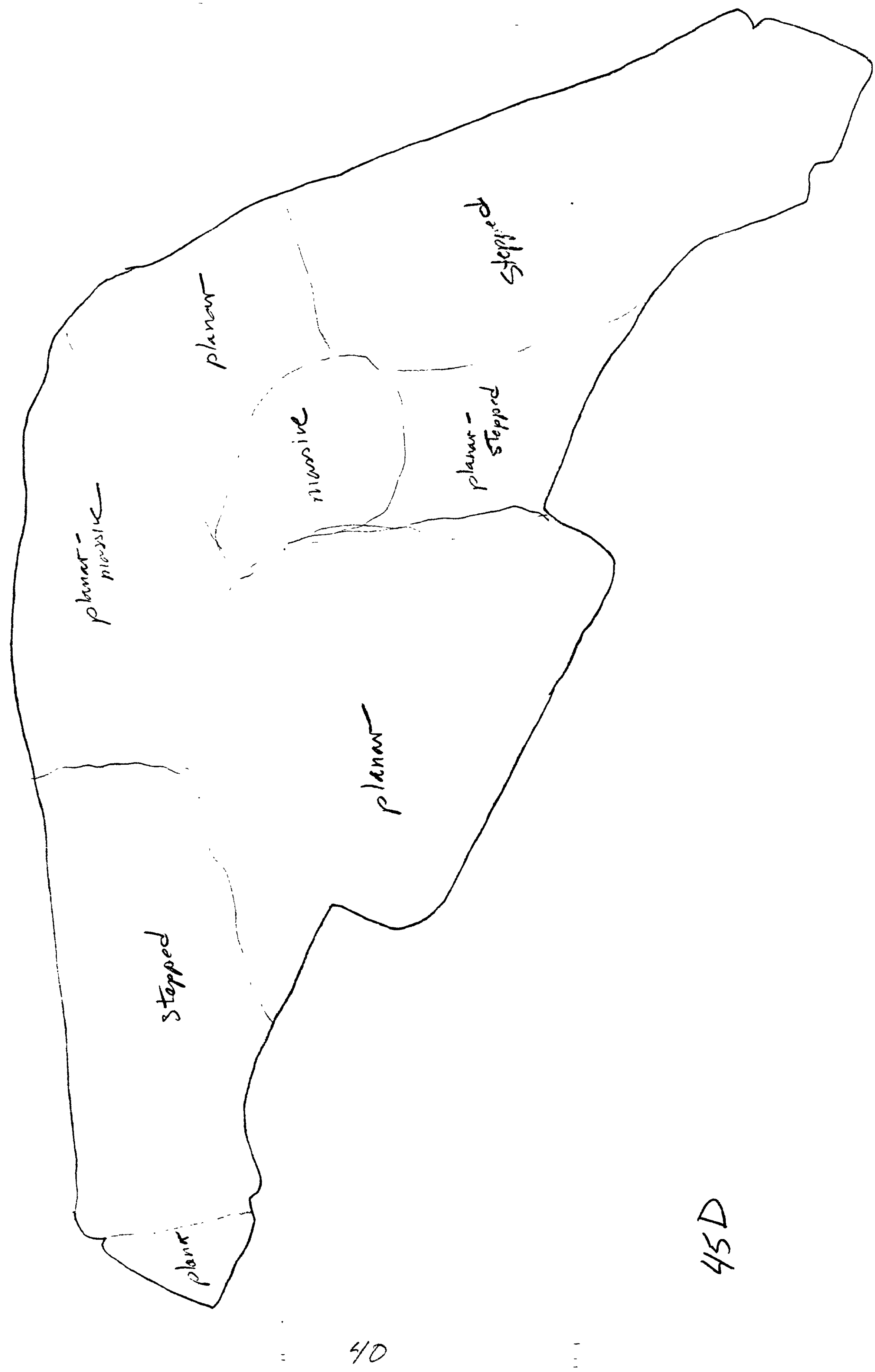


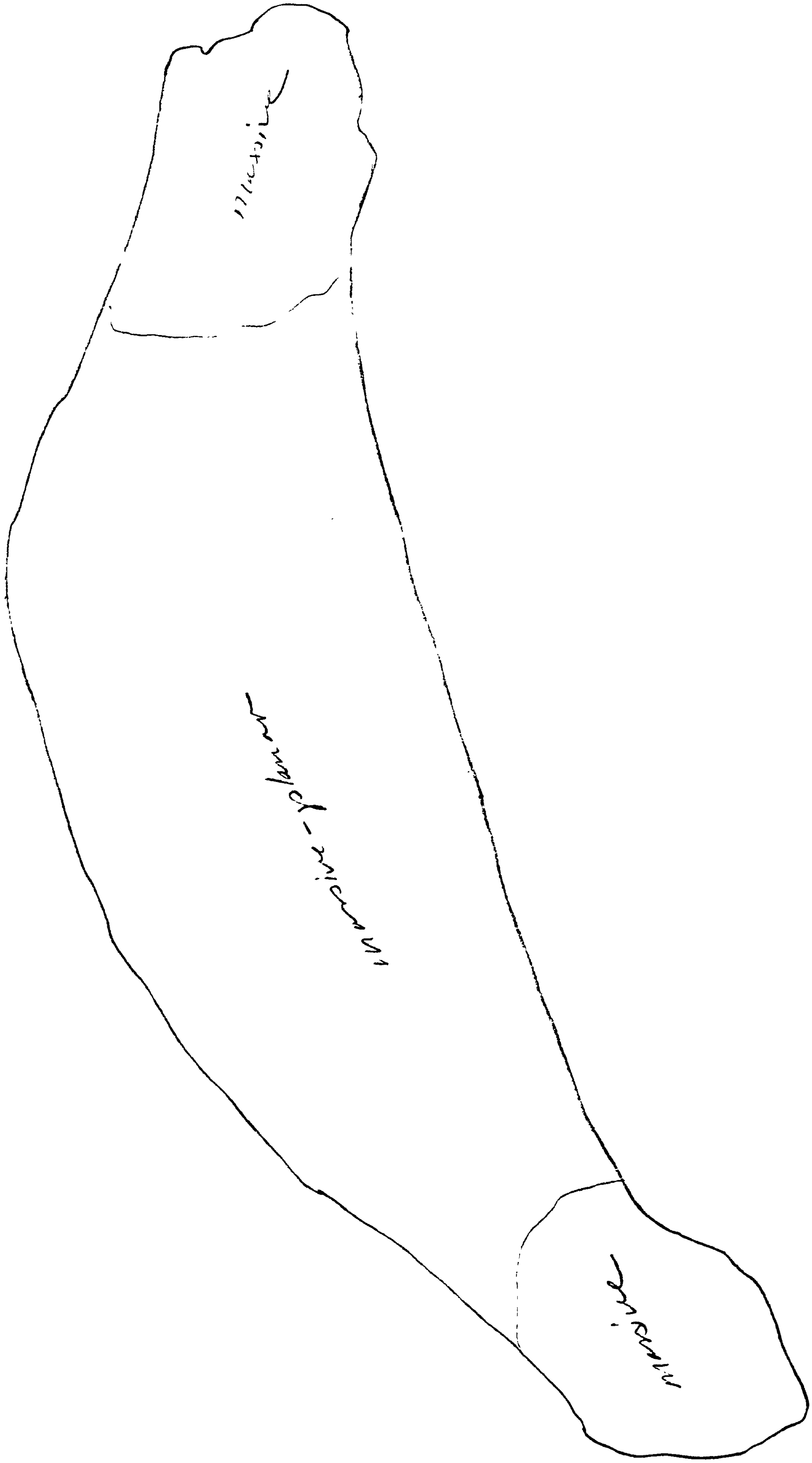
40A

note: it is a little hard to see fracture surface here because of the adhesive remnants


stepped
massive
planar
stepped
planar-massive
planar-stepped
planar-stepped
planar-stepped

43B


stepped
planar
massive
planar-stepped
planar-massive
planar
stepped
planar
45D



51D

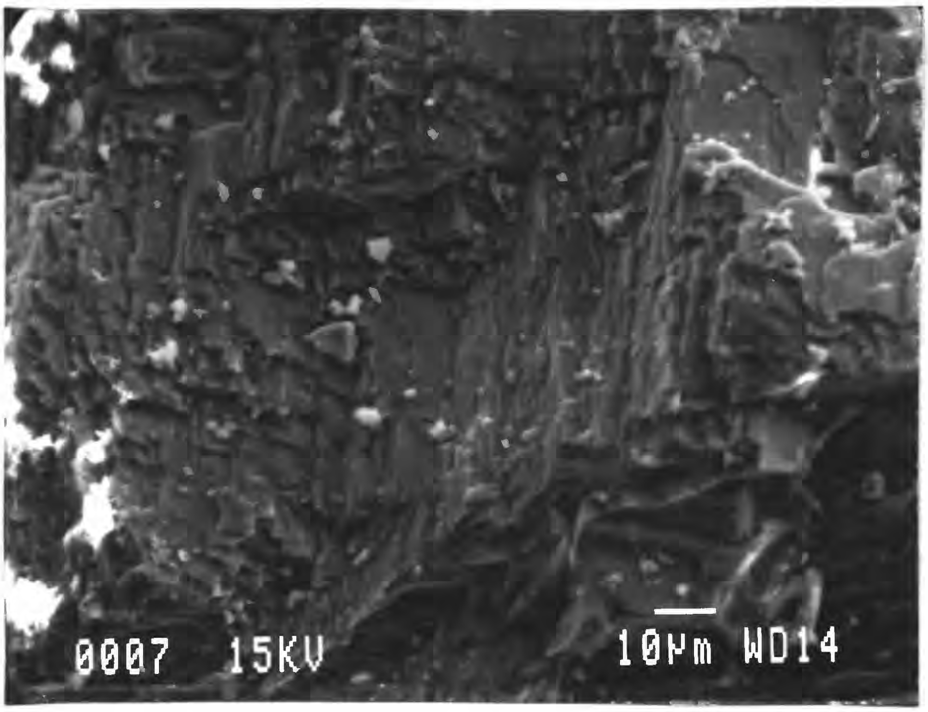
Appendix 2. Examples of Features Observed Using Scanning Electron Microscopy

Scanning electron micrographs were taken of various features on the samples to document the type of characteristics seen. Some of the photographs are included as figures in the report, but a few more are given here to show some of the typical features observed on each of the samples. For each of the samples, brief descriptions of the photographs are given and references are made to other photographs of the sample that are included in the body of this report. Scales for all photographs are shown in the lower right hand corner, usually in microns (μm).

Sample 15A:

0007 - stepped habit of calcite

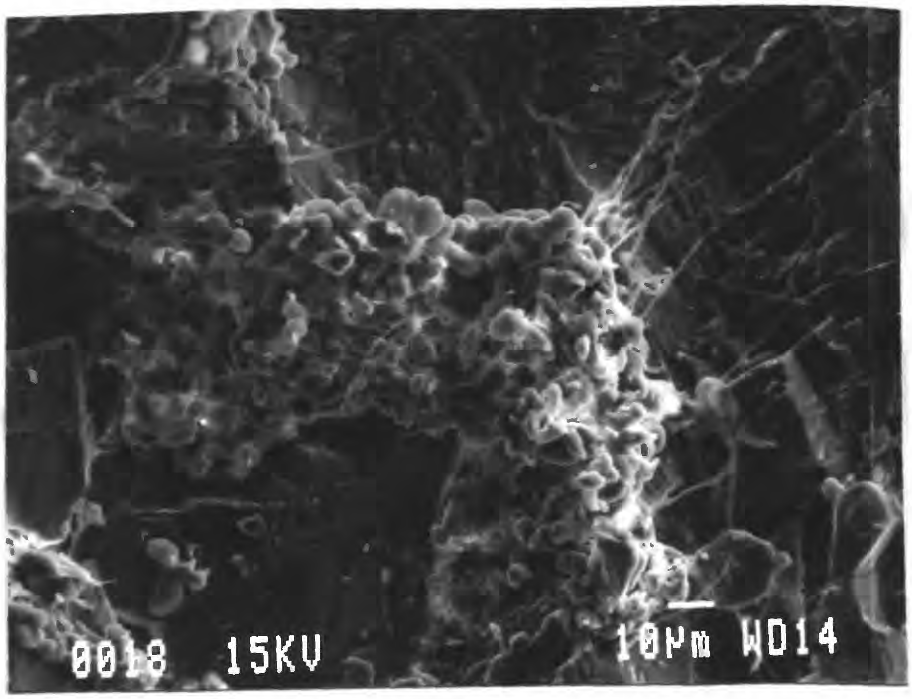
See also figures - 4, 11.

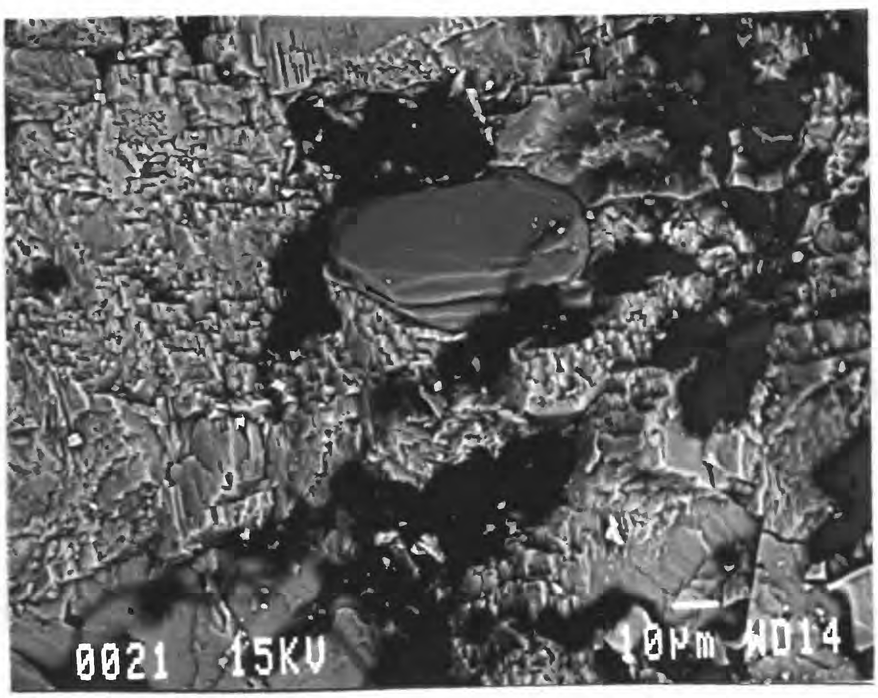


Sample 25C:

0018 - organic material on blocky calcite

0021 - blocky calcite, with a muscovite inclusion (smooth, rounded grain at center), and organic material (black); backscattered electron image.



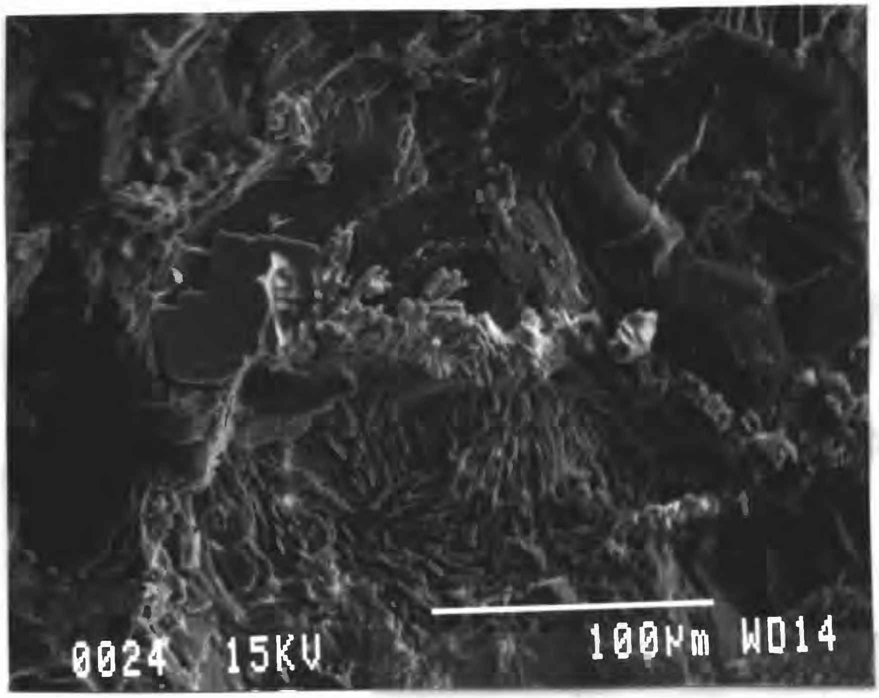


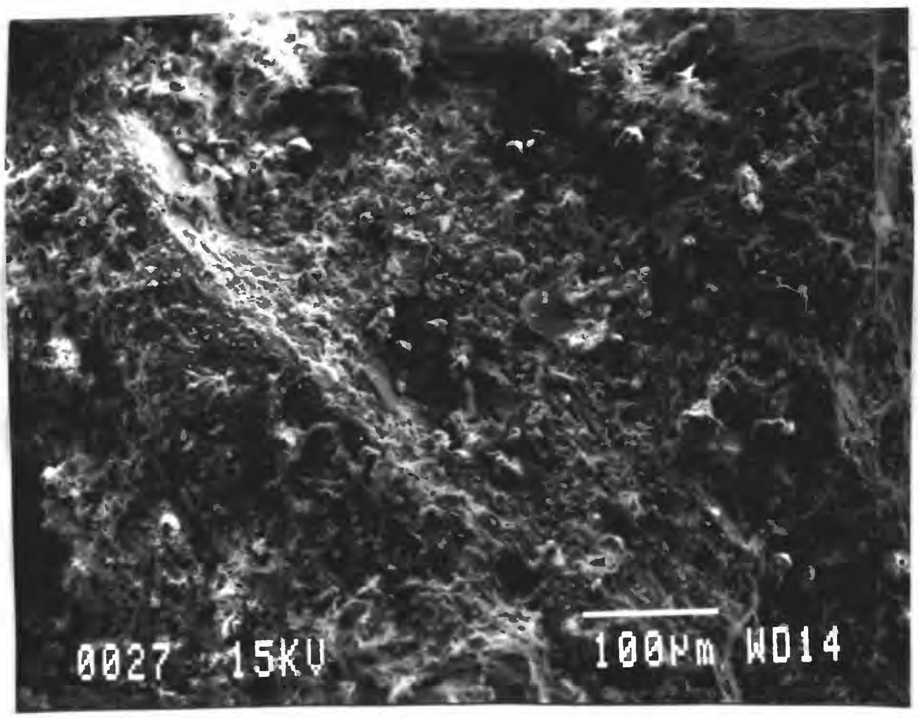
Sample 25C:

0024 - gypsum crystals (rectangular grains, clustered near lower center), covering an area of blocky calcite.

0027 - dirt covering and obscuring the calcite surface

See also figures - 5, 10.

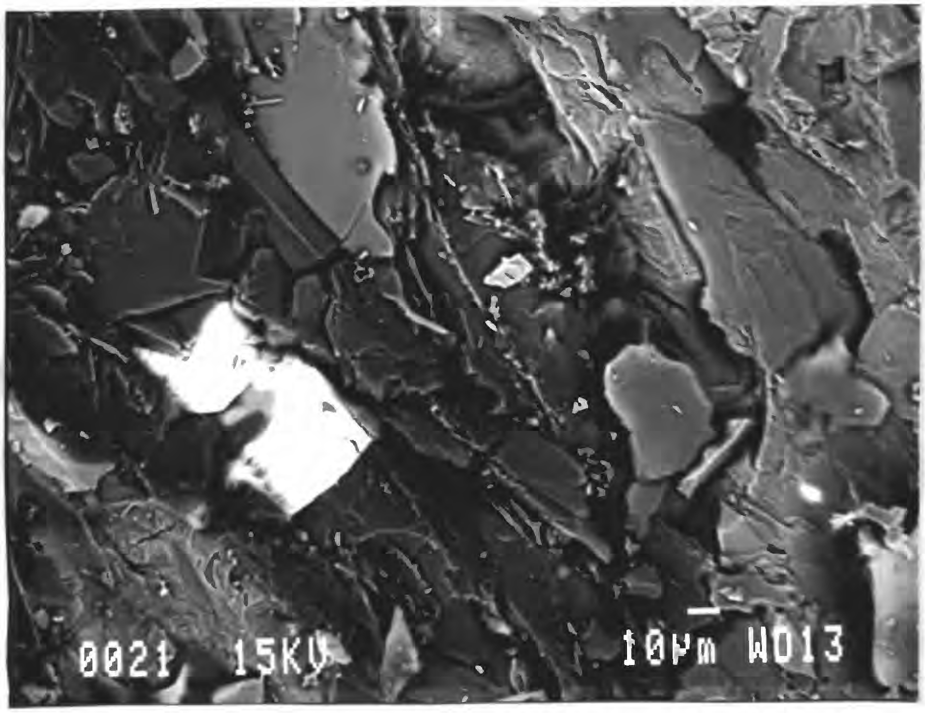




Sample 26D:

0021 - backscattered electron image of chlorite + phlogopite rich area; bright white grains are pyrite.

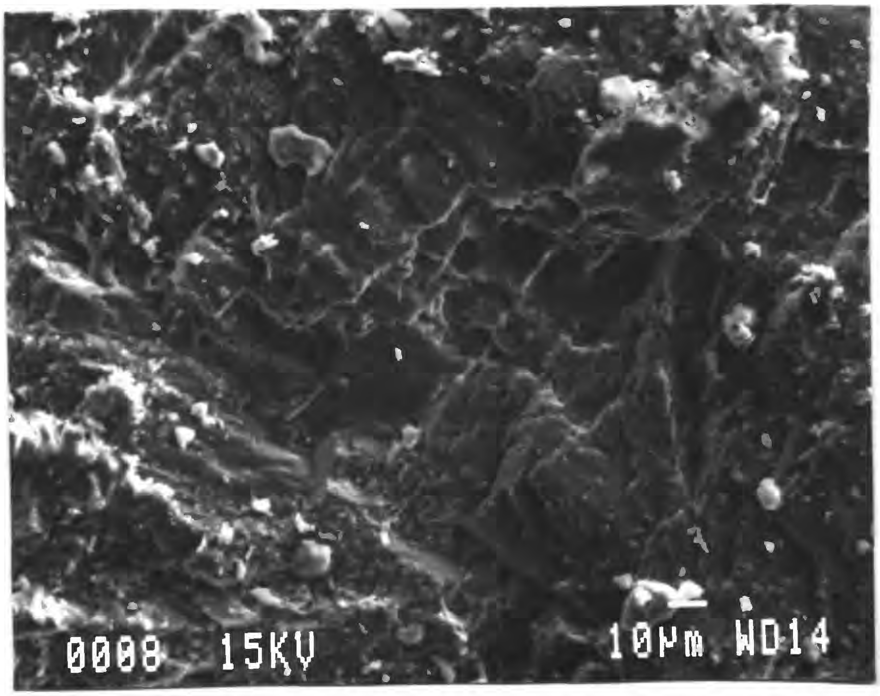
See also figure - 9.

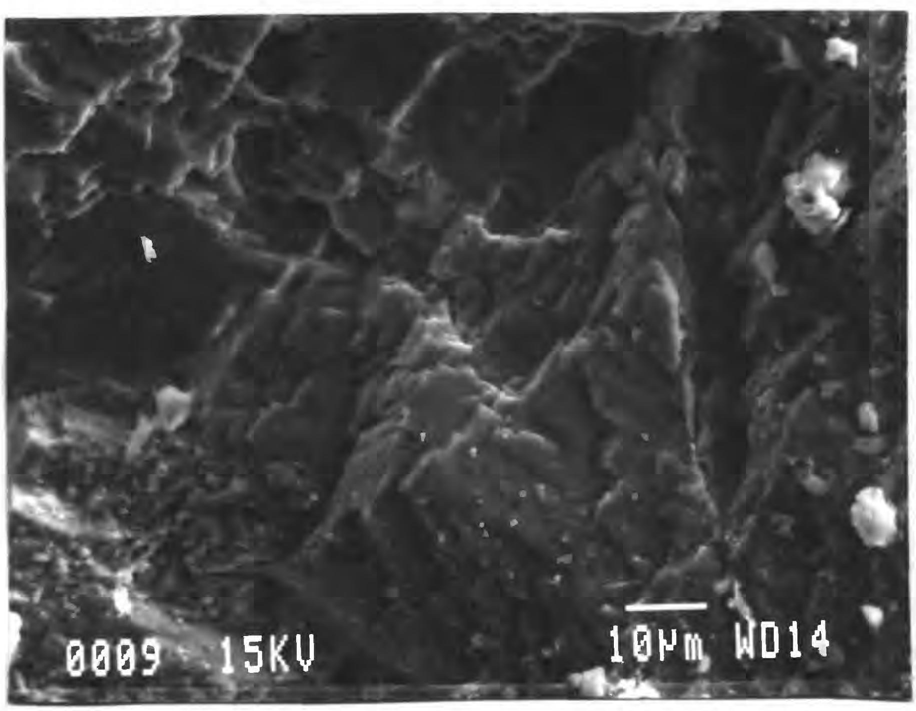


Sample 38A:

0008 - stepped calcite surface with some dirt accumulation.

0009 - detail of stepped calcite in photo 0008.

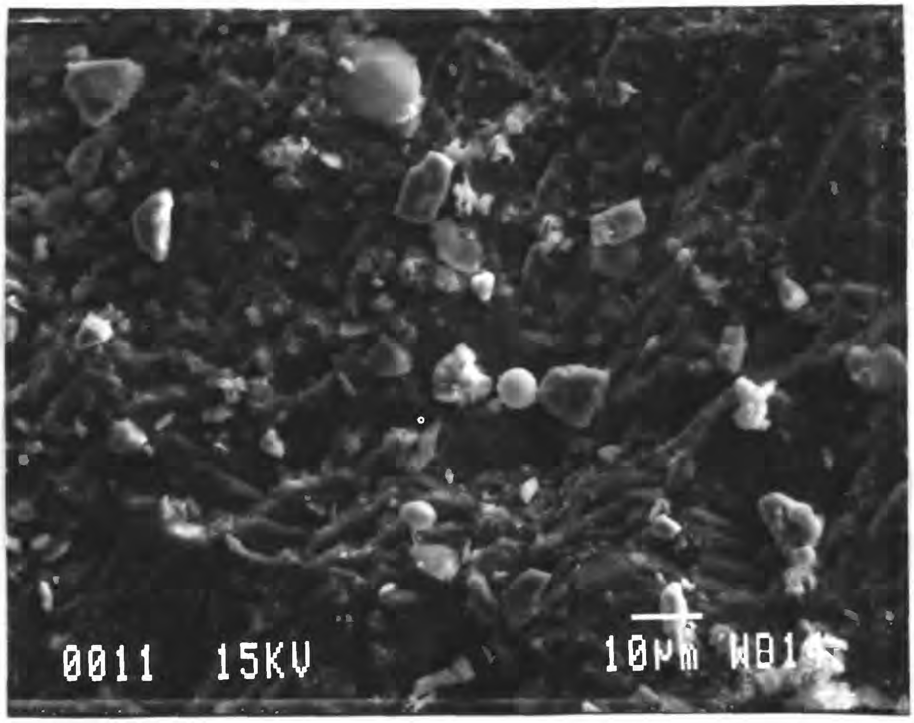


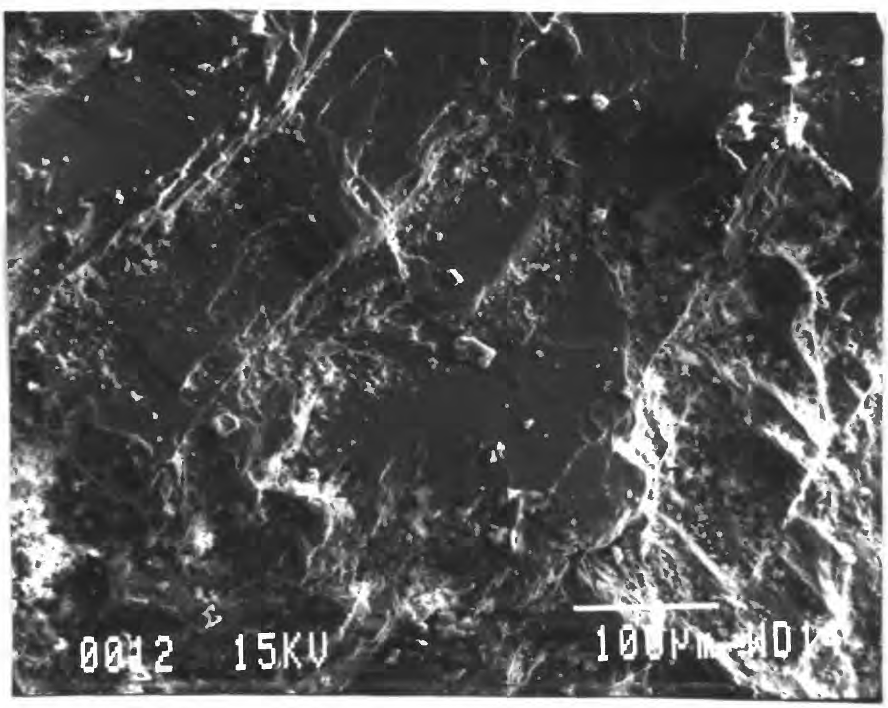


Sample 38A:

0011 - calcite surface with dirt accumulation; particles rest on calcite surface without indicating any reaction has occurred between the dirt and the calcite.

0012 - planar habit of calcite.

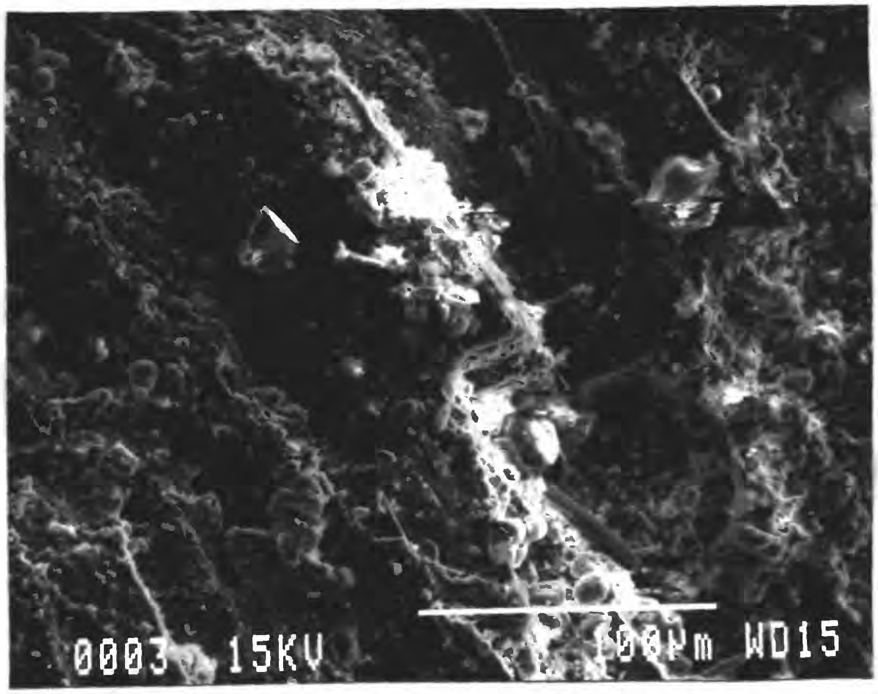


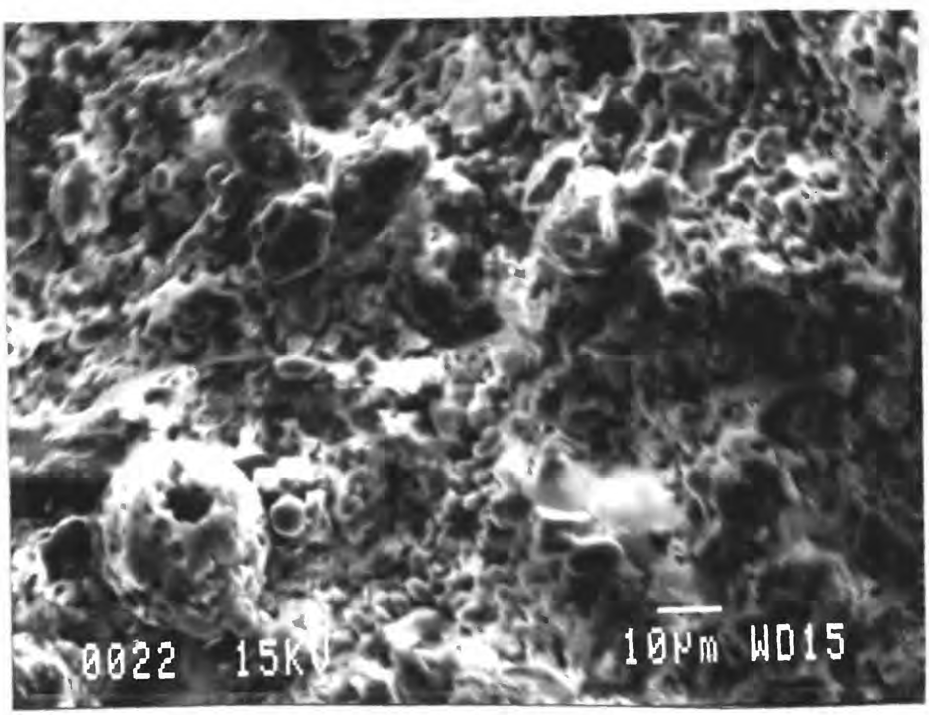


Sample 40A:

0003 - stepped calcite, with minimal surficial dirt accumulated.

0022 - crust and dirt accumulation; calcite surface is hidden.

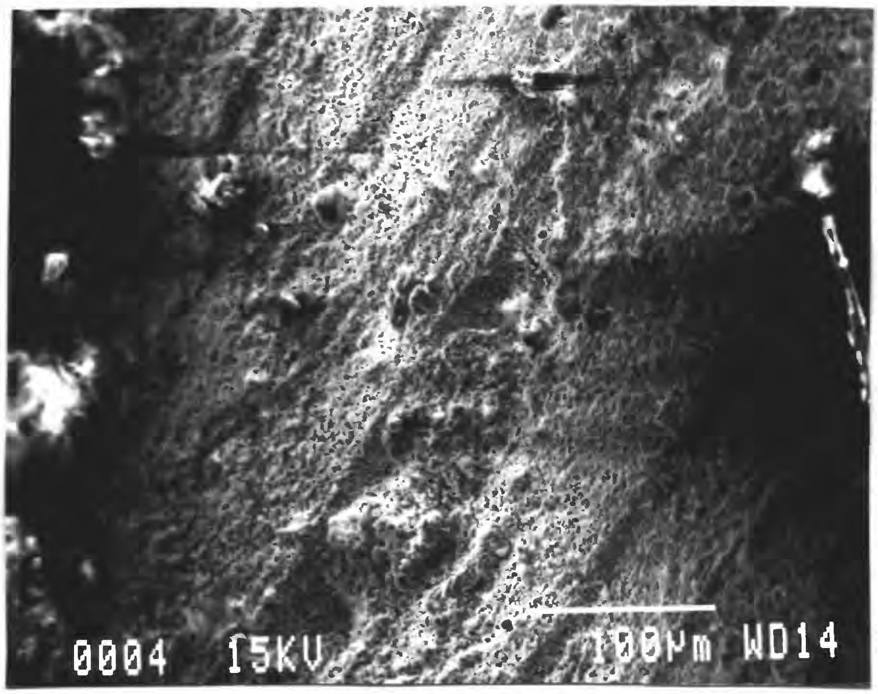


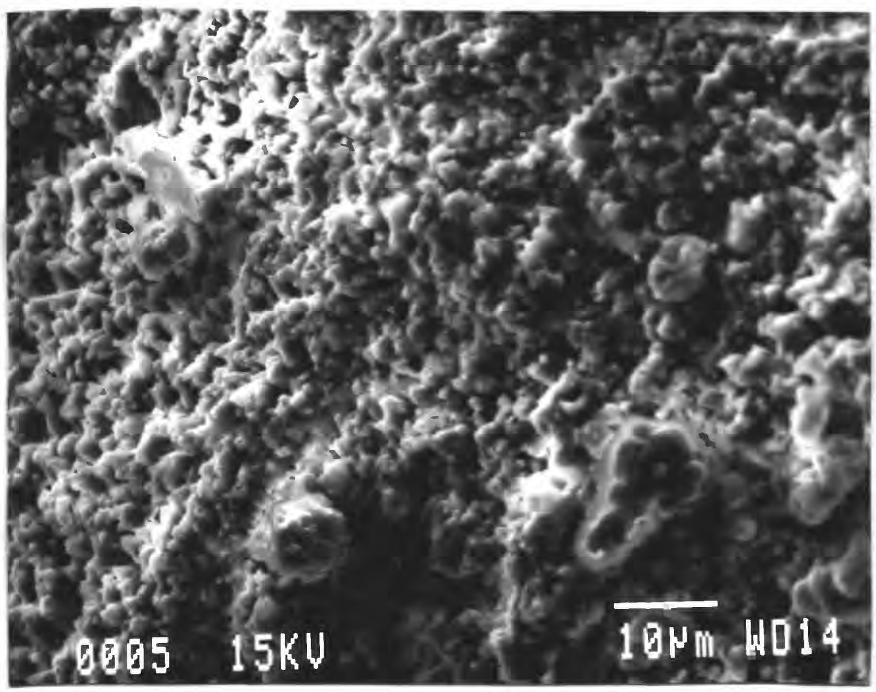


Sample 40A:

0004 - original surface is completely covered but some reflection of underlying calcite steps can be seen (darker "ridges" from lower left to upper right of photo).

0005 - detail of the grains that cover the surface of this sample; possibly adhesive or reprecipitated calcite.

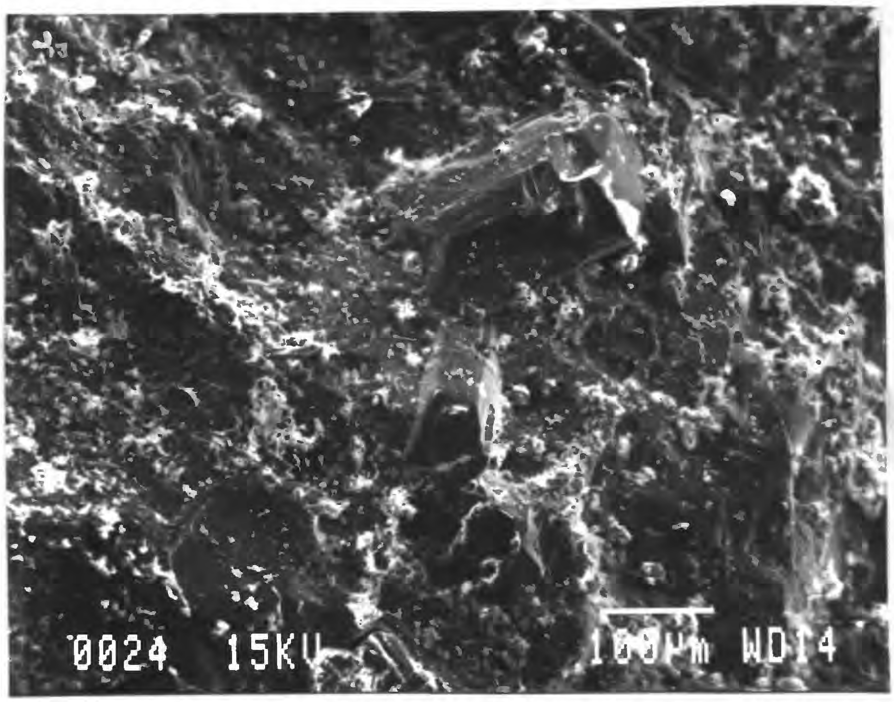


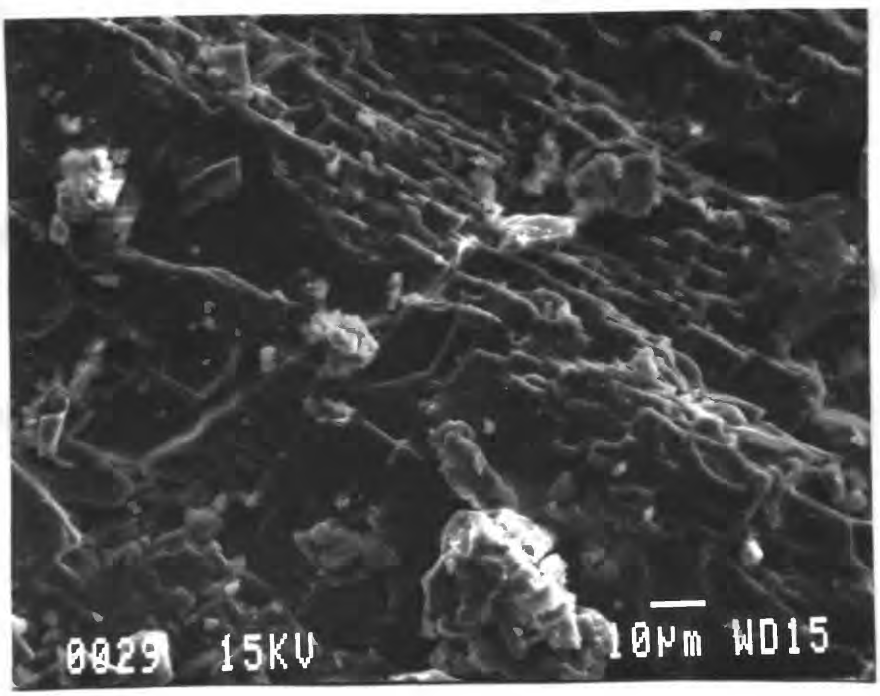


Sample 43B:

0024 - calcite, with surficial dirt; large blocky grain at upper center is a feldspar inclusion.

0029 - stepped calcite with minimal dirt.

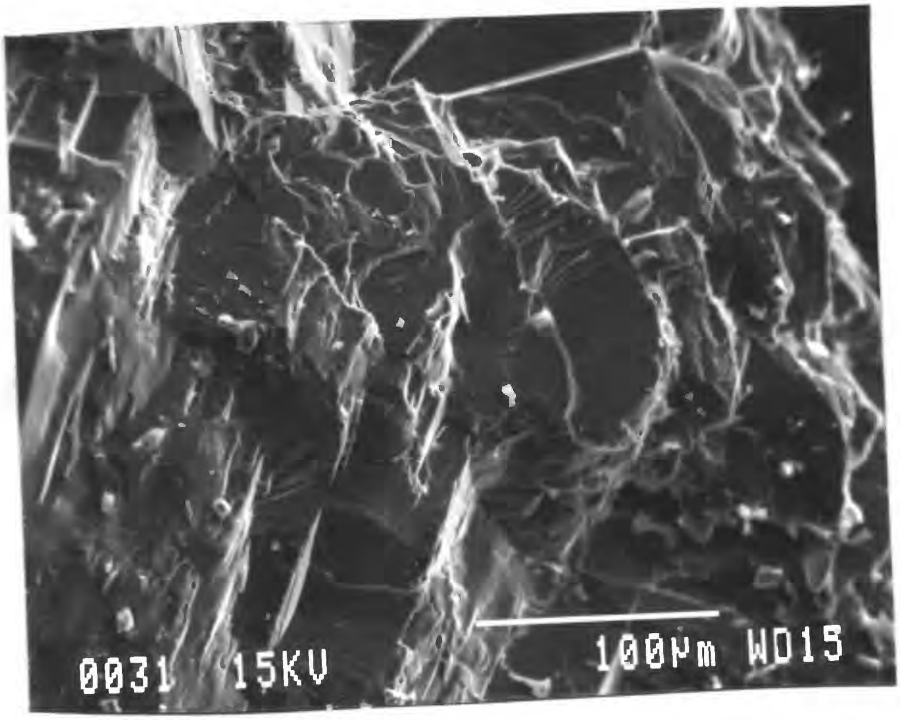


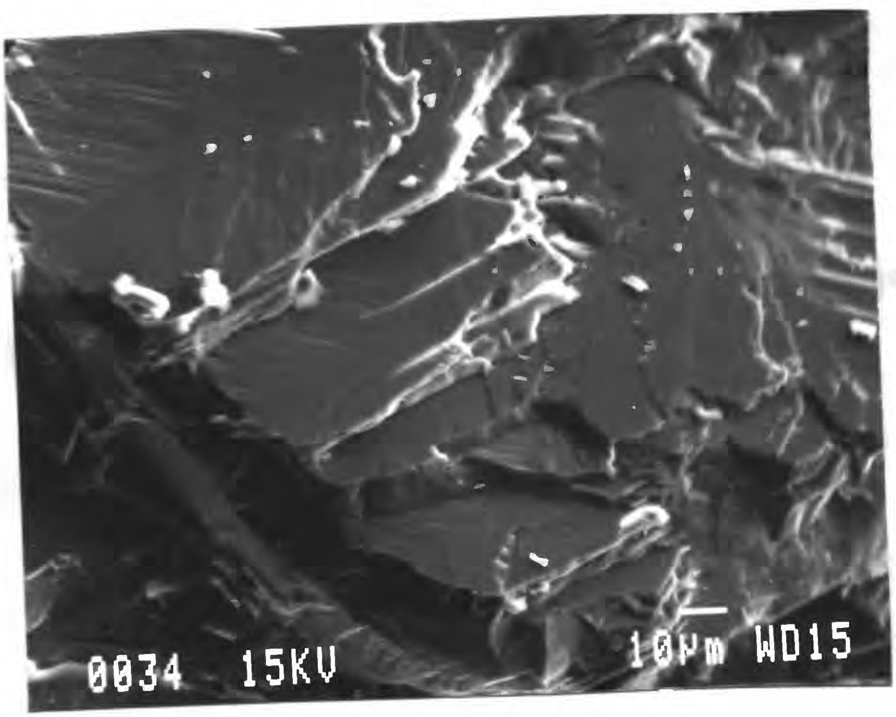


Sample 43B:

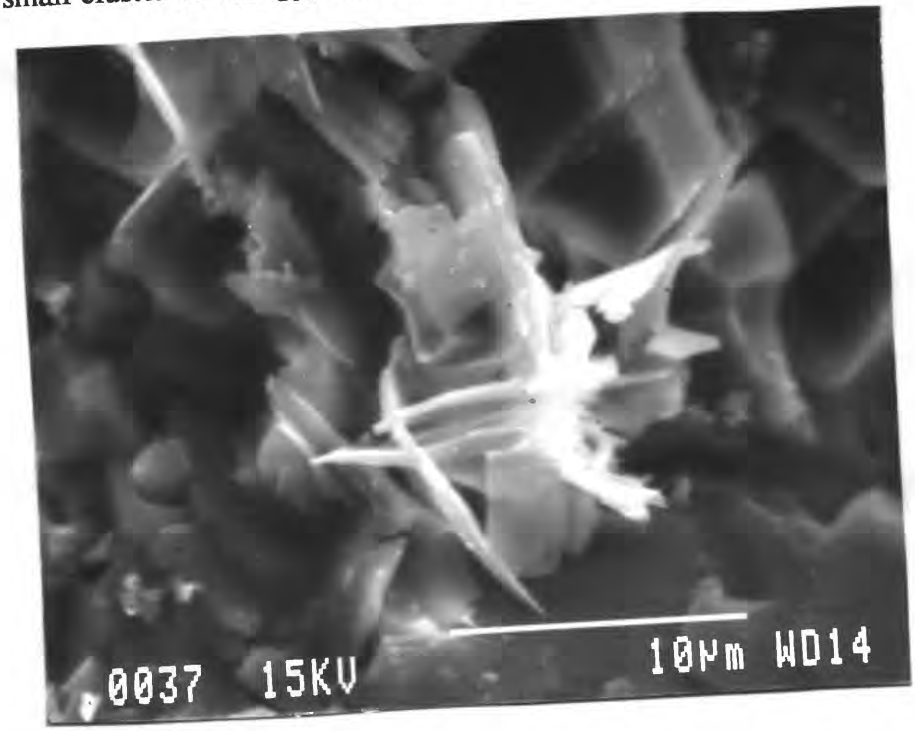
0031 - planar calcite and stepped calcite.

0034 - calcite steps persist even at a very small scale.

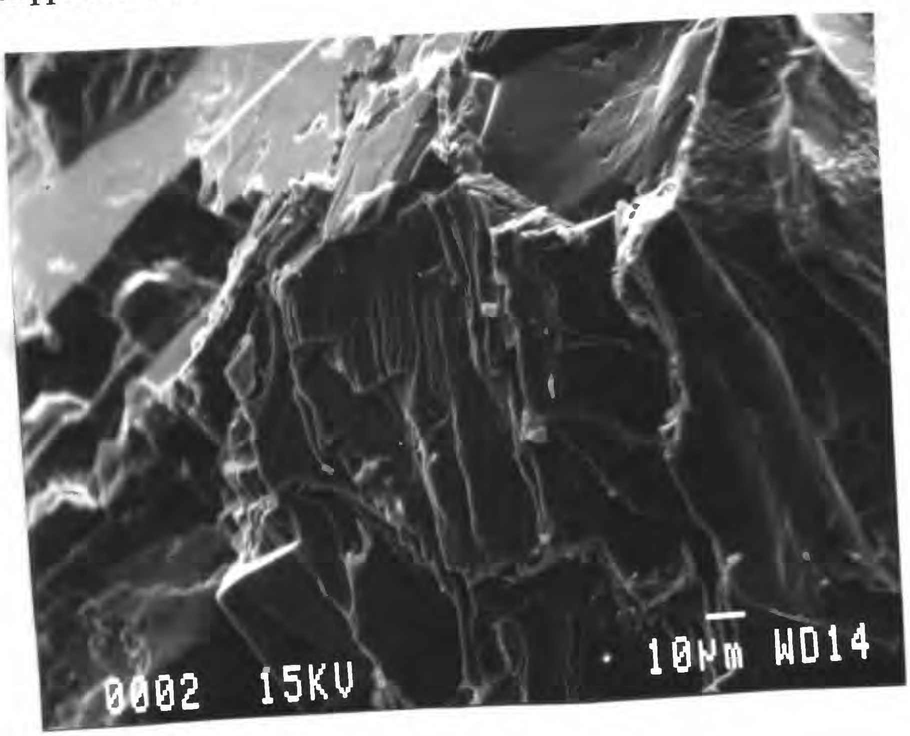




Sample 43B:
0037 - small cluster of thin gypsum crystals (lighter grains at center) on blocky calcite.



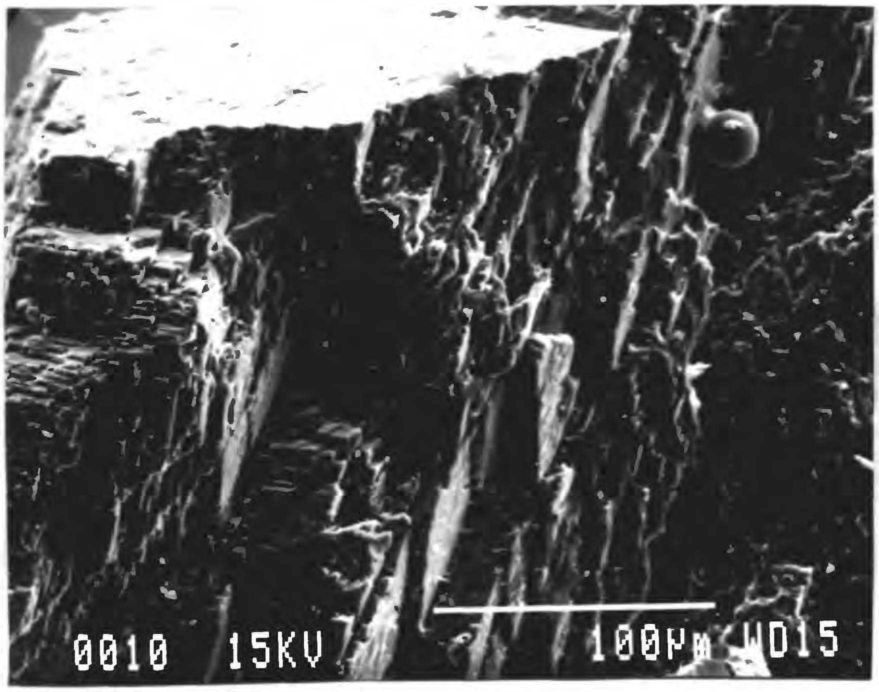
Sample 45D:
0002 - stepped calcite.

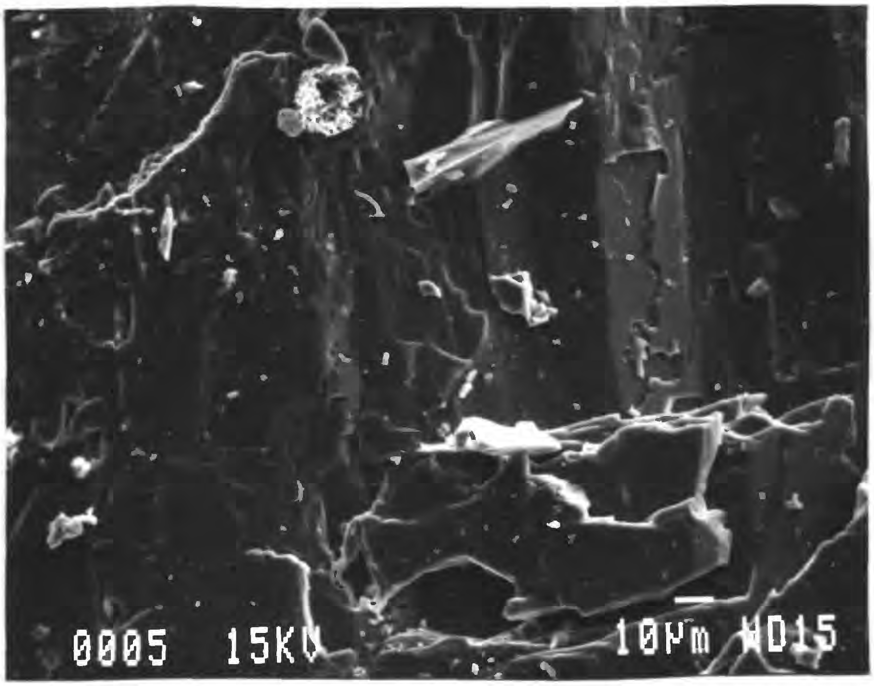


Sample 45D:

0010 - blocky calcite, showing typical cleavage of this mineral.

0005 - calcite with an almost rounded planar surface habit.

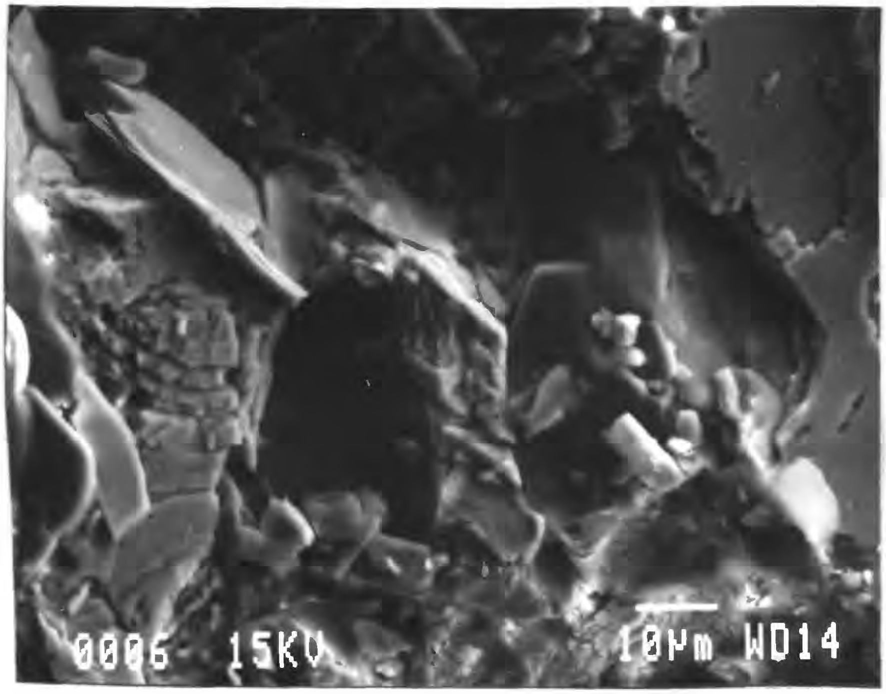


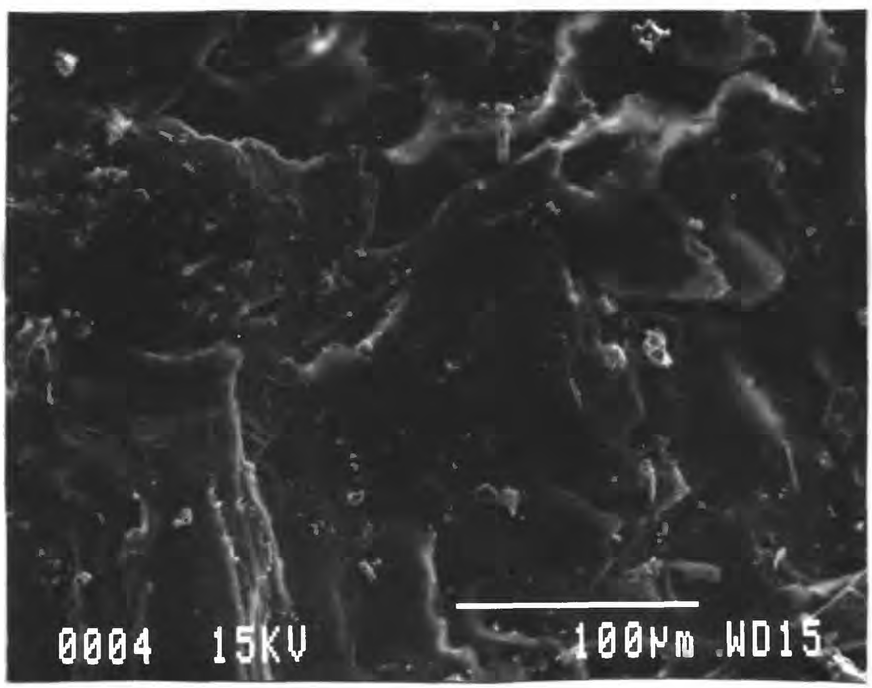


Sample 45D:

0006 - calcite + chlorite; contrast blocky, cracked grains of calcite with smooth, flat surfaces of chlorite grains.

0004 - an area of intergrown mica, chlorite, and calcite, co-planar with each other and with a surface habit similar to some inclusion free areas of the sample (see 0005).

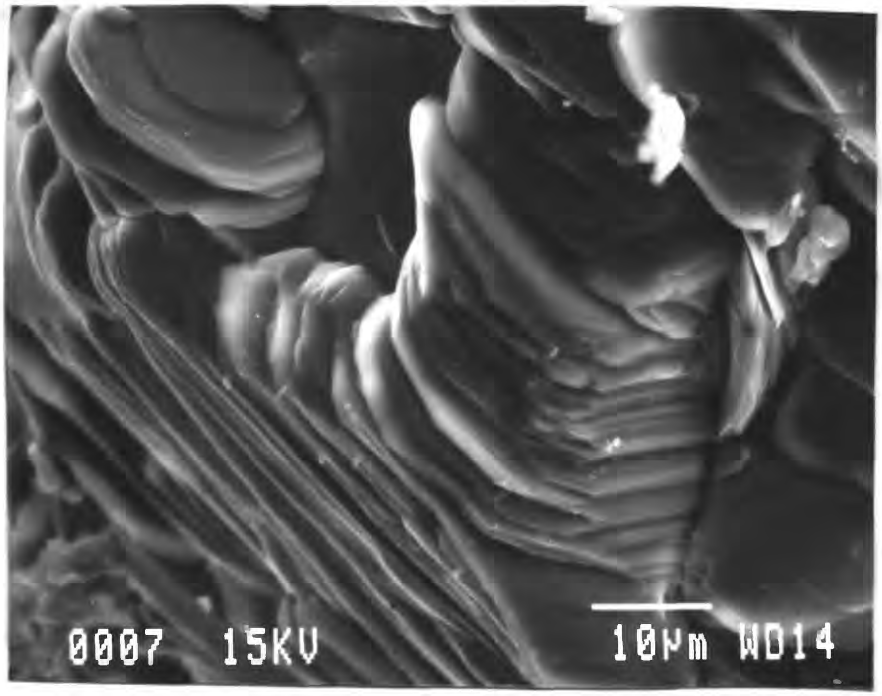


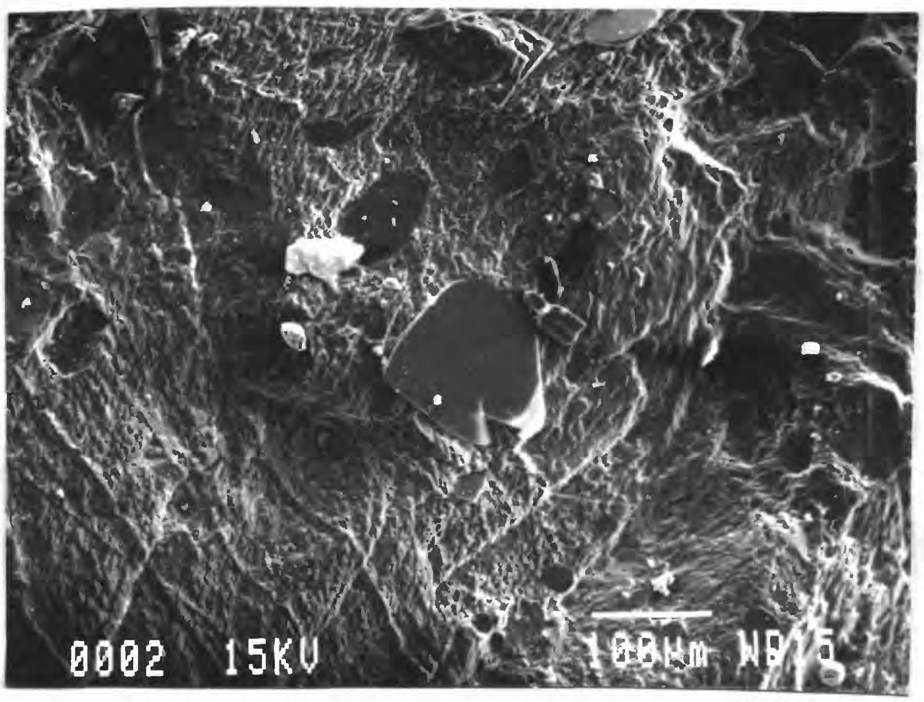


Sample 45D:

0007 - local area of chlorite grains, chlorite forms a cluster of ledges with smooth surfaces and slightly rounded edges that contrast with calcite rich areas.

0002 - typical occurrence of stepped calcite with randomly scattered minor muscovite mica inclusions (smooth, slightly rounded grains)

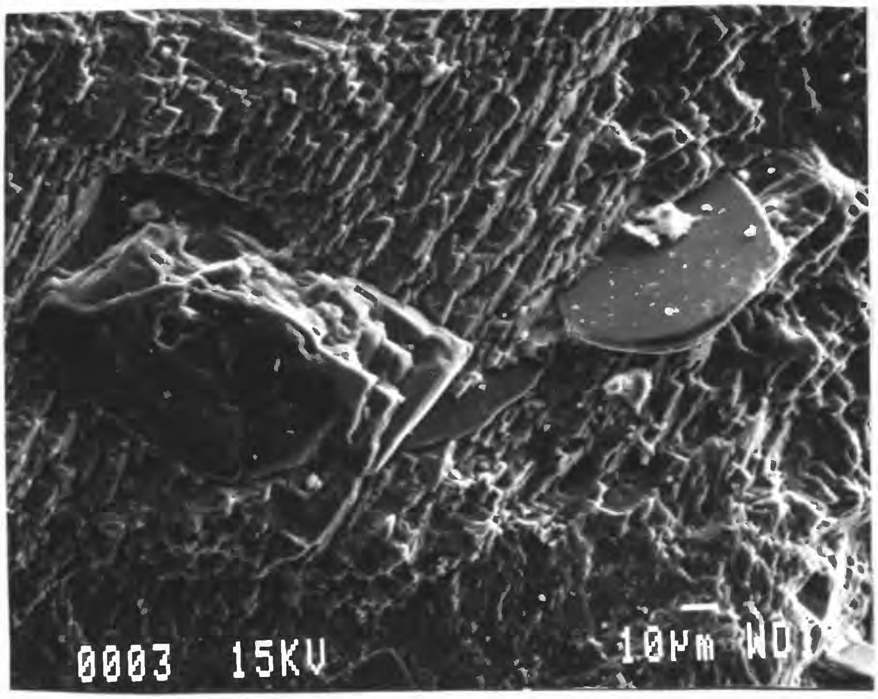


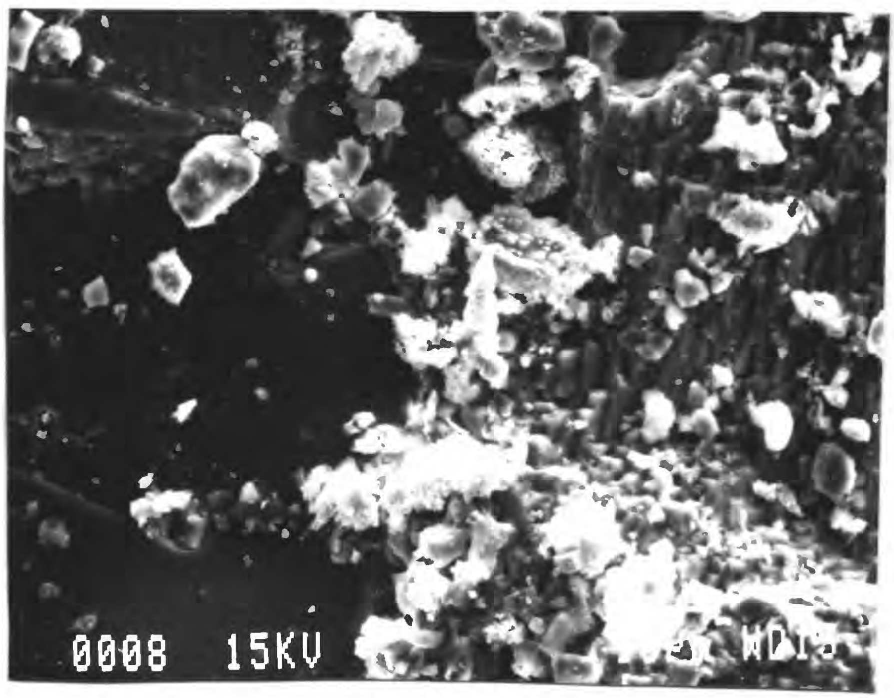


Sample 45D:

0003 - calcite + muscovite mica.

0008 - calcite + muscovite (dark grain on left side), both with surficial dirt .

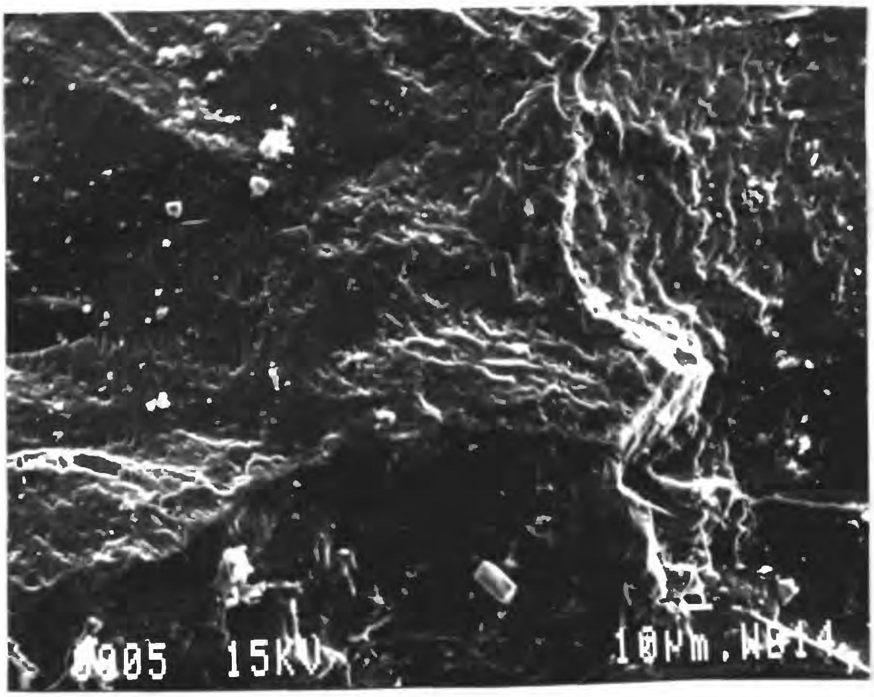


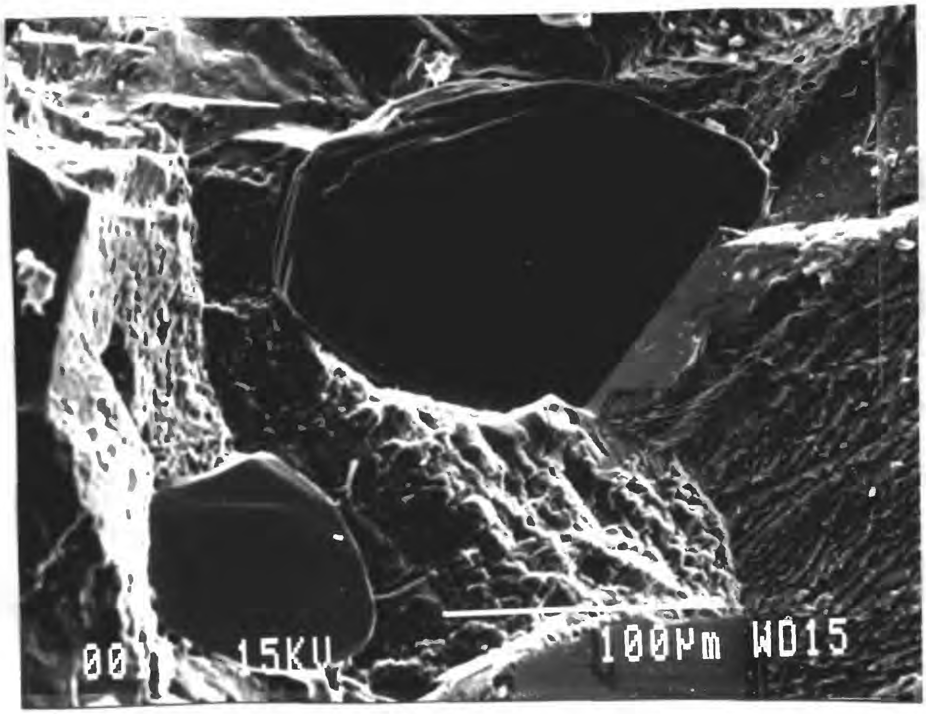


<u>Sample 51D:</u>

0005 - calcite steps.

0014 - contrast in surface texture of calcite with muscovite inclusion grains (smooth, darker, slightly rounded).

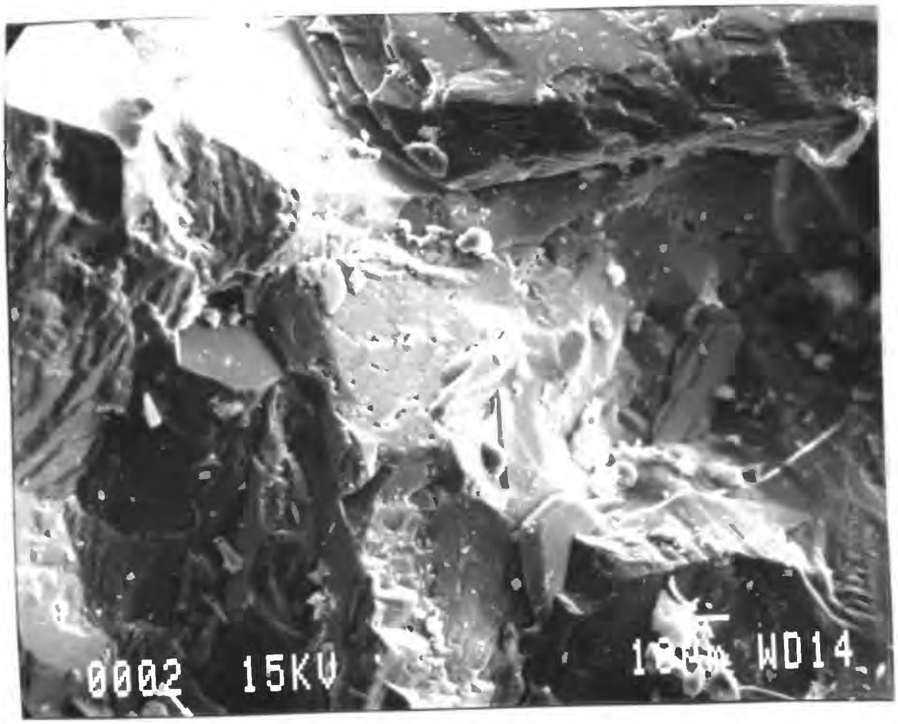


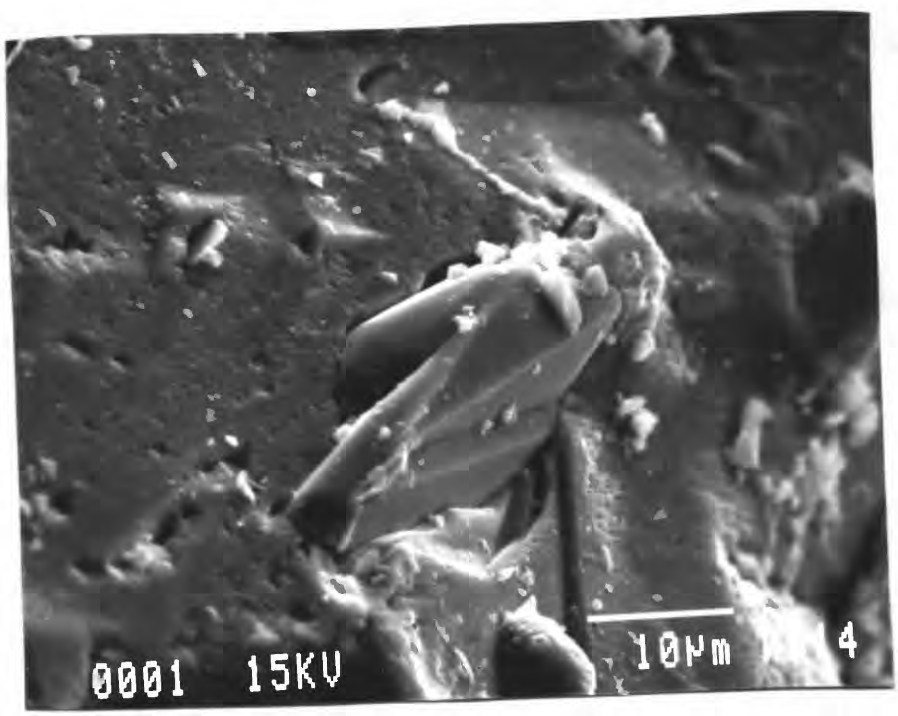


Sample 51D:

0002 - randomly oriented muscovite inclusions with calcite.

0001 - muscovite inclusion in calcite.

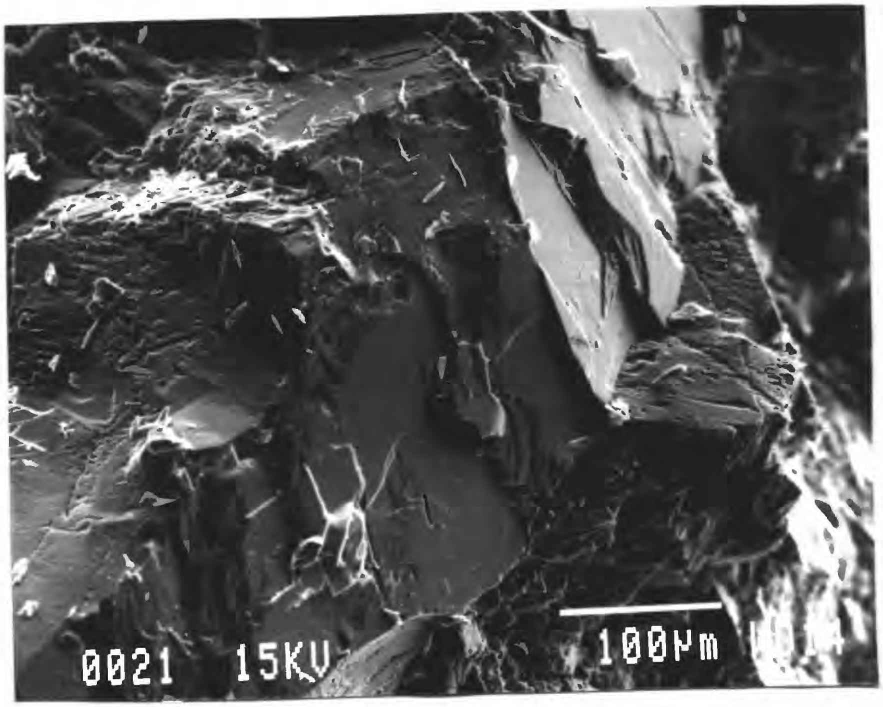


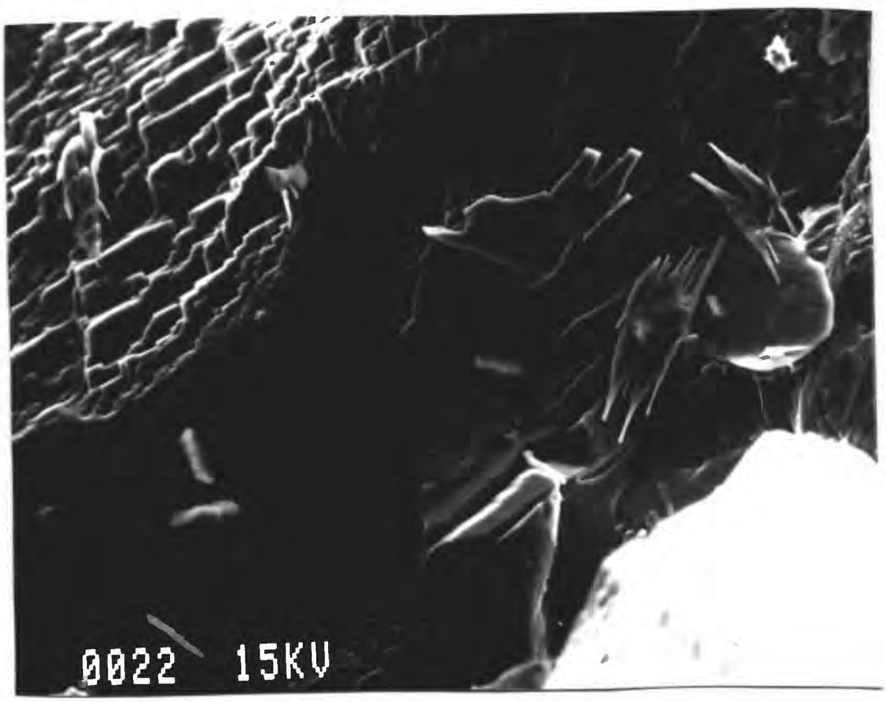


Sample 51D:

0021 - fine needles of gypsum on calcite.

0022 - gypsum crystal "mats" on calcite.

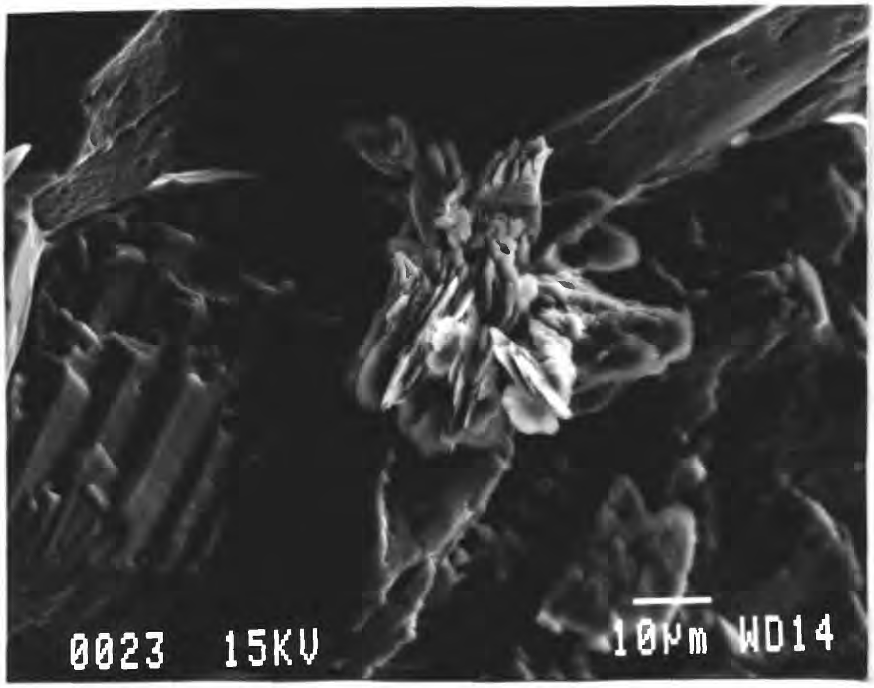




Sample 51D:

0023 - small cluster of gypsum crystals on calcite.

See also figures - 6, 7, 8, 12.



Appendix 3. Background information and references on marble characteristics

Some background information on marble constituents and characteristics, with references to further details are presented here.

Marble and its constituents

Compositions of some of the main mineral phases found in marble:

Carbonates:	calcite	$CaCO_3$
	dolomite	$CaMg(CO_3)_2$
Layer silicates:	phlogopite	$K_2Mg_6Si_6Al_2O_{20}(OH)_4$
	muscovite	$K_2Al_4[Si_6Al_2O_{20}](OH,F)_4$
	chlorite	$(Mg.Al)_{12}(Si,Al)_8O_{20}(OH)_{16}$
Framework silicates:	quartz	SiO_2
	albite (feldspar)	$NaAlSi_3O_8$
	feldspar	$KAlSi_3O_8$, $CaAl_2Si_2O_8$
Non-silicates:	rutile	TiO_2
	pyrite	FeS_2
	apatite	$Ca_5(PO_4)_3(OH,F,Cl)$

Deer, Howie, and Zussman (1966) is a general source of information on the characteristics and typical compositions of major rock forming minerals.

Properties of calcite

Some of the chemical and physical properties of calcite are distinctive, and may have a bearing on the durability of marble because it is the predominant mineral constituent of marble. Some of calcite's properties that may be of particular concern for marble durability include: its susceptibility to acid and physical properties such as its cleavage, its tendency to glide along certain crystal planes under some stresses, and its thermal expansion and contraction properties.

A test that is commonly used to identify calcite in the field, is to look for effervescence when weak acid is dropped on it, because calcite dissolves readily in weak acid. Natural rain has a slight acidity (pH = 5.6) that comes from the dissolution of carbon dioxide from the atmosphere, a factor that contributes to the normal weathering of calcite bearing rocks. The durability of stone in buildings may be further at risk because of the greater acidification in urban air that comes from pollutants. Typically the effect of acid dissolution on marbles is seen as a sugaring of surfaces that are regularly exposed to rain.

Cleavage is the tendency of a mineral to break along surfaces related to its crystal structure, thus all grains of a given mineral will tend to break preferentially in certain directions. Calcite has perfect rhombohedral cleavage, meaning that it tends to break along planes that form angles of 75° and 105° with each other. The blocky, stepped fracture pattern observed in the samples in this study may reflect the cleavage habit of calcite. Translation gliding occurs when a crystal is exposed to stresses, it deforms by slipping along certain planes and in certain directions in the crystal. A study by Knopf (1949) suggests that marble undergoes intragranular gliding or movement along two sets of intersecting glide planes. Translation gliding has been induced in calcite by applying a force in one direction to calcite crystals (Bell, ref in Knopf, 1949). Bloss (1971) shows that mechanical twinning and gliding can be induced in calcite by careful pressure from a razor blade (see figure 10-30, A&B in Bloss, 1971). The thermal properties of calcite have also been suggested as a destructive force in marble (Zezza et al., 1985; Sage, 1988). When heated, calcite expands along one crystal direction (c axis) while it contracts in the directions perpendicular the expansion (along the a axis), as shown in the figure 11-16 A in Bloss (1971). Although the expansion and contraction of each crystal is slight in normal temperature ranges, some problems in marbles have been observed where there is a large effect from solar radiation and a definite repeated cycling of thermal changes (Kessler, 1919).

Slickensides on fault surfaces

The appearance of most of the fracture surfaces in this study (especially those described as planar or stepped) is very similar to the slickenside surface observed in fault planes. Slickensides are polished or striated surfaces that result from friction along a fault plane. Some of the literature on fault surfaces suggests that the steps and striations found in the field and on experimentally fractured stone (including marble) may indicate the direction of movement of the fault (Billings, 1942; Tjia, 1964). It has also been suggested (Durney and Ramsay, 1973) that the elongate minerals that form the grooved striations grew there after the faulting.

References:

Billings, M.P. 1942. Structural Geology. Prentice Hall, Inc., New York, 473 p.

Bloss, F.D. 1971. Crystallography and Crystal Chemistry. Holt, Rinehart and Winston, Inc., New York, 545 p.

Deer, W.A., Howie, R.A., and Zussman, J. 1966. An Introduction to the Rock-Forming Minerals. Longman Group Ltd., London. 528 p.

Durney, D.W. and Ramsay, J.G. 1973. Incremental strains measured by syntectonic crystal growths. in DeJong and Scholten (eds.) Gravity and Tectonics. John Wiley and Sons, New York. p67 - 96.

Kessler, D.W. 1919. Physical and chemical tests on the commercial marbles of the United States. Technologic Papers of the Bureau of Standards, no. 123. 54 p.

Knopf, E.B. 1949. Fabric changes in Yule marble after deformation in compression. American Journal of Science, v 247, p433 - 461; p537 - 569.

Sage, J.D. 1988. Thermal microfracturing of marble. in Marinos and Koukis (eds.) Engineering Geology of Ancient Works, Monuments and Historical Sites. Balkama, Rotterdam. p1013 - 1018.