

# *Collection Forum*



**SPNHC**

*Society for the Preservation  
of Natural History Collections*

Spring 1993  
Volume 9  
Number 1

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*Collection Forum*, the official journal of the Society for the Preservation of Natural History Collections (SPNHC), is published twice a year to disseminate substantive information concerning the development and preservation of natural history collections. The journal is available by subscription (\$26US per year) and as a benefit of membership in SPNHC (\$21US per year for individuals; \$40US per year for associate members). Address all communications involving membership dues and subscriptions to the SPNHC Treasurer.

*Collection Forum* (ISSN 0831-4985) is published by SPNHC, 5800 Baum Blvd., Pittsburgh, Pennsylvania 15206. POSTMASTER: Send address changes to *SPNHC* % Suzanne B. McLaren, Treasurer, 5800 Baum Blvd., Pittsburgh, PA 15206. Copyright 1993 by the Society for the Preservation of Natural History Collections.

# NATURE OF THE ALTERATIONS WHICH FORM ON PYRITE AND MARCASITE DURING COLLECTION STORAGE

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*Abstract.*—The processes involved in the decomposition of specimens of pyrite and marcasite are incompletely understood. An important step is to determine what secondary minerals have formed and whether these minerals exhibit any change with variations in relative humidity. Twelve sulfates were found to have formed on museum specimens of pyrite and marcasite. They were identified by optical and X-ray diffraction techniques. The ferrous sulfates (szomolnokite, rozenite and melanterite) change hydration state with changes in humidity. Rhomboclase, roemerite and melanterite deliquesce at high humidity. With a fall in relative humidity, some of these do not recrystallize but form what appear to be hardened colloids. These colloids may play a significant, but as yet undetermined, role in corrosion of pyrite and marcasite. The presence of aluminum-bearing sulfates, alunogen and halotrichite, indicates that clay in sulfide specimens may promote decomposition. Other secondary minerals which were not observed to change during the year are kornelite, coquimbite, quenstedtite, gypsum and a phase tentatively identified as hydronium jarosite.

Pyrite- and marcasite-bearing specimens are notorious for decomposing in collections. Waller (1987) and Howie (1978) have discussed this problem and attributed much of the decomposition to the formation of ferrous sulfate. This substance occurs in three different hydration states: the monohydrate (szomolnokite), the tetrahydrate (rozenite) and the septahydrate (melanterite). They suggest that a change to higher hydration state causes expansion of the sulfate and physical disruption of the specimen. A weakness with this hypothesis is the incomplete documentation of what minerals comprise the alteration coatings and of mineralogical changes occurring due to humidity variations. Whereas work is continuing on deducing the processes involved in specimen alteration and subsequent destruction, the main purposes of this paper are to document which minerals are present under various relative humidities and to describe their habit and associations in museum and natural environments.

## METHODS

Specimens in the collection of the Newark Museum plus several from private collections were chosen for study ( $N = 14$ , see Table 1 for descriptions). These specimens showed alteration which varied from very little to extensive. All had been stored in uncontrolled ambient situations. Several had been stored in basements where humidity was very high during the summer. After being selected for study, the specimens were stored on an open shelf in the office/laboratory area of the Museum, and the humidity and temperature were monitored with a hygrothermograph (Fig. 1).

The alteration coatings on the specimens were studied by X-ray diffraction (XRD) and polarized light microscopy (PLM). The samples for XRD analysis were removed with a dental pick from the specimen surfaces. Pyrite or marcasite contaminants were carefully removed with a fine needle while the material was observed through a binocular microscope. After the sulfides were removed, each sample was gently ground with an agate mortar and pestle and then placed on a piece of double-sided tape which had been positioned on a glass slide. The sample was scanned from  $4^\circ$  to  $40^\circ 2\theta$  at  $2^\circ$ /minute on a GE XRD-5 Diffractometer using Cu radiation and a Ni filter. Where values for XRD are reported herein, the data come from the *Mineral Powder Diffraction File* (Joint Committee on Powder Diffraction Standards, 1980).

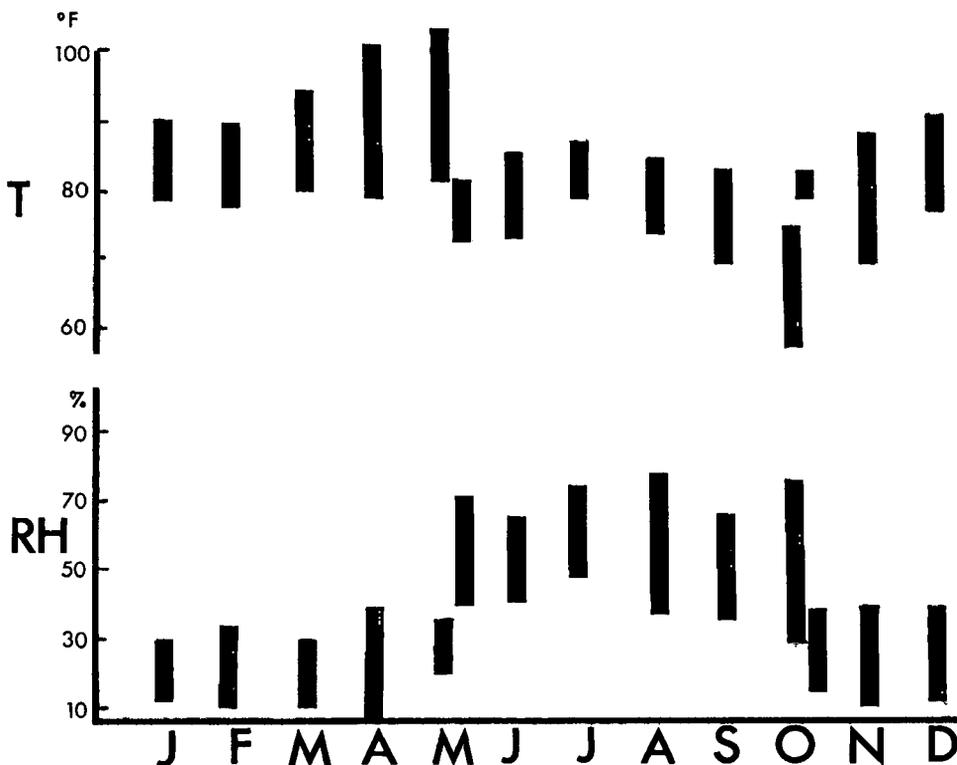


Figure 1. Bars indicate the variation of temperature (T) and humidity (RH) during each month (indicated by first letter) of specimen storage area. The double bar for May (M) shows the change when the heating plant was turned off for the season, and the bars for October (O) when it was turned on.

The PLM analysis requires microgram quantities of powder. Samples were removed with a fine needle and placed on glass slides (unground) with mounting medium and cover glasses. Some of the sulfates seemed to react with the normally used refractive index (R.I.) liquids so most samples were first prepared with Canada Balsam as the mounting medium. If refractive index other than 1.540 (Canada Balsam) was needed, the sample was prepared with an R.I. liquid and observed without delay before any reaction could occur. Specific optical data reported in this paper are taken from Winchell and Winchell (1951).

In this study, I was interested in mineral phase changes with variations in relative humidity. Generally an optical analysis preceded XRD analysis because a much smaller sample is required for the former. If a change was observed using PLM, then an XRD sample was prepared and run. Care was exercised in preparation of the X-ray diffraction sample to prevent a change of phase of the sample due to grinding or to temperature and/or relative humidity changes before or during XRD runs. In most cases the two methods, XRD and PLM, yielded the same results. In those cases where differences were observed, optical analysis of the XRD sample which had been run demonstrated that a phase change had occurred, and the sample was reprepared for analysis. Whereas it is clear that one must exercise great care to prevent alteration during preparation of the hydrated minerals being studied, I believe that the examination with two or more techniques served to eliminate incorrect identifications.

The geological literature contains many papers that may be valuable to the museum professional interested in alteration of pyrite and marcasite. Much work is being done on the decomposition of pyrite associated with coal deposits because it is responsible for acidic mine drainage (McKibben and Barnes, 1986; Taylor *et al.*, 1984; Reardon and Beckie, 1987; Wiess *et al.*, 1987; Storr *et al.*, 1983; Zodrow and McCandlish, 1978; Paratt and Kullerud, 1979; Young and Nancarrow, 1988; and Raymond *et al.*, 1983). In addition, very detailed studies of the mineralogy and paragenesis (order of

Table 1. Description of specimens used in the study (D = Disbrow collection, added to the Newark Museum collection before 1922).

	Date of addition to collection	Description
Pyrite, Elba, Italy	1949	Large pyrite crystal with several smaller pyrite crystals and hematite intergrown
Marcasite, Baxter Springs, KS	1942	Cockscomb crystal cluster
Marcasite, South River, NJ	1933	Botryoidal marcasite with tiny (<1 mm) flat lying bladelike crystals coating the surface
Pyrite, Gilpin Co., CO	1933	Massive pyrite with cubic crystals (approx. 2 cm) on the surface
Pyrite, Woodbridge, NJ	D	} Hemispherical mass of cubic intergrown crystals
Pyrite, Sayreville, NJ	D	
Pyrite, Sayreville, NJ	1952	Pyrite coating on dolomite
Pyrite, Guanajuata, Mexico	D	Cubic pyrite crystals (approx. 1 cm) on magnetite
Pyrite, Chester Co., PA	D	
Pyrite, Galena, IL	1950	Botryoidal mass of pyrite with a drusy coating of cubic crystals
Pyrite nodules (three specimens), Columbia, MO	1962	Irregular nodules obtained from clay pits
Marcasite, Pitcher, OK	1956	Cockscomb marcasite crystals on chert

formation) of the secondary sulfates in sulfide deposits in Chile and other regions occurs in the older literature (Bandy, 1938; Merwin and Posnjak, 1937). Because of limited space the literature will be discussed only briefly, and interested persons are encouraged to study these papers in their entirety.

#### SECONDARY MINERALS OBSERVED

Eleven iron, aluminum or iron-aluminum sulfate minerals have been determined by X-ray diffraction and optical techniques to occur on museum specimens containing pyrite and/or marcasite (Table 2). These sulfate minerals are assumed to have formed on the specimens since they were accessioned into the collection between 10 and 100 years ago.

Table 2. Minerals found in pyrite and marcasite alteration crusts.

Kornelite	$\text{Fe}^{+3}(\text{SO}_4)_3 \cdot 7\text{H}_2\text{O}$
Coquimbite	$\text{Fe}^{+3}_2(\text{SO}_4)_3 \cdot 9\text{H}_2\text{O}$
Quenstedtite	$\text{Fe}^{+3}_2(\text{SO}_4)_3 \cdot 10\text{H}_2\text{O}$
Szomolnokite	$\text{Fe}^{+2}\text{SO}_4 \cdot \text{H}_2\text{O}$
Rozenite	$\text{Fe}^{+2}\text{SO}_4 \cdot 4\text{H}_2\text{O}$
Melanterite	$\text{Fe}^{+2}\text{SO}_4 \cdot 7\text{H}_2\text{O}$
Rhombochase	$\text{HFe}^{+3}(\text{SO}_4)_2 \cdot 4\text{H}_2\text{O}$
Roemerite	$\text{Fe}^{+2}\text{Fe}^{+3}_2(\text{SO}_4)_4 \cdot 14\text{H}_2\text{O}$
Alunogen	$\text{Al}_2(\text{SO}_4)_3 \cdot 17\text{H}_2\text{O}$
Halotrichite	$\text{Fe}^{+2}\text{Al}_2(\text{SO}_4)_4 \cdot 22\text{H}_2\text{O}$
Gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$
Hydronium jarosite	$(\text{H}_3\text{O})\text{Fe}^{+3}_3(\text{SO}_4)_2(\text{OH})_6$

### Hydrated Ferrous Sulfates

*Szomolnokite* ( $\text{FeSO}_4 \cdot \text{H}_2\text{O}$ ), *rozenite* ( $\text{FeSO}_4 \cdot 4\text{H}_2\text{O}$ ), and *melanterite* ( $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ ). — The hydrated ferrous ( $\text{Fe}^{+2}$ ) sulfates occur as white, powdery coating on pyrite and marcasite surfaces. Examination of specimens at various times of the year indicates that the hydration state depends on the relative humidity of the air. Szomolnokite is present during the winter when the humidity is about 20% RH for prolonged periods. Melanterite is present during the summer when the humidity is high. Rozenite is usually observed to occur with szomolnokite, melanterite or both. It is common to see polycrystalline clumps with grains of lower hydration minerals inside higher hydration ones (Fig. 2A, B). Apparently the transformation is slow so that the inner grains do not change during the seasonal periods of high relative humidity.

On museum specimens, hydrated ferrous sulfates may be present as white, powdery crusts up to a centimeter or more thick (Fig. 3) or may be present as minor traces. When abundant, they are commonly accompanied by alunogen or halotrichite. Rhombochase and roemerite occur with minor amounts of ferrous sulfate. This is probably because ferrous sulfate is consumed in the reaction that produces the ferric ( $\text{Fe}^{+3}$ )-ferrous and ferric sulfates as has been noted by other investigators (Buurman, 1975; Palache *et al.*, 1951).

Optical properties can be used to differentiate these minerals, and the polarizing microscope is useful to detect when the sulfate crusts change hydration state. Szomolnokite has higher refractive indices than balsam; rozenite has indices near balsam and melanterite well below. Under crossed polars, szomolnokite generally shows very small particles and polycrystalline grains of a first-order gray birefringence color. Although the mineral has moderately high birefringence ( $\Delta n = 0.072$ ), the small particle size keeps the color low. Rozenite generally shows a gray color ( $\Delta n = 0.014$ ), and sometimes shows its crystal shape. Melanterite particles are usually irregular to rounded in shape ( $\Delta n = 0.012$ – $0.015$ ) and often contain small water inclusions which look like bubbles.

XRD patterns are diagnostic for these three minerals (Table 3). Szomolnokite characteristically shows a strong peak at  $25.89^\circ 2\theta$ , rozenite at  $19.86^\circ$  and melanterite at  $18.10^\circ$ .

The mineral associations on museum specimens are similar to those described in the geological literature. Szomolnokite is formed very early in the weathering of sulfide deposits at Chuquicamata, Quetena and Alcaparrosa mines in the arid

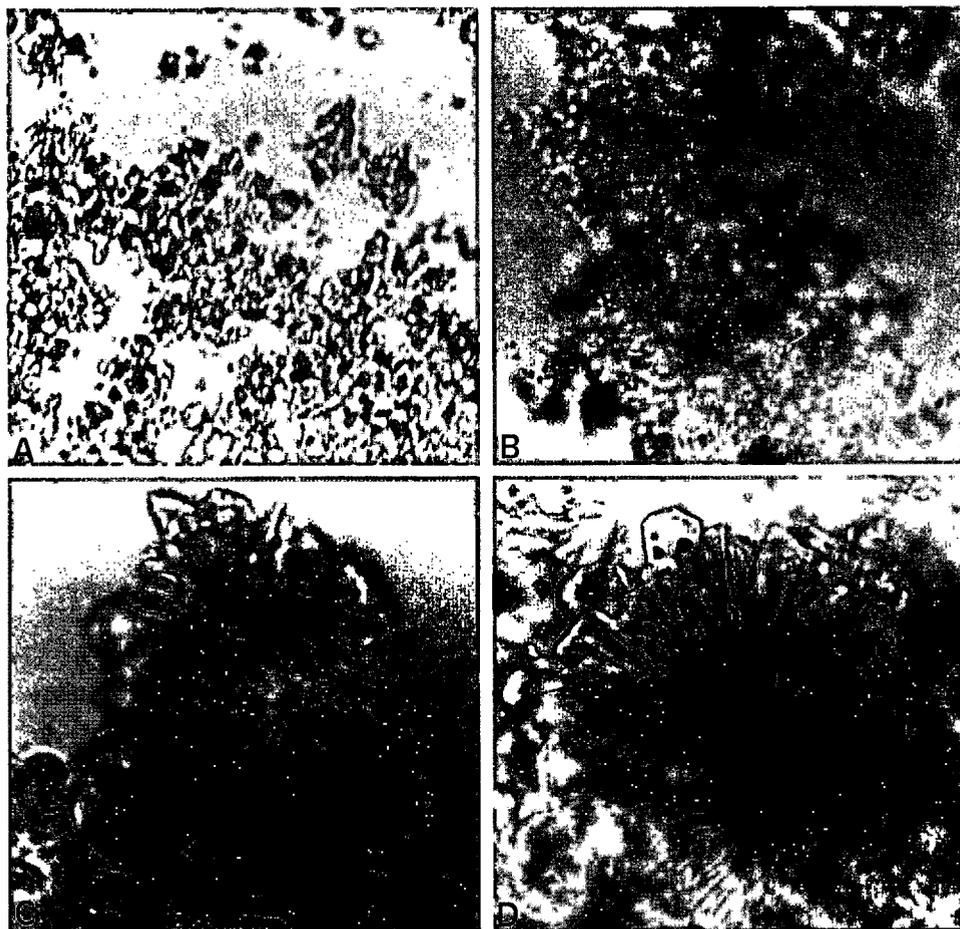


Figure 2. A. Rozenite and szomolnokite in 1.584 refractive index liquid. Note that the two minerals are difficult to distinguish in this refractive index liquid. Width of view for all photomicrographs is 0.1 mm ( $\times 40$  objective) unless otherwise noted. B. Same sample as that shown in A but in 1.540 refractive index liquid. Szomolnokite grains can be seen inside rozenite. The boundary of the rozenite appears cloudy because it nearly matches the 1.540 liquid. C. Rhomboclase in balsam. D. Roemerite in balsam.

climate of Chile (Bandy, 1938). Palache *et al.* (1951) indicate that it occurs in the Santa Elena Mine, Argentina and the Tintic Standard Mine, UT, also localities with arid climates. Melanterite has been described in coal mines in Nova Scotia (Zodrow and McCandlish, 1978) where the humidity runs 81–90%. Rozenite occurs with melanterite there, but it is not clear what the equilibrium relations are. Melanterite has been found in decomposing black shale in Quebec (Berube *et al.*, 1985), in roofing slate in Melbourne, Australia (Shayan and Lancucki, 1984) and in heaving foundation soils in Germany (Tietze, 1981).

Experimental work by Ehlers and Stiles (1965) on rozenite and melanterite indicated that rozenite is stable at humidities less than 70–80%, whereas melanterite is stable at higher values. Szomolnokite did not appear during their experiments in which the lowest RH used was 36%.



Figure 3. Decomposed pyrite nodule. The powdery alteration product consists of ferrous sulfate and alunogen ( $15 \times 10 \times 6$  cm).

*Rhomboclase* ( $HFe^{+3}(SO_4)_2 \cdot 4H_2O$ ).—Rhomboclase occurred in mixtures with other sulfates but made its presence known by imparting a sulfur-yellow color to the alteration coatings of the specimens studied. Under the microscope, this mineral is very distinctive. It has a high birefringence under crossed polars so that the rosettes are very bright (Fig. 2C) and generally are yellowish due to inherent color of the mineral. The individual crystals are platy. Refractive indices are 1.638, 1.553 and 1.534 so that one index is generally near that of balsam regardless of orientation.

Rhomboclase occurs with szomolnokite and rozenite. Under conditions of high humidity it deliquesces, i.e., goes into solution, and so does not occur with melanterite (Winchell and Winchell, 1951). Rhomboclase often occurs with roemerite, and the ratio of these minerals varies during the year. It is not clear if this is due to deliquescence of rhomboclase or to the formation of roemerite from rhomboclase and melanterite as described by Palache *et al.* (1951).

Geological occurrences are restricted to sulfide deposits in arid regions. Bandy (1938) observed that sulfate minerals occurred in zonal arrangements around pyrite grains at the Alcaparrosa Mine, Chile. The szomolnokite and rhomboclase are found nearest to the pyrite indicating that they were formed by more direct alteration of the pyrite than those minerals occurring in the outer zones. The experiment of Buurman (1975) also suggests a direct formation of rhomboclase early in the formation of alteration crusts.

*Roemerite* ( $Fe^{+2}Fe^{+3}_2(SO_4)_4 \cdot 14H_2O$ ).—Roemerite occurs as thin coatings on pyrite and marcasite surfaces. It may impart a rusty or shiny appearance to the sulfide crystals upon which it has formed (Fig. 4). Under the microscope roemerite

crusts can be seen to consist of tabular crystals often in radiating aggregates (Fig. 2D). In cross-polarized light, the crystals appear very bright with medium-order interference colors ( $\Delta n = 0.059$ ). A very characteristic feature of this mineral is an abnormal interference color when crystals are oriented perpendicular to  $X$ . In this position the crystals never go into extinction but show a deep blue color.

Roemerite is frequently found with rhomboclase on museum specimens. It is sometimes found with relatively minor quantities of ferrous sulfates. Geologically roemerite has been described in sulfide deposits of arid regions (Bandy, 1938). In Greece, under humid conditions, Kyriakopoulos *et al.* (1990) found iron and magnesium sulfate efflorescences on walls in caves excavated for the extraction of native sulfur before and during World War II. They found roemerite to be a major component in some alteration zones. It occurred along with rozenite or melanterite. The sulfur which permitted sulfates to form at the Greek location was related to volcanic activity and does not appear to involve sulfide alteration.

*Coquimbite* ( $Fe_2(SO_4)_3 \cdot 9H_2O$ ).—Coquimbite occurs as a tan to brownish crust often sandwiched between the iron sulfide surface and ferrous sulfate, i.e., szomolnokite, rozenite or melanterite. This mineral is easily identified with PLM because of its abnormal blue color which exists in most orientations. In addition, its refractive index matches the balsam (1.547 and 1.552). Occasionally in refractive index liquids which differ appreciably from the mineral, tiny hexagonal crystals have been observed, but usually the mineral appears granular.

On pyrite nodules from southern New Jersey, coquimbite consistently occurs sandwiched between the pyrite surface and ferrous sulfate, and it is possible that coquimbite may have been produced by direct reaction of pyrite and ferrous sulfate in the presence of moist air. On other specimens, coquimbite can be found by optical techniques on recently fractured pyrite surfaces with very little alteration where it must have formed by direct oxidation reaction of pyrite with sulfuric acid. The distinctive blue color under crossed polars causes this mineral to be obvious even when it occurs in very small amounts.

Coquimbite is reported to be found abundantly in the three deposits in Chile studied by Bandy (1938). It is associated there with paracoquimbite, voltaite, szomolnokite, roemerite, copiapite and other secondary sulfates. In terms of the time of formation, Bandy indicates that coquimbite formed after szomolnokite, rhomboclase, halotrichite and roemerite.

*Kornelite* ( $Fe_2(SO_4)_3 \cdot 7H_2O$ ).—Kornelite is a lower hydrate than coquimbite. On specimens studied, kornelite was found on a single specimen at the lower part of cockscomb marcasite crystals (Fig. 4). The kornelite coating consisted of fine (<1 mm) white radiating needles on the marcasite. X-ray diffraction showed that roemerite was associated with kornelite on that part of the specimen. The upper tips of the cockscomb crystals were coated with roemerite and rhomboclase.

Kornelite is easily distinguished from the other needle-type alteration minerals observed in this study. The index of refraction is significantly higher than balsam ( $X = 1.572$ ,  $Y = 1.586$ ,  $Z = 1.640$ ) and its birefringence is moderately high (0.068) giving rise to a very colorful array of tiny needles under the crossed polars. In comparison, needles of alunogen and halotrichite appear gray under crossed polars.

In the geological literature, kornelite is described as a secondary mineral which occurs with voltaite and coquimbite in a pyrite mine at Szomolnok, Hungary. Kornelite has been reported as an efflorescence with coquimbite, roemerite, vol-

Table 3. d-spacing of X-ray diffraction peaks (in angstroms) and peak positions in degrees  $2\theta$  ( $\lambda = 1.5418\text{\AA}$ ) for minerals observed to occur on altered pyrite and marcasite. Lowest  $2\theta$  peak plus peaks with relative intensity (I) of 4 (maximum intensity 10) or greater are shown for each mineral. The most intense diffraction peak for each pattern is underlined.

Alunogen			Kornelite			Coquimbite			Rhomboclase			Rozenite			Halotrichite		
d	$2\theta$	I	d	$2\theta$	I	d	$2\theta$	I	d	$2\theta$	I	d	$2\theta$	I	d	$2\theta$	I
<u>13.5</u>	<u>6.55</u>	<u>10</u>	<u>10.0</u>	<u>8.84</u>	<u>10</u>	9.44	9.36	4	9.15	9.67	4				15.9	5.56	3
			7.04	12.57	6	<u>8.26</u>	<u>10.71</u>	<u>10</u>				6.85	12.92	5			
			6.64	13.33	8	5.45	16.26	6				5.46	16.23	9			
									4.74	18.72	4				4.97	17.85	5
4.49	19.78	9	4.67	19.00	8	4.60	19.30	5				<u>4.47</u>	<u>19.86</u>	<u>10</u>	<u>4.81</u>	<u>18.45</u>	<u>10</u>
4.39	20.23	8	4.39	20.23	4												
4.33	20.52	8	4.30	20.66	6												
									4.05	21.95	5				<u>4.30</u>	<u>20.66</u>	<u>10</u>
															4.15	21.41	5
3.97	22.40	8													4.10	21.68	5
3.90	22.82	5										3.97	22.39	7			
3.68	24.22	5	3.50	24.45	4	3.64	24.45	4									
									3.55	25.08	5				<u>3.50</u>	<u>25.45</u>	<u>10</u>
						3.36	26.52	6	3.33	26.77	5	3.40	26.21	6			
												3.22	27.70	5			
			3.14	28.42	6				3.29	28.10	4						
									<u>3.11</u>	<u>28.68</u>	<u>10</u>						





Figure 4. Altering cockscomb marcasite. The tips of the crystals are coated with rhomboclase and roemerite, and the lower part of each crystal is covered with kornelite and roemerite ( $10 \times 8 \times 4$  cm).

taite and rhomboclase at the Copper Queen Mine, Bisbee, AZ (Merwin and Ponsjak, 1937).

*Alunogen* ( $Al_2(SO_4)_3 \cdot 17H_2O$ ) and *halotrichite* ( $Fe^{+2}Al_2(SO_4)_4 \cdot 22H_2O$ ).—Alunogen and halotrichite are needle-like sulfates which form alteration coatings that appear fuzzy or fluffy and are generally white in color. Often the needles do not appear to be projecting out of or growing from the sulfide surfaces but appear to be in random orientation mixed with szomolnokite, rozenite and/or melanterite. Whereas these minerals can be easily distinguished by X-ray diffraction (Table 3), they are often difficult to distinguish by optical techniques. They both have indices which are lower than balsam (alunogen: 1.460, 1.461 and 1.470; and halotrichite: 1.480, 1.486 and 1.490) and require using a refractive index liquid of 1.475. Likewise, the extinction angles are similar with  $42^\circ$  for alunogen and  $36^\circ$  for halotrichite. Halotrichite (Fig. 5A) rarely shows distinctly terminated crystals, whereas alunogen often shows well formed crystals (Fig. 5B).

The presence of a sulfate alteration product containing aluminum was somewhat of a surprise. In fact, the identification of alunogen as a major component of an altered pyritized brachiopod fossil was the original inspiration for this study which has shown that these aluminum-bearing minerals are not uncommon in our specimens. They occur in six of the fourteen specimens studied. The aluminum has likely come from clay minerals. In several of the specimens, XRD patterns of kaolinite could be obtained. It must be concluded, in agreement with Wiess *et al.* (1987), that aluminum possibly contributes to the decomposition of some pyrite and marcasite samples.

In nature, halotrichite is found as a product of weathering of pyrite in aluminous

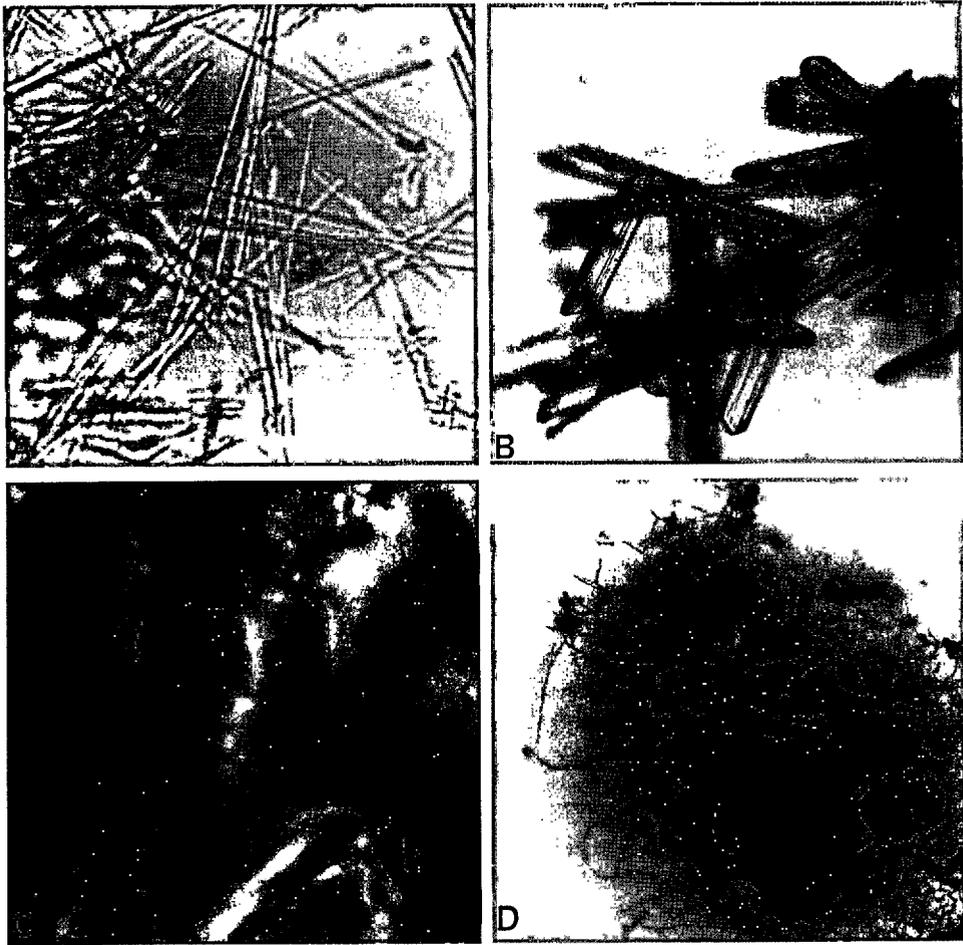


Figure 5. A. Halotrichite needles in balsam. Width of view of photomicrographs is 0.1 mm ( $\times 40$  objective) unless otherwise noted. B. Alunogen crystals in air. C. Hydronium jarosite (hexagonal crystals) in a sample with halotrichite and szomolnokite. Sample in balsam. Width of field 0.05 mm, photographically enlarged. D. Cracked amorphous material formed from rhomboclase. Black spots are pieces of opaque marcasite. Width of view 0.5 mm ( $\times 10$  objective). See text for further explanation.

sedimentary and other rocks. It occurs in gossans in arid regions and as an efflorescent deposit in sheltered places such as recent mine workings. Alunogen occurs in similar associations. Specifically listed (Palache *et al.*, 1951) are occurrences in more humid climates such as Smoky Mountain, Jackson Co., NC and on weathered shale in Ithaca, NY. The two minerals occur together along with pickeringite, epsomite, alums, gypsum, melanterite and other iron sulfates.

*Jarosite mineral.*—In a number of samples examined optically, tiny hexagonal platelike crystals were noted (Fig. 5C). These crystals were insoluble in water and have tentatively been identified as hydronium jarosite,  $(\text{H}_3\text{O})\text{Fe}^{+3}_3(\text{SO}_4)_2(\text{OH})_6$ . This identification has not been substantiated by X-ray diffraction or chemical analysis because of the lack of sufficient material. Shayan and Lancucki (1984) have described hydronium jarosite with melanterite and halotrichite in decayed roofing slate in Melbourne, Australia. It has also been described as a constituent

of gossans with other jarosites. In the United States, it is found at the Eureka Hill Mine, Tintic District, UT (Palache *et al.*, 1951).

*Quenstedtite* ( $Fe_2(SO_4)_3 \cdot 10H_2O$ ) and *gypsum* ( $CaSO_4 \cdot 2H_2O$ ).—Quenstedtite was noted in only one sample at one time of the year (April, 10–40% RH). It occurred as a trace component on an altered pyrite nodule along with halotrichite, coquimbite and rozenite.

Gypsum was present as a very minor component on a number of samples that also contain calcite. It was particularly obvious in a fossil pelecypod, *Exogyra costata*, where gypsum and rozenite had formed inside the outer lamina of the shell and had cracked it. The pyrite inside probably had formed in the marine environment. Solutions responsible for the pyrite had gained access through the outer surface of the shell by means of small holes which had been left by boring organisms. It is possible that some of the pyrite alteration took place in the weathering zone before the specimen was collected, but most of the destruction was observed to take place more recently.

#### DISCUSSION

The twelve sulfate minerals found on decomposing pyrite and marcasite specimens are also known to occur in a variety of natural environments. The geologic literature is useful to obtain information about the mineral associations and paragenesis. It is clear from this study showing the similarity of associations that the same or similar processes are taking place in museums as in natural environments. The climate where minerals geologically occur, interpreted with care, can provide useful information. The microclimatic conditions of natural occurrences may be utilized as indicators of artificial conditions for similar assemblages of minerals, bearing in mind the effects of seasonal variations, changing water tables and water compositions, and other factors. In addition, the sulfates of interest are quite soluble, for the most part, and in wetter climates they may be preferentially dissolved. Nevertheless, the literature reflects which minerals are stable in more humid air. Rozenite, melanterite, roemerite, kornelite, halotrichite and alunogen are examples of those minerals which although found in arid climates probably were formed in humid microclimates. They also occur as efflorescence in sheltered places in humid regions.

In addition to determining which minerals were present, a number of changes were observed during the year as the humidity varied. These include (1) the hydration and dehydration of ferrous sulfates, (2) a transformation between halotrichite and alunogen and (3) the deliquescence of several sulfates.

The ferrous sulfates go through reversible dehydrations and hydrations during the course of the year. During the winter when the humidity is consistently below 30%, szomolnokite is present and at RH greater than 50%, melanterite. Rozenite is present at intermediate relative humidities. The changes seem to be sluggish and to respond to the average humidity over several months. Ehlers and Stiles (1965) state that conversion of melanterite to rozenite or rozenite to melanterite is "usually accomplished within an hour" at about 70% RH. In the present study, rozenite was rarely found without szomolnokite and/or melanterite. The explanation for this is probably the difference in experimental conditions. Ehlers and Stiles were investigating finely powdered material over which air was forced to

flow, whereas, in this study the specimens were irregular and the only air movement was due to normal room circulation.

The observation of alunogen on a specimen at one time and halotrichite at another is not as straight forward as the change from one ferrous sulfate to another. Alunogen seemed to occur during periods of high humidity and halotrichite during periods of low humidity, but this did not always hold. Halotrichite could often be found on the same specimens as alunogen during high humidity. The instability of alunogen at low humidity has been commented upon in the literature. Fang and Robinson (1976) indicated that alunogen crystals decompose during the low humidity of winter. Palache *et al.* (1951) state that heating of alunogen will cause dehydration with the alteration products being isotropic. Further, they state that the product will not rehydrate. Examination of actual specimens, however, indicates some type of direct relation between alunogen and halotrichite. For example, in a pyrite nodule from southern New Jersey, alunogen and szomolnokite were present in May (40–70% RH), alunogen and coquimbite in July (45–75% RH) and coquimbite and halotrichite in November (15–45% RH) and January (10–30% RH). A preparation containing coquimbite and halotrichite no longer in contact with pyrite changed to one containing coquimbite and alunogen after being placed in 85% RH overnight. This suggests a transformation from one to the other. It is possible that associated melanterite (below detection level of XRD) might have deliquesced so that the transformation from halotrichite to alunogen took place in solution. However, the reverse reaction to halotrichite probably could not have taken place in this manner. Thus, the relation of these minerals remains unresolved.

Finally, some minerals have been observed to deliquesce at high humidity. A particularly good case is rhomboclase. At high humidity, it became wet and once this occurred, the material did not recrystallize as the humidity dropped. The material simply solidified generally with cracking but remained amorphous as determined by optical and X-ray techniques (Fig. 5D). Melanterite was found to deliquesce but did recrystallize. Deliquesced roemerite recrystallized in part but did not return to the original mineral phase. The identity of the recrystallized form has not been determined in most cases since only tiny amounts were available for study.

The noncrystalline solids formed from deliquescent minerals (subsequently referred to as the *amorphous phases*) are believed to be colloids based on preliminary infrared and SEM analyses. Scans of the 300–4,000  $\text{cm}^{-1}$  range using an FTIR microspectrometer showed a large amount of loosely held water in the amorphous-phase sample examined. The original crystallized material and the phase formed by exposure to 83% RH followed by a return to ambient conditions (approx. 50% RH) were analyzed. Both showed strong absorption bands in the sulfate bonding region 1,200–900  $\text{cm}^{-1}$ . The significant difference was, however, in the  $\text{H}_2\text{O}$  bonding region where the amorphous phase showed a very intense, broad water band at 3,376 and 3,246  $\text{cm}^{-1}$ . The crystalline material which consisted of a mixture of roemerite and rhomboclase showed less intense narrow bands at 3,540, 3,329 and 3,080  $\text{cm}^{-1}$  from the waters of crystallization.

Colloids are defined as suspensions of finely divided particles in a continuous medium, especially a gaseous, liquid or solid substance. Generally the particles range from 5 to 5,000 angstroms and are so small in size that they do not settle

out or filter readily (Vianna, 1977). The very sharp IR absorption from  $\text{SO}_4$  bonding observed in this study suggests that the amorphous phase consists of something more complex than simple sulfate ions in solution. Further, water is clearly abundant. Van der Marel and Beutelspacher (1976) and Ryskin (1974) state that IR absorption at  $3,220\text{--}3,250\text{ cm}^{-1}$  indicates an ice-like pattern of water adsorbed on a surface, i.e., particle, or possibly in pores. The  $3,247\text{ cm}^{-1}$  in my pattern is indicative of the presence of adsorbed water on particles giving credence to the fact that particles are present despite not having been resolved by means of PLM and SEM (scanning electron microscopy).

Examination of the literature indicates that colloids play a very important role in corrosion of metals such as steel. Matijevic (1978a, b; Matijevic *et al.*, 1975; Matijevic and Kallay, 1983) points out that colloids are almost always involved in corrosion and that the reacting complexes responsible for the damage generally exist in the colloidal state. Many of the more important anions, with a dramatic effect upon the alteration, may not appear as crystalline constituents in the resulting product. This has implications for the type of PLM-XRD study reported here where the methods can only identify crystalline phases. Further, Matijevic points out that sulfate ions have an essential effect in the generation of many of the colloids causing corrosion of metals. The identification of colloids and their possible involvement in museum specimen alteration is a significant finding in this study. For this reason, more work is underway utilizing IR, SEM and TEM methods to illuminate the nature and role of colloids.

#### CONCLUSIONS

The causes of specimen damage are still under investigation; however, any theory on the decomposition of pyrite and marcasite should explain the phenomena observed in this study. The important observations are:

1. Ferrous ( $\text{Fe}^{+2}$ ) sulfates are abundant on some specimens and absent or nearly so on others.
2. Ferric ( $\text{Fe}^{+3}$ ) sulfates are present on some specimens, apparently in reverse proportion to ferrous sulfate.
3. The presence of ferrous versus ferric sulfates does not appear to be related to the length of time the specimens have been exposed to air, at least in so far as the length time of storage in the collection is concerned.
4. Aluminum containing sulfates were found on more than a third of the specimens randomly selected for study which indicated that complicating interactions with associated minerals had taken place.
5. Macroscopic and microscopic examination of cracks in pyrite and marcasite generally show that only traces of alteration minerals are present.
6. Colloids may play a role in specimen alteration.

A final word with regard to colloids and their possible part in alteration: years of research have been invested in corrosion research of steel and other industrially important metals, yet understanding is still incomplete. This situation is due in part to the fundamental difficulty in characterization of colloids. We should not expect a quick or simple answer in the quest to understand what is happening to the specimen materials in museum collections.

## ACKNOWLEDGMENTS

I thank P. Goss and D. Frederick of OMYA, Inc., for doing FTIR and SEM analyses of selected samples, W. Gavienoski and other members of the Rutgers University Dana Library staff for procuring interlibrary loan material and to reviewers, R. Waller and R. Ramik, for useful and constructive suggestions.

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# CONSERVATION OF A DINOSAUR TRACKWAY EXHIBIT

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*Abstract.*—In 1939, large sections of a dolomitic Lower Cretaceous dinosaur trackway from Glen Rose, TX, were removed for exhibition at the American Museum of Natural History, Texas Memorial Museum, and a few other museums. The TMM section of the trackway, housed in a small building outside the main museum, shows severe deterioration, including surface spalling and exfoliation associated with growths of epsomite crystals. Comparable damage has been reported in no other section of the trackway exhibited in museums, and spalling has been noted in only a few in situ tracks exposed to simultaneous high water saturation and freezing. The surface deterioration appears to be the result of the development of epsomite and other soluble salts as the result of prolonged exposure to excessive humidity and temperature fluctuations, caused in part by the breakdown of the moisture barriers once provided by the trackhouse. Contemporary documentation suggests that the materials and design of the dinosaur trackhouse, combined with the physical damage caused by removing the blocks, have contributed to the problem. Plans for stabilizing the trackway include surface cleaning of the breakdown debris, immediate and long-term modifications of the building, and ongoing environmental monitoring.

Dinosaur footprints in the Lower Cretaceous deposits of the Paluxy River, Glen Rose (Somervell County), TX, have been known since 1908 (Farlow, 1987), and were first described by Shuler (1917). This site, the remnant of a bay or lagoon system (Nagle, 1968), is noted for its long series of exceptionally well-preserved carnosaur and sauropod footprints in immediate proximity to each other. The surface of the trackway also shows excellent preservation of holes and burrows caused by bioturbation of the original mud by invertebrates. Most of the tracks are relatively undisturbed in situ and are protected by the Texas Parks and Wildlife Department (TPWD), which established Dinosaur Valley State Park and its interpretive center (now Dinosaur Valley National Monument) in 1988 (Spain, 1987).

Roland T. Bird of the American Museum of Natural History (AMNH) arrived at the Paluxy River site in 1939 to collect sections of the trackway, as part of a Work Projects Administration (WPA) project jointly supervised by the University of Texas and the AMNH. Bird supervised WPA workers and Glen Rose citizens in cleaning and removing large blocks of the track-bearing dolomite. The sections were hammered out of the parent trackway, numbered, transported by truck and train, and eventually reassembled at their destinations.

The largest contiguous section of removed tracks was divided; one part was sent to the AMNH, the other to Texas Memorial Museum (TMM). These two sub-sections, in spite of their present geographic separation, are considered to be a single section for taxonomic purposes. Farlow (1987) designated the sauropod tracks in this section of the trackway as the type specimen of the ichnogenus *Brontopodes*.

At TMM, the track section was reassembled on a bed of unconsolidated sand on a concrete slab outside the main museum; an unidentified commercial plaster compound was used to rejoin the blocks. Once in place, the tracks were completely overpainted in a gray water-based paint to mask the plaster joins and to simulate the natural appearance of the stone in situ. The exact nature of the paint used has

not been determined after standard tests. The trackhouse, a limestone-block structure with a single viewing window along one side, was built over the reassembled trackway. This has been on continuous exhibit outside the main TMM building since 1941.

The structure of the dinosaur trackhouse has contributed significantly to the deterioration of the trackway. Weathering, the physical damage caused by a clay-caliche soil with a high shrink-swell capacity (which causes much volumetric change in the substrate and consequent cracking of the house), and construction projects in the immediate vicinity have all contributed to the physical instability of the building.

Much of the history of the track removal and reassembly project has been conjectural to date, and reports of the processes have been unconfirmed and contradictory. Bird's autobiography, *Bones for Barnum Brown* (1985), provides an excellent retrospective account of the removal of the tracks from the Paluxy River bed. Several sources for the present-day problems with the tracks are suggested by following the chronological progress of the project from removal of the tracks to the opening of the trackhouse exhibit, as described by field reports, correspondence, and other papers recently found in TMM archives.

Rains or other adverse weather conditions limited work during part or all of six work weeks in the spring and summer of 1940, and the track sections were undoubtedly collected while the dolomite was saturated. Inundation of the in situ Paluxy River tracks is a frequent spring occurrence, normally causing little damage; the excellent condition of the in situ tracks suggests that periodic flooding and drying are not often a source of severe damage.

Archival records suggest that the current problems with the TMM dinosaur track exhibit are less likely due to the original collection of flood-saturated dolomite (which may have had a chance to dry normally after reassembly) than by the rapid construction of the dinosaur trackhouse and downgrading of original building specifications. The trackhouse was built at a time when WPA funds were drying up and the Second World War was imminent, and the design and materials used for the trackhouse are far inferior to those proposed. The trackway section has consequently been provided with poor housing and protection from the start.

In September 1988, while studying all the Paluxy River sections removed from the original site, former TPWD exhibits specialist Peggy Maceo noticed severe deterioration of the surface of the TMM trackway section. Prior to her study, the trackhouse was only entered when fluorescent tubes lighting the surface were changed; thus, it is not known when the damage to the surface began. TMM exhibits and conservation staff initiated an analysis of the problem to determine the source of the deterioration and the appropriate course of action.

#### OBSERVATIONS

The TMM dinosaur trackhouse is built of native fossiliferous limestone blocks assembled directly over the trackway. The house is flat-roofed. One long side of the building has a window along its full length to provide a viewing area. Fluorescent lights have been recessed under the windowsill, directly above the surface of the tracks closest to the viewing area, to facilitate viewing at night. There is no barrier between the track surface and the wooden windowsill supports or the base of the stone wall. The rest of the trackway is immediately surrounded by a

curved plaster interior wall and an interior plaster ceiling, both installed in the 1960s.

Profound deterioration of the trackway surface is most evident at the edge closest to the viewing window. The dolomite of the trackway and the plaster used to join the sections are degraded to powder, beyond any possibility of effective consolidation. At the sites where the wooden windowsill supports have been in prolonged contact with the stone, deterioration of both the wood and the stone is severe (Fig. 1).

The dolomite in this area has spalled and crumbled, leaving a coarse-grained debris. This deterioration is associated with mat-like areas of small white crystals at the sites of plaster joins. These crystals appear to have originated slightly under the trackway surface and may have contributed to the surficial spalling. Once the deterioration products in these areas have been removed by gentle brushing, little or none of the original surface is left, and there are no remaining track impressions or signs of invertebrate bioturbation.

Above the tracks, the plaster ceiling has shown large seasonal blooms of mold, as has the plaster wall. Evidence of old leaks from the flat roof includes waterstains on the interior wall and ceiling, as well as staining and partial dissolution of the paint covering the trackways.

Other problems noted include the breakdown of mortar between the building blocks, especially those at or close to the slab and those under the viewing window (Fig. 2), which has allowed the entry of a diverse fauna of invertebrates and small vertebrates; the presence of old electrical wiring for the viewing lights, which is at some points in contact with the stone surface; and the complete lack of ventilation, air exchange, or climate control. The house is uncomfortable to work in for more than a few minutes at a time, due in large part to the high humidity levels inside. An underlying assumption that the stone was inherently stable may have obscured awareness of the problem in its early stages.

#### GEOCHEMICAL ANALYSIS

The dolomite of the Paluxy River trackway was analyzed by Lewin in 1977 as part of a frost damage survey for TPWD. It is a heterogenous mixture, containing 70% dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ), 25% quartz ( $\text{SiO}_2$ ), and 5% clay minerals. This allows a highly differential expansion and contraction of the stone in fluctuating humidity conditions, causing many small cracks and cleavages which contribute further to the high porosity of the stone. Lewin also noted the inclusion of unmineralized or partially mineralized "vegetable fibrous tissues," which are associated with cleavage areas (S. Z. Lewin letter to K. E. Smith, TPWD, 1977).

#### *Saturation, Expansion, and Freezing*

Dolomite is susceptible to thermal expansion at low temperatures. The clay content and pore size of dolomites also contribute to the problems observed with prolonged environmental exposure. Clay-containing dolomites are more susceptible to frost damage than are limestones with an equivalent amount of clay (Dunn and Hudec, 1966). This is largely because rejection of the clay particles during the process of recrystallization of dolomite tends to form continuous bands between the tiny dolomite grains; these bands then tend to transport and adsorb water (Winkler, 1973). Hudec (1977) suggests that adsorbed water, not freezing,



Figure 1. Damage under the sill of the viewing area, showing plaster deterioration, surface breakdown of the stone, and wood rot from the rising damp. Note the proximity of the damage to toe impressions in the stone.

is the primary reason for failure of most carbonate aggregates, and contends that most of the "frost-sensitive" rocks saturate critically under conditions of high humidity; most of their contained water is in adsorbed water. This adsorbed water can expand to cause disruption of the stone without directly freezing. Stone with mid-sized pores with a mean diameter of five micrometers is most susceptible to water and frost damage, due to inability of the water to migrate from the pores (Winkler, 1973). The Paluxy River dolomite unfortunately falls into this category.

#### *Subflorescence and Salt Migration*

Subflorescence is the phenomenon in which salts move toward the stone surface (as in efflorescence), but without reaching the surface. The salts crystallize beneath a crust of weathered rock, dust, and soot, forming a thin, indurated skin. As this skin loses its support and begins spalling, the remaining surface begins to form another skin which will spall in turn. The major source of salts in the TMM trackway appears to be the hydration of the plaster (calcium sulfate hemihydrate,  $\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$ , to gypsum,  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ), as well as the hydration of the magnesium sulfates (kieserite,  $\text{MgSO}_4 \cdot \text{H}_2\text{O}$ , to hexahydrate,  $\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$ , to epsomite,  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ ) (Winkler, 1973).

#### *Damage to Stone on Exhibit and in situ*

The damage seen to the stone in the TMM trackway is comparable to the severe and irreversible damage seen in some small sections of the in situ trackway only after severe winter weather conditions. Hydrological studies have shown that exposure to freezing temperatures while the stone is saturated is the single most damaging hazard to the in situ tracks (Spain, 1987). Tracks exposed to freezing

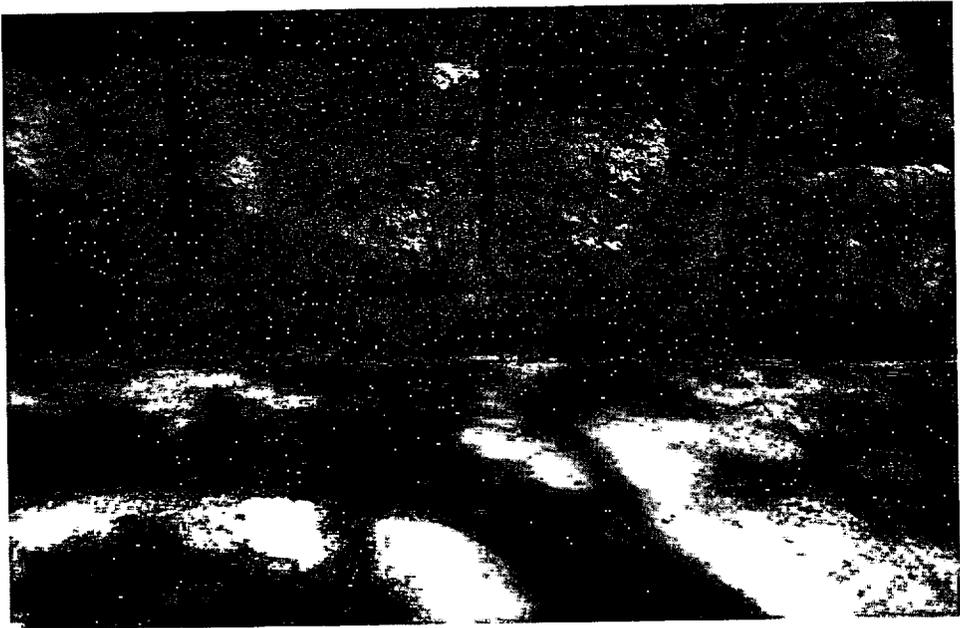


Figure 2. Exterior view of the masonry under the sill, showing cracks and mortar failure on the other side of the trackway section shown in Figure 1.

temperatures suffer surface destruction from ice wedging from expansion of adsorbed water which does not itself freeze, resulting in a breakdown which is visually similar to the breakdown seen in the TMM track section. This condition has never been noted in the AMNH section or in other small sections on exhibit elsewhere. The TMM analysis thus focused on those factors unique to the TMM exhibit situation which might be analogous to forces operating on the in situ tracks.

Lewin (S. Z. Lewin letter to K. E. Smith, TPWD, 1977) subjected Paluxy River dolomite samples to several tests, including wet-dry cycling, mechanical abrasion, and chemical consolidation. The result of the wet-dry cycling was the gradual enlargement of cracks and fissures, until the specimens broke in to several pieces (after five to eight such cycles). Lewin concluded that the hydration and swelling of clay minerals and vegetable matter are the principle causes of the breakage. He also found that the stone is highly vulnerable to acidic air pollutants and mechanical abrasion, and rejected the use of chemical consolidants because of the tendency of any material having volumetric characteristics different from those of the stone to produce fissures and fragmentation under environmental stress similar to the effect of the wet-dry cycling.

#### *Significance of Epsomite Formation*

The studies cited above and the immediate observations suggest that the problem with the TMM dinosaur trackway is associated with the effects of moisture saturation of the dolomite and plaster; soluble salt migration and subflorescence connected with saturation; fluctuations in moisture level of the stone as well as in humidity at the surface of the stone; and, secondarily, exposure to freezing

temperatures. No records of environmental monitoring have been maintained for the trackhouse prior to 1990. In 1988, the senior author collected samples of the crystal growths for X-ray diffraction analysis (using the equipment and facilities of the University of Texas Department of Geological Sciences). The crystals proved to be mostly epsomite, a hydrated magnesium sulfate, which is only stable at conditions of 68–90% relative humidity. This alone suggests that the interior of the trackhouse tends to remain at a high level of humidity.

Epsomite crystals are most evident around the areas of plaster joins, where the plaster and dolomite are in direct contact (Fig. 3). Because epsomite is a hydrated magnesium sulfate ( $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ ), it may be a reaction product between plaster ( $\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$ ) or gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) and dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ). There may be sufficient magnesium in commercial plaster preparations to account for the formation of epsomite from the hydration of plaster minerals alone (Land, pers. comm.). The possibility of dolomite-plaster reactions has not, however, been discounted. In either case, the hydration of the plaster provides a wealth of soluble salts to migrate and cause structural damage.

Environmental monitoring began in September 1990, as part of an Institute of Museum Services Conservation Project survey grant. The range of relative humidity fluctuations has been found to vary as much as 30% in a week. This exceeds the outside humidity range of 23% for the same period (March 1991) and probably reflects both the ambient relative humidity changes and the amount of moisture held in the stone. The fluctuations showed a strong diurnal cyclicity, with peak levels occurring during the day.

The presence of epsomite crystals is a major factor in the deterioration of the trackway. The migration of this and other soluble salts is not seen in any other trackway sections. High relative humidity, the presence of large amounts of aging commercial plaster, and the inherently porous nature of the dolomite have acted in concert to produce a system in which subflorescing salts are rupturing the surface of the stone. Since tracks and other trace fossils are only impressions in the surface of the stone, this loss is particularly damaging to the scientific value of the section.

#### STRUCTURAL ANALYSIS

Although the trackhouse was built with ventilation slits on its sides, any effective air flow was blocked by installation of the interior plaster wall and ceiling. This has undoubtedly contributed to the rise of ambient humidity of the building, as there is now neither climate control nor ventilation.

The concrete slab underlying the trackway is about 19" below the surface on its exterior edges with minimal footing; it is impossible to core the center depth without irreparable damage to the trackway. Peripheral excavation showed no evidence of any vapor barrier or reinforcing steel. During the initial analysis and cleaning of the trackway, a serious crack in the slab was noted at the rear wall. Further investigation showed several cracks in mortar joints between stones in the front and rear walls of the building, as well as radial cracks in a raised walkway in front of the building. This has apparently been caused by a lack of reinforcing piers or more massive footing beneath the slab, and suggests that a major source of stone saturation is moisture rising from the clay-caliche substrate. With nothing



Figure 3. Damage to the stone surface is most pronounced in the areas of plaster joins. The white area to the upper left of the degraded stone is an epsomite efflorescence.

between the trackway and the cracked slab except a bed of unconsolidated sand, moisture uptake is inevitable.

In the 1980s the university began construction of a multi-story parking garage immediately northwest of the trackhouse. During excavation for this, soil was piled against the rear wall of the trackhouse to a depth of 11" above grade. This created drainage from the garage toward the trackhouse's back wall, so that runoff water seeped through the earthen berm, struck the limestone structure and permeated the sand bed.

Blooms of mold on the interior plaster wall and ceiling confirmed the presence of water from roof leakages. The roof decking was sheathed in seamed galvanized sheet metal, which has severely corroded. A tar-gravel matrix which originally covered the roof has weathered and crumbled, and tree and insect detritus collects on the roof surface.

The front (window) wall, site of the worst trackway deterioration, does not match the specifications found in the TMM archival files. Instead of a sloping sill, workers installed a flat sill. Rotting of the wooden sill supports has caused the window base to slope to the interior of the building. Water pools on the sill during rains and seeps to the untreated wood surfaces, providing a base for fungal growth. In addition, the ceiling joists are also the roof rafters, so that there is no headbeam over the window wall; the glass framing is, therefore, directly supporting the roof. Leakage and wood rot, combined with dolomite deterioration at the base of the sill supports, could in time lead to further settling of the roof and cracking of the window.

The TMM dinosaur trackway problem thus seems to be a problem of migrating salts spurred by fluctuating moisture and humidity, which in turn appear to be

the result of poor building design and drainage. Rising damp has saturated the dolomite and plaster, causing damage associated with adsorbed water and soluble salt migration in a sensitive and heterogenous stone, increasing the risk of severe damage.

#### CONSERVATION

Conservation of the TMM dinosaur track exhibit is proceeding along a twofold plan: stabilization of the dolomite and plaster, and modifications of the physical structure of the building to eliminate sources of moisture and prevent future damage. While removal of the trackway to a more climate-controlled structure would be ideal, the expense and risks of this are so great that the trackway will undoubtedly remain in its current housing for the foreseeable future.

Consolidation of the trackway is not recommended at this time. Lewin's experiments suggest that most consolidants will not lessen the damage associated with repeated hydration cycles, and may exacerbate such damage. It is probable that consolidation would only result in even larger fragments breaking and spalling from the surface, and that the migration of salts will not be stopped by consolidation (R. R. Waller, pers. comm.).

Cleaning the trackway of breakdown debris by gentle dry-brushing and spot vacuuming has been successful to date. This removes deteriorating paint and exposes the areas of plaster joins (Fig. 4). Since these areas appear to be most susceptible to the growth of epsomite crystals, they should not be masked by paint, which would prevent early detection of a recurring growth of crystals. Removal of deteriorated plaster may be one strategy in controlling the sources of soluble salts.

Modification of the building will require improved drainage, addition of a vapor barrier, prevention of leakage, and subsurface stabilization of the concrete slab. Removal of the earthen berm left by the garage construction has eliminated one source of long-term moisture retention. The proposed installation of tiled drainage leading downhill and away from the building will mitigate the problem of moisture rising into the trackway from saturated soil.

High relative humidity in the trackhouse cannot be controlled by desiccation of the air; it is largely associated with the problem of rising damp. Desiccants will not be used to lower atmospheric relative humidity until a vapor barrier between the trackway and the substrate can be guaranteed. Otherwise, desiccation of the air will cause faster migration of the rising damp and further soluble-salt damage to the dolomite.

In the long term, dealing with the trackway deterioration will require consolidation of the concrete slab rather than consolidation of the trackway surface. Several options for this have been suggested. It is possible to excavate the slab on one side at a time, pour a larger footing with a mechanical connection to the existing slab, and install a vapor barrier into the excavation.

Leakage from the roof will continue to be a threat as long as the roof is flat and covered with an unstable tar-gravel mixture. The covering is now being removed. Increasing the pitch of the roof with steeper joists, and adding decking and a vapor barrier, will significantly reduce the risk. In the long term, the installation

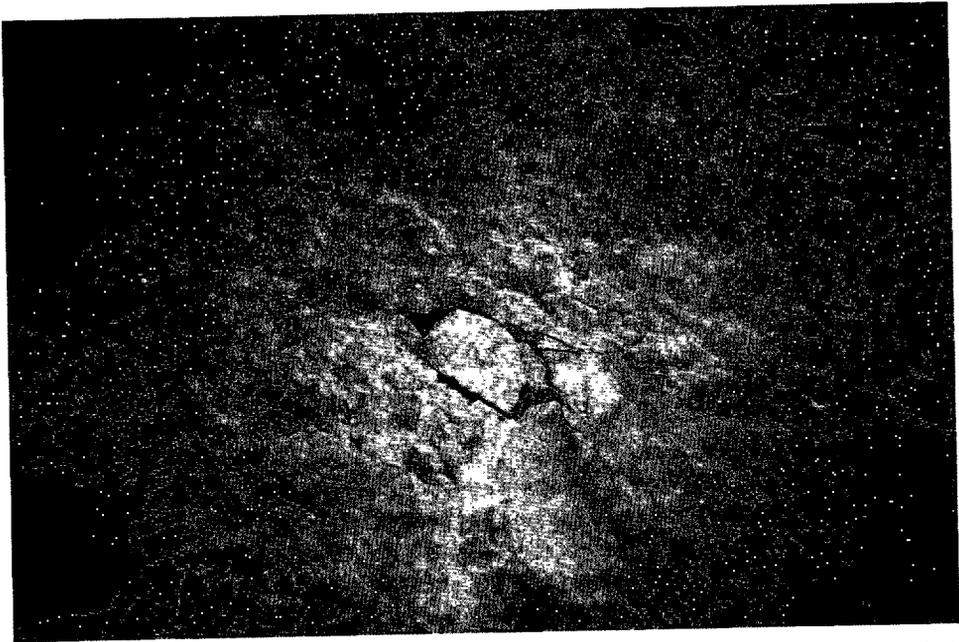


Figure 4. Removing the masking paint from the trackway exposed the original plaster joins, which can now be better repaired and monitored for signs of further deterioration.

of a new vaulted roof with a gable configuration, and with a continuous soffit vent, will reduce moisture buildup. Addition of a clerestory will aid in the illumination of the tracks.

Plans to correct the roof and window problems simultaneously have been submitted to the university administration. The glass and its aluminum sash will be removed to facilitate the installation of a laminated support beam across the window opening to support the gable roof. When new glass or acrylic windows are installed, the new sill will be slanted at least  $10^\circ$  outward to provide sufficient runoff.

A recording hygrothermograph is now installed in the building and will be monitored indefinitely. Once building modifications stabilize environmental fluctuations and trackway deterioration, further treatment may not be necessary so long as the surface is stable. While some slight masking of the joins may be desirable, the trackway as a whole will not be repainted for the sake of reproducing its in situ appearance (as was done previously), so that the joins can be checked for signs of continuing epsomite growth.

This is visualized as a five-year project. Cleaning of the surface and monitoring the interior climate have begun and will proceed as long as necessary. Improved drainage down to street level will be undertaken in 1993. Roof and window modifications will follow. Correction of the slab problem will require cautious planning and a significant commitment on the part of all agencies concerned. The condition of the stone will be monitored at all times, but particularly at times of severe cold or exceptionally high rainfall (as was the case in 1992, when subfluorescence briefly increased). Only this suite of building modifications will save the trackway in its present housing.

## CONCLUSIONS

The TMM dinosaur trackway problem began as a geochemical analysis of stone deterioration and ended as a study in archival history and exhibit architecture. Identifying the true nature of the problems and designing an appropriate solution has required an interdisciplinary approach. It has proved impossible to deal with this complex situation in any other way.

Archival records, including contemporary newspaper clippings, Bird's original field reports, and original maps and blueprints, were located during this study and have proved tremendously useful in clearing up many of the most puzzling problems concerning the trackway reassembly and trackhouse structure.

Various short-term strategies suggested, including consolidation and adhesion, were rejected in light of the long-term implications of such approaches. The vast majority of these approaches would at best gloss over symptoms of deterioration with no consideration for their sources, and at worst could fail to control, and might even exacerbate, existing problems. It is not necessary to destroy the TMM trackway in order to save it. The rejoining and housing of this section of the Paluxy River trackway has, to date, put it at more risk of deterioration than it would have faced in situ. The cleaning, monitoring, improved drainage, and staged implementation of building modifications are aimed at saving the fragile stone surface. Dinosaur trackways are, after all, simply detailed and revealing impressions in the surface of the stone. No loss of that surface is acceptable, and measures to retard or arrest the deterioration have been, and will continue to be, implemented.

## ACKNOWLEDGMENTS

The authors wish to thank Peggy Maceo, formerly of TPWD, D. Riskind of TPWD, and G. Evans for their invaluable information on the history of the Paluxy River trackway collecting project. Thanks also to M. Jeffreys, J. Lang, B. Moore, W. Langston, Jr., L. Denton, W. Reeder, and D. Hollingsworth of TMM; E. Lundelius, R. Rainey, and R. Toomey of the Vertebrate Paleontology Laboratory, TMM; L. Land, of the Department of Geological Sciences, University of Texas; R. Waller of the Canadian Museum of Nature, Ottawa; E. Gaffney of the AMNH; and J. Farlow of the University of Indiana. Special thanks to I. N. M. Wainwright of the Canadian Conservation Institute; John Ashurst, D. Arch, FSA; and Janet Waddington of the Royal Ontario Museum for their painstaking and encouraging reviews and suggestions. This is publication No. N. S.-18 of the Texas Memorial Museum.

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# INSTITUTION-WIDE POLICY FOR SAMPLING

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*Abstract.*—Numerous disciplines have recognized the need for policies and procedures to handle requests for destructive sampling of collection specimens. Recognizing that specimens were collected in order to be used for research, the intention of such policies is primarily to minimize the impact of invasive procedures. An analysis of existing literature, policy statements, and workshop discussions involving representatives of various disciplines revealed common concerns among the disciplines. These concerns are addressed with five primary aspects of an institutional policy for destructive sampling: intent of the policy, relevance to collections and institution, establishment of authority and responsibility, evaluation of requests, and establishment of operational policies.

Specimens in natural science collections are collected or obtained with the express purpose of being used for research. In many instances, specimens used for research purposes are left in the physical state in which they were initially prepared. However, it is not always possible to leave the specimen intact and still gain sufficient information to answer the questions posed. Therefore, museum specimens have to be sampled routinely.

Sampling of collection specimens takes numerous forms in the different natural science disciplines (Table 1). Objects from archeological collections are sampled for dating, invertebrate specimens are dissected to reveal taxonomically important characteristics, a portion of frozen tissue is consumed for electrophoretic analysis, and half of a geological core sample is removed for content analysis. The result of the sampling process varies. In some instances, the bulk of the specimen may remain intact with only a minute sample removed. In others, there may be a complete loss of the specimen and only the data remain. When a sample is removed from a specimen, the sample may be destroyed completely, or it may be altered in form, resulting, for example, in a slide preparation or a cleared and stained sample. However, it must be recognized that sampling, by its very nature, results in the partial or complete destruction or alteration of the original specimen, sometimes making further analysis of the specimen difficult or impossible. Logically, one would assume that when sampling processes begin to impact negatively on the long-term research value of specimens, individuals responsible for the care of the collections would begin to question the extent to which sampling should be permitted. In fact, that has happened.

During the last few years, colleagues at collections representing a number of disciplines have independently developed policies and procedures for responding to requests for invasive sampling of specimens. These policies have been developed primarily on the basis of personal experience and discussion among a limited number of colleagues. Literature dealing with policy concerns has focused primarily on the needs of frozen tissue collections (e.g., Richardson, 1982; Dessauer *et al.*, 1988; Cato and Schmidly, 1991) and archeology collections (Bohnert and Surovik-Bohnert, 1991). Only more recently have institutions begun to develop single institution-wide policies to address the issue.

From an institution's perspective, it is necessary to look at the common denominators among the discipline-based policies and accepted procedures. These

Table 1. Examples of destructive/invasive sampling.

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Removal of teeth from skulls for sectioning
Removal of insect genitalia from specimens
Removal of skulls from fluid-preserved specimens
Gross anatomy dissections—mollusks
Clipping feathers for heavy metal studies
Histological preparations from fluid-preserved specimens
Pollen preparations
Rehydrating botanical specimens to retrieve insects
Chemical or biochemical analysis of specimens
Leaf, stem, entire plant
Mollusks
Amino acid testing
Frozen tissue samples
Analysis of geological cores
Trace element analysis—artifacts
Dating of archeological specimens
Removal of ectoparasites from study skins
Measuring thickness of egg shells
Preparation of samples for SEM study
Stomach content analysis in vertebrates

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common denominators must be considered in view of both an institution's research program as well as written policies for use and preservation of specimens. Once the common elements among the disciplines are identified and clarified relative to the institution's needs, a policy for destructive sampling can be established as can a mechanism for handling individual requests equitably.

The purpose of this paper is to report on the author's efforts to analyze existing sources of information to clarify disciplinary and institutional concerns relative to destructive sampling and to propose a model for addressing those issues. Methods included a literature search, a review of other existing policies, discussion among collection staff at the Virginia Museum of Natural History (VMNH), and discussion by participants at a workshop focusing on this particular topic. The resulting model will be useful as a prototype for other institutional efforts and as a focus for discussion among disciplinary and museum professional societies.

#### LITERATURE AND EXISTING POLICIES

Very little literature exists on the subject of destructive sampling. Problems resulting from sampling are perpetually discussed in professional circles, but specifics have not appeared in print. Two disciplines in which destructive sampling of museum specimens has become routine are molecular biology and archeology. The initial concerns about the use of frozen samples for molecular analysis resulted primarily in statements that encouraged more routine retention of the samples for use by others and the importance of treating the material as a collection, in the traditional museum sense (Richardson, 1982; Dessauer *et al.*, 1988). The sensitive and volatile nature of the material was immediately recognized, however, and the need for conservation emphasized. A workshop sponsored by the Association of Systematics Collections in 1983 focused on the importance of this type of material, why and how it should be treated as a formal collection, and some of the curatorial problems associated with such materials. Baker and Hafner (1984)

discussed procedural difficulties for these types of samples, and briefly touched on acquisition and deacquisition policies. With regard to the latter, they stated that samples should be sent out on a carefully selected basis with the criteria to include the rarity of the specimen (and/or size of the sample) and the research direction of the potential recipient. Dessauer *et al.* (1988) suggested user policies for a proposed national, networked, synoptical frozen tissue collection. They proposed that samples be made to qualified individuals, "based on the individual's reputation as a capable and productive scientist"; that conservation of material was critical because samples are consumed entirely during experimentation; and that "any material remaining from the sample must be returned to the network collection that provided it, unless specified otherwise by the curator, in writing." They also recommended the existence of an appeals process should a researcher be denied a request to obtain samples. Dessauer *et al.* (1990) have synthesized information from a number of papers concerning the practical aspects of collecting tissues, and have reiterated the need to treat these materials as a formal institutional collection, not a personal collection. Cato and Schmidly (1991) stated that policies for the use of ancillary preparations should address (1) the concern of providing equitable access to the samples, and (2) the conflict between consumption of samples for current research and conservation of samples for future reference. The policy developed for the Texas Cooperative Wildlife Collection at Texas A&M University included the formation of an advisory committee to monitor the use and maintenance of the materials. The committee would review requests to use samples based on information provided by the researcher, e.g., species requested, type and quantity of material needed, a short description of the proposed use of the material, and the nature of the borrower's research. As techniques for molecular analysis have become more sophisticated, however, molecular studies can now use samples from traditionally prepared vertebrate study skins to answer systematics questions. Therefore, policies established just a few years ago for dealing with sampling of frozen tissues may not be adequate today to deal with the latter situation.

Based on a review of policies of four institutions with major archeological collections (Museum of Indian Arts and Culture/Laboratory of Anthropology, Museum of New Mexico, Santa Fe, NM; National Museum of Natural History, Washington, DC; Peabody Museum of Archaeology and Ethnology, Harvard University, Cambridge, MA; and The University Museum, University of Pennsylvania, Philadelphia, PA) and their own collection management experience, Bohnert and Surovik-Bohnert (1991) summarized issues that should be addressed within the scope of policies on destructive analysis of archeological material:

1. What are the scheduling requirements for collection access?
2. Who will review submitted proposals?
3. The importance of maintaining and respecting the integrity of each object.
4. Who will ultimately determine where and how samples may be removed from an object?
5. Who will perform restoration treatment on an object and who will pay for it?
6. When is retesting of an object permitted?

7. What are the reporting requirements, including object documentation and research data?
8. What happens to samples or portions of samples remaining after the testing?
9. Who will be held financially responsible for any damage to the object beyond the approved test area?
10. Where will testing be done?
11. What are the recommended standard handling and conservation procedures?
12. If objects leave the premises, what are the prescribed loan procedures that must be followed?
13. Is permission necessary to test objects in custody of the institution but owned by a third party?

The authors also present recommendations for the minimum information needed from the researcher requesting objects, including details concerning the research goals and techniques that would be used for destructive analysis. As with recommendations for sampling frozen tissue material, review of the request relies heavily on whether the researcher is qualified. In addition, however, there is an increased emphasis on preservation of the original object and whether it can be tested without impacting negatively on future use. Use of a committee is recommended for the review process (Bohnert and Surovik-Bohnert, 1991).

In addition to referring to available literature, policies from nine collections/institutions were reviewed by the author (Table 2). Several other individuals contacted indicated that their institutions did not have a formal written policy and that each request was considered individually. The policies vary in scope and complexity; most, however, are departmental policies and strongly reflect the individual needs of the discipline represented.

#### DISCUSSIONS AND WORKSHOPS

Acknowledging the reality that working standards might exist among the disciplines even though they were not formally approved standards, it was necessary to generate discussion on the various issues with a broad representation of disciplines. The first step was an in-house discussion involving VMNH curators and the VMNH Collections Manager. The curators represented the disciplines of geology, vertebrate paleontology, invertebrate paleontology, Recent invertebrates, mammalogy, herpetology, and archeology. Both the mammalogist and herpetologist maintained frozen samples for molecular studies. Collection conservation and management was represented by the collections manager. Each curator at VMNH was provided a packet of information containing example policies from other institutions and a list of issues and questions that had been compiled on the basis of the review of literature and existing policies. Comments, questions, examples, and exceptions were numerous during the discussion which focused on relating the individual disciplinary needs to the needs of the institution.

An additional effort was made to obtain a broad disciplinary perspective, to actively look for problem areas and to search for possible alternatives, through discussions held at a workshop on destructive sampling during the 1991 annual meeting for the Society for the Preservation of Natural History Collections (SPNHC). The 30 participants in this workshop represented the following types

Table 2. Destructive/invasive sampling policies reviewed.

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Anthropology Department, Field Museum of Natural History, 1990
Anthropology Department, National Museum of Natural History, 1988
Vertebrate Zoology, Bernice P. Bishop Museum, draft, 1991
Core and Sample Repository, Geological Survey of Canada, 1990
Denver Museum of Natural History, draft, 1991
Mammal Division, National Museum of Natural History, U.S. Fish and Wildlife Service and Smithsonian Institution, draft, 1990
Ocean Drilling Program, Texas A&M University, 1989
Texas Cooperative Wildlife Collections, Texas A&M University, 1987
The University Museum of Anthropology and Archaeology, University of Pennsylvania, Philadelphia, 1987

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of collections: archeology, botany, invertebrate paleontology, vertebrate paleontology, general geology (including minerals), core repository, marine geological samples, invertebrate zoology, malacology, mammalogy, ornithology, and paly-nology. As a point of departure, participants were presented with information similar to that provided to the VMNH curators in addition to some of the comments and points raised during that discussion. Each participant was asked to describe his/her own situation and to raise particular issues of concern. These were discussed by the group both in general terms and in relation to the needs of specific institutions.

One topic raised during the workshop that had not been previously discussed in the literature or in other workshops centered on terminology. Was a process considered "consumptive," "destructive," or "invasive"? Was it regarded as "sampling," "testing," or "analysis"? How critical was the precise terminology? Can a single term be universally applied?

Table 3 summarizes definitions from the American Heritage Dictionary (1985) for these various terms. Possible combinations of the terms are:

Destructive sampling	Destructive testing	Destructive analysis
Consumptive sampling	Consumptive testing	Consumptive analysis
Invasive sampling	Invasive testing	Invasive analysis

Each of these phrases has a slightly different nuance. Some workshop participants appeared to have a preference for a specific phrase, and the combination of terms used can effectively influence how researchers and collection care staff might react to requests. For example, it was pointed out that some dissections are invasive, resulting in an alteration of the preparation form, but the result is not a complete destruction of the sample. Thus some individuals carrying out dissections might ignore a policy titled "destructive sampling," assuming it did not apply to their situations when in fact it does. At the same time, the term "destructive" was considered more effective at drawing attention to concerns by focusing on the need to deal with the problem of sampling effectively. A consensus was not reached concerning the most effective or appropriate terminology for sampling policies.

Another major area of concern voiced by participants of the workshop involved the "aftermath" of sampling; the primary concern and fear was that the information gained from the sampling process might not become available to other

Table 3. Definition of terms (American Heritage Dictionary, 1985).

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Consumptive—	Tending to consume [= to expend, use up, waste, squander, destroy totally].
Destructive—	Causing or wreaking destruction [= act of ruining completely, tearing down or breaking up, demolishing, rendering useless or ineffective].
Invasive—	Tending to invade [= to enter and spread harm through, to enter by force].
Analysis—	The separation of a substance into its constituent elements to determine either their nature or their proportions.
Sampling—	The process of selecting a portion, piece, or segment that is representative of a whole.
Testing—	A means of examination or trial by which a substance may be detected or its properties ascertained.

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researchers. This concern focused on what should happen to any remaining portions of the original specimen as well as the raw data that resulted from the sampling or analysis. It was generally agreed that both should be returned to the institution that provided the sample to become part of the specimen's permanent record. It was recognized that researchers need a period of confidentiality to complete publication activities, but participants considered it the researcher's obligation to make the data available as part of the specimen's record. This process of returning data to the institution is important not only to provide future researchers access to data pertaining to the specimen, but to reduce the need to resample the same specimen or object using the same techniques. The idea of returning data to the institution has been advocated elsewhere (Richardson, 1982; Dessauer *et al.*, 1988; Bohnert and Surovik-Bohnert, 1991). Participants agreed, however, that such an idea is not always popular among many researchers using the collections and that enforcement of such a policy is difficult. To encourage fulfillment of this policy, some collections require researchers to sign a statement agreeing to return copies of the data as well as unused sample material with the understanding that if they do not, they may lose the privilege of sampling specimens in the future (e.g., Core and Sample Repository, Geological Survey of Canada).

In addition to stressing the importance of returning raw data to the collection, participants emphasized the need to document thoroughly the extent and methods of sampling as well as the analytical procedures used. Such documentation permits the tracking of the cumulative effects of sampling. It also makes it possible to alert future users of the same specimen, because the effects of some techniques may make the specimen useless for other techniques.

Workshop participants strongly supported the need to insure a balance of perspectives during the evaluation and recommendation process for granting destructive sampling requests. Specifically mentioned was the need to balance the perspective of the use with that of preservation. The intention was not to prevent use but if at all possible to minimize the damage to the specimen and its potential for *future* use. Input by an appropriate collection manager was deemed important to be sure that an individual specimen was evaluated relative to its importance to the entire collection as an institutional resource. Was this the only specimen of a particular species owned by the institution? Were there any restrictions on the specimen due to its scientific or historic value? Had this specimen already been sampled for the same analytical process by another researcher? A number of alternatives for providing a review process with multiple perspectives were

discussed; these varied with respect to the individual's institutional structure. The primary emphasis, however, was on the involvement of one or more researchers with expertise in the discipline of the request and one or more collection care professionals with expertise in management and conservation principles.

It was not the intention of the workshop to obtain a consensus on all issues, but rather serve as a forum for discussion and problem solving. In spite of this, the majority of participants seemed to agree on many of the concerns and approaches for dealing with requests.

#### ISSUES TO BE ADDRESSED WITHIN INSTITUTIONAL POLICIES

The development of an institutional policy requires a consideration of profession-wide standards in light of the mission and day-to-day operational reality of the institution. The information that follows is a synthesis of recommendations and professional standards observed by a variety of scientific disciplines and the museum profession relating to policies for destructive or invasive sampling. Culled from the literature, existing policies for destructive sampling, professional standards for developing collections policies (Malaro, 1985; Porter, 1985), the discussion by VMNH curators, and the SPNHC workshop, this synthesis is presented in the perspective of an institutional setting in which one general policy provides the umbrella guidelines for a variety of disciplines. The issues that should be addressed by an institutional policy can be grouped into five major aspects: intent of the policy, relevance to collections and institution, establishment of authority and responsibility, evaluation of requests, and establishment of operational policies. The development of the policy should involve direct input by individuals representing the conflicting perspectives of use and preservation. The most effective policy is likely to be one that results from a consensus of opinion by researchers, collection managers, and conservators.

*Intent.*—The institution needs to clarify the intent of the policy so that there are no misconceptions about the goals of the policy. It should recognize that specimens were collected to be used. However, the policy should also acknowledge that unnecessary and excessive damage to specimens can occur as the result of sampling processes, and that the institution has a responsibility to preserve specimens held in its collections. The purpose of such a policy, regardless of its title, should be to maximize the research potential of specimens by minimizing unnecessary damage that might result from sampling and testing.

*Relevance to collection and institution.*—A policy for destructive sampling should be developed within the framework of an institution's collections policy, with particular reference to its policy for access to specimens. The disciplines and collections within the institution that might be affected need to be identified. If rigid restrictions have been developed for certain groups of specimens, such as holotypes or endangered species, these should be clearly described.

Terms should be clearly defined, recognizing the nuances of different phrasing for terms such as consumptive, destructive, and invasive. Examples might be provided to clarify the issue and improve awareness of the problem. In addition, commonly used terms, such as loan, transfer, exchange, etc., should also be clarified so that transactions involving samples are appropriately described. For example, a loan implies the return of material; if that is not going to be the case,

the transaction should not be called a loan but instead should be referred to as a transfer or gift.

*Establishment of authority and responsibility.*—Clearly identify the lines of authority for recommending and approving a course of action relative to a request for destructive sampling. In doing so, insure that there is a balance of input and authority for the perspectives of use and preservation during the evaluation of individual requests. The latter generally requires the involvement of at least two or three professionals with demonstrated expertise in (1) the pertinent research discipline, and (2) the field of managing and preserving natural science specimens. If necessary, use consultants to achieve a balance of views from these perspectives. Clarify lines of responsibility for processing and documenting requests and use.

*Evaluation of requests.*—An evaluation process for requests to use specimens for destructive sampling should comply with the institution's general policy for access to specimens, though in all likelihood, it will be more restrictive. The criteria that are used for evaluating requests should be clearly stated. The following are recommended by the literature and workshop discussions:

1. Requests shall be evaluated on the basis of written information provided by the researcher.
2. The intended use should have merit.
3. The researcher must demonstrate competence with proposed methods.
4. The researcher must have sufficient resources to carry out the method.
5. The researcher should demonstrate that the technique proposed is the least intrusive analytical means for obtaining intended results.
6. The technique is likely to yield the intended results.
7. The data are not available from other sources.
8. The potential for compromising future utility of the specimen for other investigations is minimized.
9. The researcher intends to disseminate results of the testing within a reasonable amount of time.
10. The researcher is willing to abide by the institution's operational standards for processing and documentation.

The method for completing the evaluation should be clearly described so that an individual submitting a request is fully informed of the process involved, how decisions are reached, and what is expected of him/her. There should be an appeals process available if requests are denied.

*Establish operational standards.*—Standards for completing the sampling process and fulfilling documentation requirements should be clearly established within the scope of the policy. Standards should include the following:

1. Usable samples and unused portions of specimens shall be returned to the institution unless otherwise agreed upon in writing.
2. The methods and extent of sampling shall be thoroughly documented for each specimen.
3. Resulting analytical data (graphs, computer printouts, etc.) shall be returned to the institution to become part of the specimen's permanent record. The researcher shall be granted a period of confidentiality (for example, two years)

during which the data would not be made available to others, to permit publication of the results.

4. The researcher requesting the sampling shall be responsible for all costs associated with the sampling unless otherwise agreed upon in writing.
5. The institution shall receive credit in publications for providing samples to the researcher.

There may be additional standards established by the institution depending on the capabilities of the staff, the equipment available and the sensitivity of the specimens. For example, some archeological collections require that samples be removed by their own staff. Individual disciplines may develop standards that are more restrictive than those proposed by the institution as a whole, making it advisable to develop written policies that amend the institutional policies for special circumstances. Disciplinary policies, however, should not be less restrictive than those of the institution as a whole.

#### PROTOTYPE

Based on the information developed during this project, the author worked with the VMNH Collections Committee and curatorial staff to develop an institutional policy for sampling. The result of this process is included here as an example (Appendix) and is by no means presented as the only solution. The intention is to use it, test it, and revise it if it is inadequate. This policy is also provided as a point for discussion by staff at other institutions developing their own policies.

#### SUMMARY

A policy on destructive sampling enables an institution to implement its conflicting responsibilities of preservation and use of specimens, even when the "use" process may result in the destruction of specimens or parts thereof. Such a policy should incorporate and balance the perspectives of use for research purposes, management of the collection as an institutional resource, and conservation of the specimen and collection.

#### ACKNOWLEDGMENTS

Thanks are extended to the numerous researchers, collection managers and conservators who provided verbal and written comments on this subject, among them: J. Beard, D. Bell, J. deMouthe, N. Fraser, K. Garrett, C. Hawks, R. Hoffman, E. Hughes, J. Klein, N. Moncrief, J. Murphy, S. Olsen, C. Patterson, A. Pinzl, C. Rose, J. E. Simmons, E. G. Snow, J. C. Solomon, E. Sullivan, A. Suzumoto, L. Ward, S. Williams. Thanks, too, to the members of the SPNHC workshops and two reviewers for ideas, comments and discussion.

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#### APPENDIX

Excerpt from "Virginia Museum of Natural History Collections Policy—15 January 1992"

**D. Destructive or consumptive sampling**—To fully realize the research potential of the collections, it may be necessary to remove samples or alter permanently the appearance or substance of some specimens. It must be recognized, however, that such sampling and alterations potentially decrease the future scientific value of the individual specimen. To balance the legitimate needs of the scientific and scholarly community with the long-term preservation of the collections for future needs, each request for sampling will be considered according to the following parameters.

1. A written request to sample a specimen or to perform any type of destructive analysis should be sent to the appropriate curator and include the following information:
  - a. a description of the project clarifying the purpose of the research;
  - b. a description of the techniques to be used and an indication of why these are appropriate to the question being asked;
  - c. a description of the specimen(s) needed;
  - d. a justification for the use of VMNH specimens; and
  - e. the name, address, and telephone number of the individual(s) responsible for the project and for performing the techniques.
2. Requests shall be evaluated and approved by the appropriate Curator and the Collections Manager. If either of these individuals so requests, additional evaluations of the researcher's request may be sought. If the specimens requested by a researcher are to be totally consumed, then the researcher's request shall be treated as a request to deaccession specimens (section VII of these policies). All decisions shall be documented in writing and the researcher notified accordingly. If a request is refused, a researcher may submit an appeal to the Collections Committee. The request shall be reviewed by an outside review panel consisting of at least three professionals in appropriate fields who are not directly affiliated with the Museum. At least one of these three must be a collection care specialist or conservator. The researcher, Curator, and Collections Manager shall each choose one individual to serve on the review panel. The Collections Committee shall determine suitable action on the basis of the results of the panel's recommendation.
3. Criteria and considerations for approval include:
  - a. The research project has merit;
  - b. The researcher(s) demonstrate competence with proposed methods and have sufficient institutional resources to carry out stated research;
  - c. The technique to be applied should yield the intended results and are the least intrusive analytical means of obtaining those results;
  - d. The amount of sample and number of specimens requested is necessary to obtain accurate results;



COMMONWEALTH OF VIRGINIA

## Virginia Museum of Natural History

Dear Colleague;

Requests to use specimens for the purpose of sampling or analysis that result in the permanent alteration of museum specimens require serious evaluation in order to balance the legitimate needs of current scientific study with the long-term preservation of the collections for future needs. Following discussions with colleagues in a variety of natural science disciplines, and a review of policies recently developed at other institutions, we have developed a set of policies and procedures to guide the evaluation process (see attached).

To assist us in evaluating destructive sampling and analysis requests, we ask your cooperation in providing:

- 1) a brief description of your project;
- 2) a description of the techniques to be used and why these are appropriate;
- 3) justification for the use of VMNH specimens (including a listing of those requested for this project); and
- 4) the names of individual(s) responsible for the project and for carrying out the procedures involved.

Publications or other documentation that demonstrates the efficacy of the technique and the investigator's proficiency with it would be appreciated. VMNH is in no way obligated to make loans for funded projects without prior knowledge or approval of the intent to sample VMNH specimens.

Attached is Destructive Analysis Agreement that must be signed before specimens may be sent to you. As a reciprocal responsibility of loan approval, we ask that usable samples be returned for storage at VMNH, where they may be made available to other researchers. We also request that copies of resulting analytical data be returned as well. These data will remain confidential for a period of two years to permit you to complete publications, then will become part of the specimen's permanent record. We feel this is a critical component to preventing unnecessary, repeated sampling of individual specimens.

We appreciate your cooperation and willingness to abide by our policies and procedures.

VMNH Research & Collections Division  
16 September 1991

1001 Douglas Avenue, Martinsville, Virginia 24112  
(703) 666-8600 FAX: (703) 632-6487 TDD: (703) 666-8638

Figure 1. Information letter describing VMNH policy for destructive sampling.

**VIRGINIA MUSEUM OF NATURAL HISTORY  
DESTRUCTIVE ANALYSIS AGREEMENT**

The sample of \_\_\_\_\_ from the collections of the Virginia Museum of Natural History is provided for destructive analysis with the following conditions:

1. Usable samples and unused portions of specimens will be returned to VMNH so they can be retained for future use.
2. All resulting analytical data, including raw data in the form of graphs, computer printouts, etc. pertaining to the listed specimens will be provided to the Collections Manager to become part of the specimen's permanent record. Such data, except published reports, shall remain confidential for a period of two years following the close of the original loan due date. During this period, the name of the researcher may be given to others proposing to use VMNH specimens for similar research projects. In this case, the second researcher may be requested to obtain analytical results from the first researcher before the additional sampling requests may be approved.
3. Methods and the extent of sampling is thoroughly documented for each specimen according to departmental guidelines.
4. All costs of the analysis, including packing and shipping from and back to the Museum, are the responsibility of the researcher, unless otherwise indicated in writing.
5. Two copies of any publication including information resulting from the analysis on the specimens will be provided to the Collections Manager.

RESEARCHER

VIRGINIA MUSEUM OF NATURAL HISTORY

\_\_\_\_\_  
Researcher's signature

\_\_\_\_\_  
Curator (signature and title)

\_\_\_\_\_  
Address

\_\_\_\_\_  
Collection Manager (signature)

\_\_\_\_\_  
Date

\_\_\_\_\_  
Date

Figure 2. VMNH Destructive Analysis Agreement.

- c. The data required are not available from other sources;
- f. The potential for compromising the future utility of specimens for other investigations is minimized; and
- g. The researcher(s) indicate a willingness to abide by VMNH operational guidelines for sampling and/or destructive analysis.
4. General operational guidelines for sampling and destructive analysis:
  - a. Holotype specimens shall not be tested in any way that lessens the specimen's value as a holotype. Requests to test holotype specimens automatically require an evaluation of an outside review panel.

- b. Usable samples and unused portions of specimens will be returned to VMNH so they can be retained for future use.
  - c. All resulting analytical data, including raw data in the form of graphs, computer printouts, etc. pertaining to the listed specimens will be provided to the Collections Manager to become part of the specimen's permanent record. Such data, except published reports, shall remain confidential for a period of two years following the close of the original loan due date. During this period, the name of the researcher may be given to others proposing to use VMNH specimens for similar research projects. In this case, the second researcher may be requested to obtain analytical results from the first researcher before the additional sampling requests may be approved.
  - d. Methods and the extent of sampling is thoroughly documented for each specimen according to departmental guidelines.
  - e. A Destructive Testing Agreement (Figs. 1, 2) shall be signed by the researcher(s) before specimens are sent.
  - f. All costs of the analysis, including packing and shipping from and back to the Museum, are the responsibility of the researcher, unless otherwise indicated in writing.
  - g. Two copies of any publication including information resulting from the analysis on the specimens will be provided to the Collections Manager.
  - h. Supplemental guidelines shall be established by Department Heads and the Collections Manager in accordance with these policies to detail requirements that are specific to individual disciplines.
5. Failure to follow VMNH guidelines may jeopardize future borrowing privileges.

# EFFECT OF RELATIVE HUMIDITY ON CRANIAL DIMENSIONS OF MAMMALS

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*Abstract.*—Mammalian systematics relies heavily on morphometric analyses of cranial dimensions with special care given to the critical evaluation of natural variation attributed to individual, age, sex, and geography. Because bone is anisotropic, responding to moisture changes in different amounts and directions, the effect of relative humidity on cranial dimensions was addressed. A series of skulls of the same species was selected to minimize recognized forms of variation. These skulls were measured at 25% and 85% relative humidity, which simulate conditions known to occur in collections. Results showed that differences do exist, but the magnitude was not sufficient to question most morphometric studies. However, it is recognized that this statistical evaluation cannot necessarily be equated with material responses to environmental conditions.

During the past few decades, mammalian systematics has relied heavily on cranial dimensions for assessing variation among and between populations, and ultimately for species identification (DeBlase and Martin, 1981; Hall, 1981; Jones and Manning, 1992; Swanepoel and Genoways, 1979). For all practical purposes, dimensional differences of mammalian skulls have been useful in documenting various forms of natural variation (individual, sexual, age, temporal, and geographic). To accurately evaluate these forms of variation, morphometric investigations usually involve precautionary measures to avoid adding additional variation through procedure. For this reason, measurements are often taken by only one individual using the same measuring device, and ideally, all measurements are taken at the same time.

To date, the collection environment has not been considered as an influence when considering causes of variation in cranial dimensions. Bone is hygroscopic in nature and anisotropic in behavior, that is the amount of response to change in ambient moisture varies with direction. The response of bone and teeth to various climatic conditions is well-documented in the literature (Currey, 1984; Lafontaine and Wood, 1982; MacGregor, 1985; Von Endt, 1984; Williams, 1991).

In view of the importance of cranial dimensions to the understanding of mammalian systematics, as well as the known behavior of bone to varying climatic conditions, there is a need to evaluate the influence of ambient moisture levels on bone dimensions. The study described herein compared measurements of a series of ground squirrel skulls at 25% and 85% relative humidity (RH).

## METHODS AND MATERIALS

An independent study of seasonal variation in thirteen-lined ground squirrels (*Spermophilus tridecemlineatus arenicola*) created a unique opportunity to select a series of similar skulls from a sample of over one hundred specimens that were collected and processed under relatively uniform conditions. To statistically examine dimensional changes in mammalian skulls responding to different RH levels, efforts were made to find twenty specimens that would be minimally influenced by natural variation (geographical, age, and individual) and treatment variation (osteological processing, pest control, and time maintained in storage). Criteria for skull selection included similar-sized, adult specimens (greatest length of skull measurement between 40.0 and 41.0 mm) and absence of prior chemical treatment.

Specimens were processed within six months of the study, using procedures described by Williams (1992). Nineteen specimens were collected from Lubbock County, TX, and one was collected from Lynn County, TX. The initial study of seasonal variation involving over one hundred specimens indicated that there was no significant difference between sexes (D. Hall, pers. comm.), thus the use of fifteen male and five female specimens for the current study was considered acceptable.

A thermohygrometer was kept with the skulls to monitor internal climatic conditions. Total acclimation was verified by monitoring weight change of an individual specimen. It was assumed that acclimation had been achieved when the weight stabilized. For this study, skulls were maintained in the controlled environments longer than necessary to insure total acclimation (preliminary testing indicated four days was adequate for acclimation and that most of the change occurred during the first day).

Skulls were subjected to 85% RH and 25% RH, levels known to occur in collection areas of Recent mammals (Williams and Hawks, 1992). A sealed glass enclosure was used to contain the desired moisture levels. The 85% RH was established with a saturated solution of potassium chloride (Green-span, 1977). The skulls were maintained in this environment for ten days.

At the end of the acclimation period, each skull was weighed and measured. Because of concerns for specimens responding too quickly to ambient differences during examination periods, standard procedure involved the immediate weighing and measuring of specimens as each was removed from the controlled environment. All weights and measurements were made by the same person. Weights were taken with a Mettler analytical balance accurate to 0.001 g. Six standard cranial measurements (three representing length and three representing width) were taken with digital calipers accurate to 0.01 mm. Cranial measurements recorded are illustrated in Figure 1 and described below:

- A) *greatest length of skull*—distance between the posteriormost part of the skull above the foramen magnum and the anteriormost part of the nasal bones.
- B) *basilar length*—distance between the anteriormost inferior border of the foramen magnum to the posteriormost margin of the alveoli of the upper incisors.
- C) *palatal length*—distance from the anteriormost point on the posterior border of the palate to the posteriormost margin of the alveoli of the upper incisors.
- D) *zygomatic breadth*—greatest distance across zygomatic arches perpendicular to the long axis of the skull.
- E) *mastoid breadth*—greatest distance across mastoid processes perpendicular to the long axis of the skull.
- F) *supraorbital constriction*—shortest distance across the top of the skull posterior to the base of the supraorbital processes.

A climate having 25% RH was created with a 13.4 molal lithium chloride solution. The skulls were maintained in this environment for thirteen days, and weighed and measured as previously described.

Standard statistics (mean, range, standard error, coefficient of variation) were calculated for the measurements recorded for each climatic condition. An analysis of variance compared differences between measurements that would be attributed to RH. The results of these analyses were used to assess the influence of the ambient moisture levels on dimensional changes of mammalian skulls.

## RESULTS

Data obtained in this study clearly indicate that dimensional changes occur when mammalian skulls are subjected to different RH levels. The dimensional and weight changes observed are summarized in Table 1. Although these differences were not considered significant ( $P \geq 0.05$ ), it was possible to detect a reduction in most measurements when the RH was dropped from 85% to 25%.

The average percent of dimensional change for the characters examined ranged from 0.25% to 0.32%. Those measurements taken parallel to the long axis of the skull had higher average percentages (0.29 to 0.32) of change than those measurements taken perpendicular to the axis (0.25 to 0.26), indicating possible minute changes in overall shape. For some individual measurements, the percentages of change were as low as 0.00% (no difference in measurements) or as high as

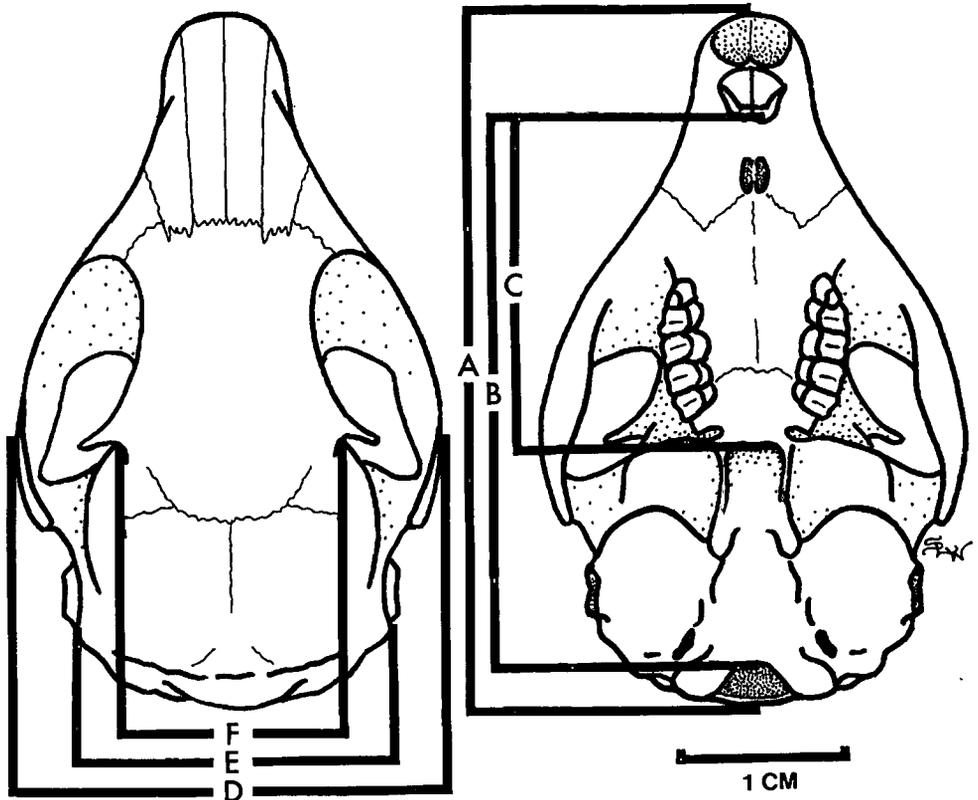


Figure 1. Illustration of a ground squirrel cranium, showing measurements (described in text) recorded for this project.

0.65%. However, these extremes were usually associated with measurements that tended to have higher coefficients of variation. The coefficients of variation obtained for all dimensions were very low and well within the limits used for mammalian morphometric studies. However, the higher values obtained for palatal length, mastoid breadth, and supraorbital constriction suggest other factors may be influencing results, such as natural variation was greater for some characters that were not used for selection purposes, specimens might be responding to RH differently for some characters, or there was some difficulty in precisely duplicating measurements for certain characters or specimens.

#### DISCUSSION

This study documents the effects of RH on cranial dimensions of mammal specimens. There is a direct correlation between high moisture levels and increased dimensions. Although dimensional differences for individual characters were not significant ( $P \geq 0.05$ ), there is a need to discuss the relevance of these dimensional changes with respect to morphometric research and specimen stability.

It is important to remember that the mammalian skull is a three-dimensional object consisting of bone and dental components that vary in size and density.

Table 1. Summary of six dimensions (mm) and weight (g) taken from 20 crania of *Spermophilus tridecemlineatus* at 85% RH and 25% RH. Standard statistics provided include mean, range, standard error (SE), and coefficient of variation (CV).

Character	85% RH		25% RH		% change	
	Mean (Min–Max) ± SE, CV		Mean (Min–Max) ± SE, CV		Mean (Min–Max)	
Greatest length of skull	40.5 (40.1–40.9) ± 0.06, 0.64		40.3 (40.0–40.7) ± 0.06, 0.65		0.32 (0.20–0.40)	
Basilar length	35.1 (34.7–35.5) ± 0.05, 0.66		35.0 (34.6–35.5) ± 0.05, 0.68		0.29 (0.20–0.40)	
Palatal length	22.1 (20.1–22.8) ± 0.13, 2.70		22.0 (20.0–22.7) ± 0.13, 2.71		0.29 (0.05–0.60)	
Zygomatic breadth	24.5 (24.0–24.9) ± 0.06, 1.11		24.4 (24.0–24.8) ± 0.06, 1.10		0.25 (0.12–0.41)	
Mastoid breadth	18.7 (18.0–19.6) ± 0.09, 2.09		18.7 (18.0–19.5) ± 0.09, 2.04		0.25 (0.00–0.56)	
Supraorbital constriction	11.8 (10.9–12.3) ± 0.10, 3.87		11.7 (10.9–12.3) ± 0.10, 3.84		0.26 (0.00–0.65)	
Weight	1.39 (1.25–1.49) ± 0.01, 5.03		1.35 (1.21–1.44) ± 0.01, 5.18		2.98 (2.58–3.50)	

Bone continuously attempts to reach equilibrium with local climatic conditions, but these changes are not always proportional because bone is anisotropic. The current study has demonstrated this through documentation of dimensional changes as well as different percentages of change between length and width dimensions.

Morphometric variation of mammalian skulls attributed to climatic conditions within collection areas has never been documented. However, evidence of such specimen responses, in the form of cracking, spalling, and deforming, has been reported (Williams, 1991; Williams and Hawks, 1992). The current study determined that the dimensional changes between 85% RH and 25% RH were detectable. Because there were no significant differences in these changes, any variation attributed to RH should not affect univariate analyses. However, further studies may be warranted to evaluate the effects of climatic change on some multivariate analyses. Because the anisotropic behavior of bone causes changes in shape, as indicated by average differences obtained between length and width measurements, the question arises that this might interfere with more sophisticated statistical analyses. In multivariate analyses, the first vector (X) is usually explained by variation in size and often accounts for over half of the observed variation (see Schlitter *et al.*, 1983; Williams and Genoways, 1978, 1980, 1981). The second vector (Y) is often associated with variation in shape. Because the influence of the second vector will often depend largely on how much variation is explained by the first vector, shape might be critical for comparisons of samples involving very close dimensions (see Choate and Williams, 1978; Williams and Genoways, 1977; Williams and Ramirez-Pulido, 1984). Although the chances of subtle shape differences affecting standard multivariate comparisons are remote, if there is a question of comparing very similar taxa, such as sibling species or disjunct populations, it may be desirable to avoid situations that subject specimens to different climatic conditions.

Williams and Hawks (1992) have documented collection RH levels as low as 19% and as high as 99%, as well as changes of more than 20% in a 12-hour period. If specimens in temperate geographical areas are not afforded some form of protection, such as collection climate control or closed-case storage, it would be possible to obtain different measurements of the same specimen at different times of the year. Similarly, specimens loaned between two climatically dissimilar institutions could result in different measurements for the same specimen. Even if the different institutions have similar climates, one should be aware of potential RH changes during transit (Hazeu and Hueck, 1966; Toishi, 1959).

The ramifications of dimensional change on the stability of osseous materials are not readily apparent. The lack of significant differences in statistical interpretation of dimensional changes should not necessarily be construed as being trivial, especially where material responses and stability are concerned. This is particularly relevant for rigid materials, such as bone. Lafontaine and Wood (1982) and Williams (1991) have demonstrated the importance of proper RH on the stability of ivory and teeth. Although not as well-documented as ivory and teeth, bone also may respond in a similar adverse manner to improper RH. The current study has shown quantitatively that non-dentary parts of the skull respond to ambient moisture levels. With regard to long-term stability, further studies involving other physical aspects of bone are needed to better understand material responses to improper RH.

## CONCLUSIONS

This study documented differences in cranial dimensions measured at 25% RH and 85% RH. Although it is very unlikely that climatic differences would ever influence morphometric research as it has been conducted in the past, there are questions about the effect of dimensional changes on rigid materials and how this might be reflected in the long-term stability of bone. As vertebrate collections continue to add new material, there is a growing need for further research to help define preferred parameters for bone preservation so that this material will be available for diversified research purposes in the future.

## ACKNOWLEDGMENTS

Sincere appreciation is extended to the late J. Knox Jones, Jr., Richard Manning, and Diane Hall for providing many of the specimens used in this study, and to Marion Mecklenburg (Smithsonian Institution) for useful comments and for reviewing the manuscript.

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# APPROACHES TO MOLD DESIGN AND CONSTRUCTION

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*Abstract.*—Many factors must be considered in the design and execution of high quality molds. The ethics of molding and casting and the rights of ownership with regards to preservation of the object, possession of the mold and distribution of any casts must be observed. In designing any mold the factors that must be considered include: the purpose of the casts and the number of casts required; choice of molding compound; material incompatibilities; molding stress on the object; consolidants; separators; shape of the original object; positioning of flanges, air vents and pour spout (possibly including a registered pour spout plug) in order to minimize air bubbles in casts and reduce demolding stress on the original object, the mold and subsequent casts. In preparing the object for molding, flanges and the pour spout are fabricated from a neutral flanging material, must be large, neat, and include keys (sufficient in size and number) and identification marks; flanges are perpendicular to the surface of the object. The use of fabric reinforcement allows production of a mold of complex design, but of a minimum of pieces, and adequate strength with an economy of molding compound. Removable vermiculite/latex filler plugs simplify mother mold construction.

Given the same object to mold and the same molding compound, no two people will make identical molds. The finished casts from these molds can range considerably in quality of reproduction. The main differences between molds show up in the effects of demolding\* on the original object, the ease in demolding both the original and the cast, and the amount of finishing (the removal and disguising of flash\* and air bubbles, etc.) required on the casts.

Design is as important a factor as experience in the manufacture of a good mold. The characters of a good mold are listed as follows:

1. The mold must be designed so as to minimize the demolding stress when the mold is removed from the original object. This will reduce the chance of damage to the mold, the original object, and subsequent casts. A corollary is that the casts are easy to demold and the useful lifetime of the mold is extended.
2. The mold will have good fidelity.
3. The presence of flash, seams and other molding artifacts\* on the casts should be either nonexistent or minimal and not readily noticeable.
4. Air bubbles in the casts should also be either non existent or minimal and not readily noticeable.
5. The casts should be as dimensionally accurate as the nature of molding and casting compounds allows and without distortion.

The end product of the process of molding is a mold that will produce precise replicas of the original object that require minimal finishing time, an important factor when many casts must be produced.

The following pages cover a diversity of topics on how to produce a better mold discussed with the intention to review some matters that are sometimes assumed

Note: Terms marked with an asterisk (\*) are defined in Appendix 1.

to be common knowledge, emphasize some up to date techniques/materials, and introduce a new technique. This paper is most useful to the novice if read together with any general review of standard molding and casting techniques, such as Schrimper (1973), Converse (1984), Feldmann *et al.* (1989), or Leiggi and May (in press). It assumes some prior experience in molding and casting.

A good quality cast is useful as a research tool, or as a reference specimen; good quality casts are also useful as teaching specimens, and in public displays. Permission must be obtained to mold an object on loan. The mold is considered the property of the owner of the original specimens, unless otherwise agreed. Control of the number of casts and their distribution is also determined by the owner of the original specimen. Consider the purpose for which this item is being replicated. What are the casts going to be used for? Will there be future demands for casts and will those casts be wanted by others for the same purpose? For instance, it is not necessary to mold an entire skull if all that is needed is a cast of the dentition. But, if a future need can be foreseen for casts of the entire skull for other features other than the dentition and there is sufficient time, then mold the entire skull. This will minimize the risk of damage to the original by reducing the number of molds taken.

#### DESIGNING THE MOLD

A good mold requires a careful examination of the object and careful planning of the mold design. Spend time turning the object over, looking at it from all angles. One has to look out for various features that will pose problems during the processes of demolding and casting. Deep holes (i.e., foramina, cracks, and gaps left by missing pieces), nasal cavities, the orbital areas, and undercuts\* are all features that can create problems during demolding. In this example, a mammalian skull is used.

Natural cavities can be packed carefully with cotton and surfaced over with flanging material. As a rule of thumb they should not be completely filled in up to the level surface but rather only to a depth proportional (e.g., one half) to the average diameter of the feature, or to a depth that looks good. This will reduce the problem of the mold snagging or getting stuck in these features yet preserve the appearance and some of the information that such features impart to the cast.

Artificial gaps left by missing pieces can be filled in completely and may have rudimentary detail sculpted on the surface in order to restore the appearance of the object to its original/intact state if desired. The filled-in areas should not be blended with the original surface, since in the future the reconstructed areas will need to be differentiated from the original surface areas.

The orbital (eye socket) regions and severe undercuts can sometimes be filled in, but this alters the appearance of the object and information from these features is lost. It is better to design the mold to accommodate these features. In the case of the orbital regions of a skull, the socket can be reproduced by both upper and lower halves of the mold. The contact between the two halves of the mold will be formed by a flange\* incorporating keys\*. The best location for the orbital flange is usually inside the zygomatic (cheekbone) area at the bottom, almost level with the palate.

## FLANGING EXAMPLE: SKULL

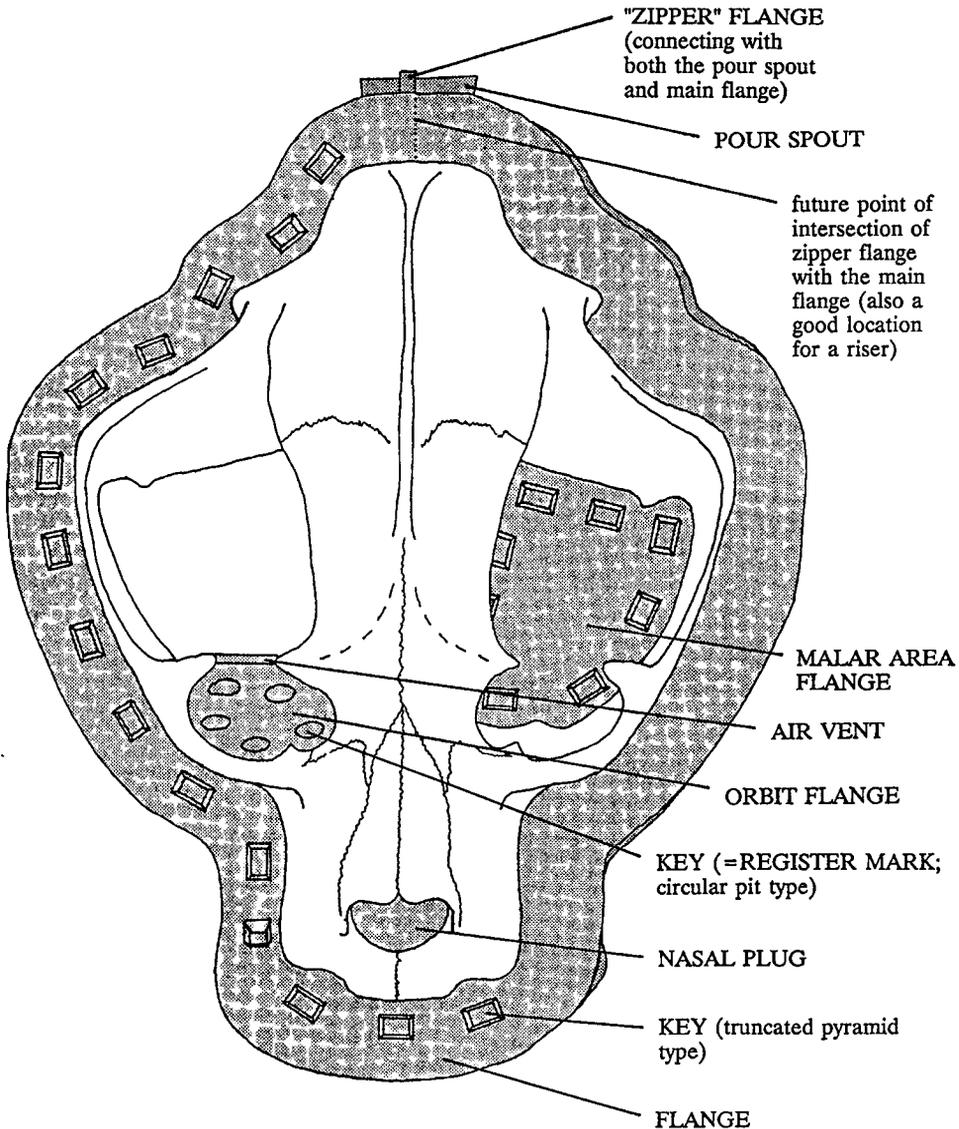


Figure 1. Dorsal view of a jaguar skull (not to scale), partially flanged with KLEAN KLAY in preparation for molding. Left orbit and right malar area not yet flanged for clarity. Keying of peripheral or main flange not yet finished.

In order to be able to demold the bones in the area of the orbit itself, the orbit should also be flanged, incorporating keys (Fig. 1). If there is no post-orbital bone the flange will end where the bone would have been. It is sometimes best in this case to create a riser\* (air vent\*) along the posterior edge of the orbit flange extending from the zygomatic to the frontal bones.

### *Pour Spouts\* and Registered Pour Spout Plugs\**

In cases where the molds will be used for solid pour casting\*, the contours of the object should be studied in order to determine the paths of fluid flow. The pour spout should be positioned such that the orientation of the mold, when poured, provides a minimum of air locks\*. The presence of some air locks is often unavoidable and they may be eliminated by the inclusion of risers. If the mold is to be used to produce a large number of casts and/or important detail is lost on the surface of the optimal pour spout location, a registered pour spout plug can be included in the design (Edmund, 1985). The addition of a registered pour spout plug to the design has several advantages. As the pour spout plug reproduces the detail otherwise lost in this area, there is greater freedom of choice for the location and size of the pour spout. The time and effort of carefully carving away and disguising the casting sprue\* left by the pour spout is saved. The mold may also be used for making hollow slush casts if appropriate.

### *Flanges*

Several factors are used to determine the position of the flanges in mold designs. It is easier to disguise the evidence of the seams of the mold by locating the flanges on naturally occurring features such as along the tops of ridges or the edges of textural features. If there is no choice but to position a flange on a smooth, relatively featureless surface, align it parallel to the grain of the bone. Flanges should be located so that the mold will not have to be stretched unduly during demolding. Flanges should follow any projecting features with severe undercuts in order to prevent the need to stretch the mold to clear those features. Demolding will be easier if the pour spout and risers, when present, are incorporated in flanges.

A flange need not be continuous. Areas of varied topography (often requiring risers) and/or angled differently from the rest of the object (such as the back of a skull), often cause difficulties during demolding and are good places to use a short flange. The short flange, with keys, should meet the nearby normal flange at a perpendicular angle (Fig. 2). If there are to be any risers in this area, incorporate them in this short flange if possible. A short flange acts much like a zipper, allowing the mold to open wider, without stretching, over very difficult features of an object. Demolding is thus made easier.

### SELECTION OF THE MOLDING COMPOUND

The nature of the molding compound that will be used is an important factor. Latex rubber is the most flexible and tear resistant molding compound. It is extremely economical compared to most molding compounds. However, latex rubbers have a limited shelf life and a limited casting life especially when used with casting compounds such as polyester resins (water extended polyester resin—W.E.P.—may be an exception). Prevulcanized latex rubbers such as MOLD-ALL 61-1000 and MOLDLENE are best, having a longer shelf life, a smaller shrinkage factor\* during curing and are more durable in use than other brands or types of latex. Avoid the ammonia-based natural non-vulcanized latex rubbers. They often exhibit an excessive shrinkage factor, commonly greater than 10%, and begin to deteriorate rapidly as soon as the mold is cured.

Room temperature vulcanizing (R.T.V.) silicone rubbers are expensive, even

## SHORT FLANGE EXAMPLE: SKULL

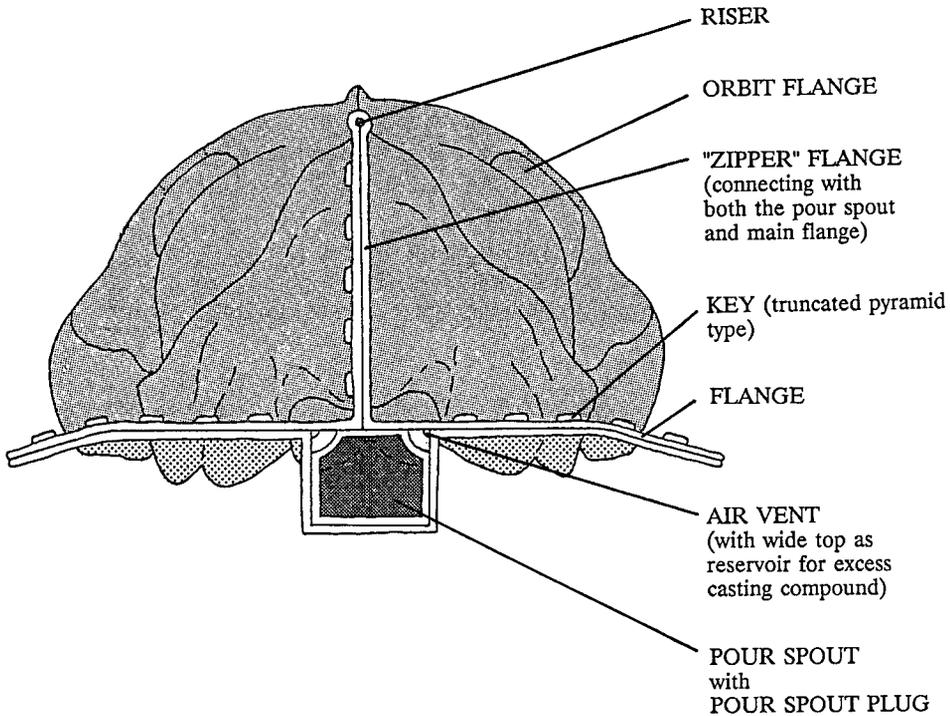


Figure 2. Posterior view of a jaguar skull mold (not to scale). Visible are upper and lower halves of the mold, with a short ("zipper") flange and riser in the former and a keyed pour spout plug with air vents in the latter.

when molds are constructed in thin layers in a manner similar to latex rubber mold (Edmund, 1985; Feldmann *et al.*, 1989), as opposed to the traditional poured block style mold. R.T.V. silicone rubbers are not as flexible or as resistant to tear as latex rubber (Chaney and Goodwin, 1989; Edmund, 1985). As a consequence, R.T.V. silicone rubber molds usually have to be more carefully designed. Unlike latex rubber molds, however, R.T.V. silicone rubber molds can be repaired.

The size and shape of an object are factors that determine whether the mold is better constructed out of latex or R.T.V. silicone rubbers. It is better to use latex rubber for molding essentially flat or very large objects. Latex rubber will adhere better to the mother mold\*, especially if keyed, reducing the chances of distortion in the casts. R.T.V. silicone rubber does not stick to the mother mold at all and the mold can distort even if keyed. R.T.V. silicone rubber is commonly used for molding small items (Waters and Savage, 1971; Reser, 1981; Rose, 1983). The selection of R.T.V. silicone rubber is indicated when little or no shrinkage and high fidelity of detail is needed, such as for scanning electron microscopy. It is the molding compound to be preferred when casting with polyester and epoxy resins.

The range of R.T.V. silicone molding compounds available is extremely large, with choice being determined by a combination of cost, suitability to the particular application, and personal preference. The author has had success in using either G.E. R.T.V. 700 (with BETA 2 or BETA 5 catalyst) or Stauffer Wacker R.T.V. SWS 04478 (with catalyst CX) as the first layer in a layered R.T.V. silicone rubber/cheesecloth laminate mold. Subsequent layers were applications of G.E. SILICONE II SEALANT (clear). To select an appropriate R.T.V. silicone, refer to the literature for recommendations in similar situations. Experiments with small samples of a selection of R.T.V. silicone rubbers on similar samples with similar methods are recommended to finalize the choice. Sources for molding compounds are given in Appendix 2.

The first good cast should be set aside for use as a master for remolding an object if the production of a large number of casts in the future can be foreseen. This will reduce the amount of stress or damage to the original object.

#### EXECUTION OF THE MOLD

It is very useful to keep a personal reference notebook, preferably looseleaf in order to maintain a logical organization of the contents. Keep a record of what you do and the time required for each step. These records can help you in the future to repeat a successful experiment, to avoid repeating mistakes, and to budget your time. Always obtain and read up to date manufacturer's material safety data sheets and information sheets and always be aware of and obey the safe handling instructions for all materials used.

Records of consolidants\*, separators\*, flanging and molding compounds and any other chemical or material treatments, with dates used, must also be associated with the original specimen (Fitzgerald, 1988). A history of conservation and molding is important to the preservation of the specimen, for instance, in avoiding material incompatibility during future conservation and molding. An example is the case where polyvinyl acetate such as VINAC B15 or an acrylic resin consolidant such as ACRYLOID B-67 OR B-72 is used on a specimen. Polysulfide rubber molding compounds attack these plastic consolidants and therefore cannot be used to mold this specimen (Chaney, 1989).

Because demolding will stress all objects being molded, the object must be assessed as to its fragility. If consolidation is required and permission to do so is obtained, the consolidant must be compatible with the materials of which the object is composed and with the molding compound. For example, polyethylene glycol (P.E.G.) of various molecular weights is often used for wood, sub-recent bone and fossil bone from aqueous Pleistocene deposits. When P.E.G. is used the mold must be made of R.T.V. silicone rubber; if latex rubber is used, cracks will appear in the first couple of coats of the latex mold, resulting in disfiguring artifacts in the casts.

Surface textures and surface relief may result in adhesion of the mold to an object. Different molding compounds have different amounts of adhesion to the surfaces of objects. The use of a separator can lessen the amount of mold-object adhesion even with molding compounds not usually requiring one. Check the manufacturer's data sheets for recommendations regarding the use of a separator. A wax separator is best applied in several thin coats that are carefully and gently

polished with about two hours of time between applications. A single thick coat can obscure detail and create molding artifacts such as brush marks. Several thin coats will also ensure complete coverage. If one is unsure about such factors as the compatibility of a particular combination of molding compound, separator, and object material, then experiment on a scrap piece of material of identical composition and consolidation (or as reasonably close as possible) to the object being molded.

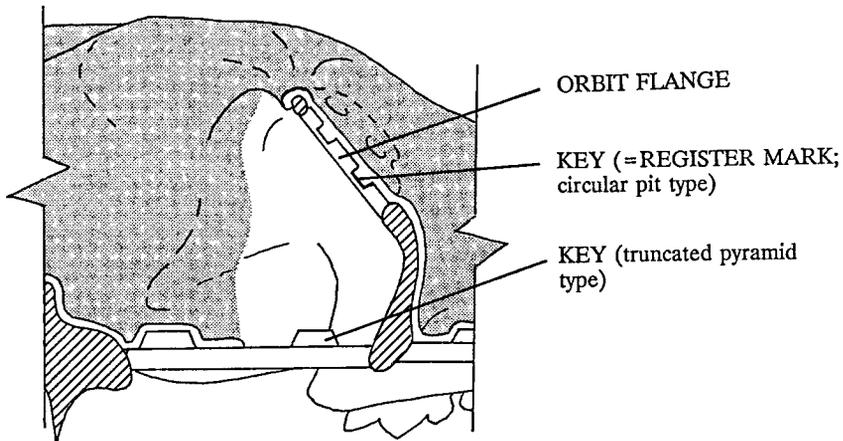
The surface of the object and the surface of the flange should intersect at an angle of 90 degrees and not form any undercuts. When fabricating the flanges, make them wide enough so that there will be enough room for the keys and leave a generous amount of flange, especially as the edges of the flange will be trimmed. If the sections of the mold are to be held together by bolts, make sure that the flange is made wide enough so that the holes for the bolts are more than 2 cm away from the object and not too close to the edge when they are drilled. Leakage either through the bolt holes or along the edge of the flange will thus be reduced considerably. The surface of the flange must be smooth and the edges neat and sharp. The keys should be sharp-cornered or angular and moderately large. There must also be a sufficient number of evenly spaced keys that the pieces of the mold will index positively with each other. Slight mismatches of mold halves that leave unsightly seams will thus be reduced or eliminated.

Use a neutral flanging material that will not react with either the material of the object or the molding compound. While the flanging material should be able to adhere to the specimen sufficiently to stay in place during application and curing of the molding compound, it should also be easy to remove from both the object and the mold. A silicone based modelling clay, such as Klean Klay (#20, neutral), is recommended. Roma Plastilina is a vegetable oil based clay. The vegetable oil base is incompatible with many molding compounds, attacking or reacting with the molding compound and inhibiting curing. The oil may also soak into the object and cause conservation problems for the object or create problems in the future if the object is remolded. If this material has been used, it requires the application of an impermeable separator, such as polyvinyl acetate. Information about the original object such as identification and catalogue numbers can be engraved in the flanging material.

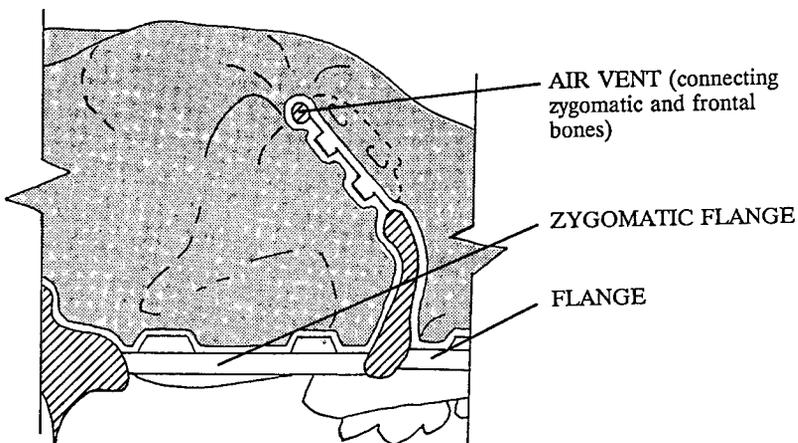
When constructing the actual mold, the molding compound should first be applied to the areas around the orbital region, including the outside surface of the eye socket flange (Fig. 3). The inside of the orbital region should not be dealt with until the section of the mold over the eye socket flange is finished and sufficiently cured to allow the flanging material, but not the air vent, to be carefully removed. Separator must be applied to the inside surface of the mold's eye socket flanges before the molding compound is applied to the inside of the orbital region to finish the upper half of the mold. This creates a mold that not only covers the outside surface of the skull but also wraps around itself in the eye socket and extends into the orbital region, thus reproducing the details of the orbital region. During application of the molding compound, one side of the short flanged (or "zipper" flange) area is molded, then the flanging material is carefully removed and the separator is applied in its place. The other side of the area is then finished.

Once one side of the mold has been made and has had time to cure, the mother mold for that portion is constructed, or a temporary support for the mold flange

## EXAMPLE: MOLDING THE EYE SOCKET



3A



3B

Figure 3. Side view, cross-sectioned through the zygomatic area of the orbit for clarity. 3A. The areal extent of the application of molding compound in the eye socket. Outer surface of the eye socket flange is molded, the interior is not. 3B. After the molding compound is sufficiently cured, the Klean Klay eye socket flange is removed, separator applied, and application of the molding compound is continued in the interior of the eye socket to finish this portion of the mold.

is added. The modelling clay flange is carefully removed and any adhering bits of modelling clay are gently scraped off the mold flange and object. It is important to apply a separator to the now-exposed inside surface of the mold flange, before fabricating the other side of the mold, otherwise they will not separate during demolding.

Make the pour spout large enough to both pour in the casting compound and

allow the air in the mold to escape. Making the pour spout too small is a common mistake for beginners. If the mold design includes a pour spout plug, the modelling clay pour spout must include keys in order to provide proper control of the plug depth when it is replaced during casting (Fig. 4). The keys should be sharp, clear, circular register pits, as deep as they are wide. The end of a pencil or any similar object may be impressed in the clay pour spout plug in order to fabricate the register pits. Alternatively, they may be added on as steep-sided squares or rectangles of flanging material as opposed to being incised. The catalogue number should also be engraved in the modelling clay pour spout so that it will identify the pieces once the mold is made. Thus the pour spout plug may be re-associated with the mold if they become separated. The pour spout should be made asymmetric in outline with parallel sides in order to provide easy alignment and proper fit of the pour spout plug when reinserted during casting.

The pour spout plug is the last piece of the mold constructed. Once the mold and the mother mold have been made, the modelling clay pour spout is carefully removed, and the exposed surface of the object and pour spout wall are cleaned of modelling clay. Separator is applied, and catalyzed R.T.V. silicone rubber is poured into the pour spout level with the top, or latex rubber brushed on. If the mold is to be used only for solid pour casting, air vents may be made in an R.T.V. silicone rubber pour spout plug after the object has been demolded, by carefully cutting out small vertical channels in the sides of the plug with a sharp scalpel. The air vents should extend upward from the highest features that the edge of the plug comes in contact with to prevent air bubble traps from being formed. In the case of a latex rubber pour spout plug, the air vents must be fabricated from modelling clay strips applied to the sides of the pour spout before the separator is applied. An R.T.V. silicone rubber pour spout can be used in a latex rubber mold. If the mold is to be used for both solid pour casting and hollow slush casting\*, the air vents can be plugged with modelling clay when the mold is used for the latter. The air vents can be omitted if the mold is to be used solely for hollow slush casting. It may be helpful to fabricate a removable latex/vermiculite plug inside a latex pour spout plug.

If the mold is to be put in a pressure tank while the casting compound sets (in order to reduce or eliminate air bubbles in the casts), the air vents must be much wider at the top in order to provide a reservoir of excess casting compound. This is in order to replace the volume of air lost as the air bubbles shrink under pressure.

Regardless of what molding compound is being used, the surface of the mold in contact with the object is the most important part. This is where the detail is being reproduced. For the best results, the molding compound should be brushed on as a very thin initial coat, being careful to prevent the entrapment or incorporation of any air bubbles, and allowed to set. The rest of the molding compound may be applied in the usual recommended manner (usually by brush, spatula, or by pouring). Refer to either manufacturer's instructions or to any of the relevant papers in the cited references.

If the molding compound is being applied in layers to create a thin sheet-like mold (as opposed to a poured-block style), the mold can be reinforced by incorporating overlapping squares of cut up cheese cloth or nylon stockings into the final layers. A single layer of reinforcing is sufficient and will considerably reduce

## EXAMPLE: POUR SPOUTS

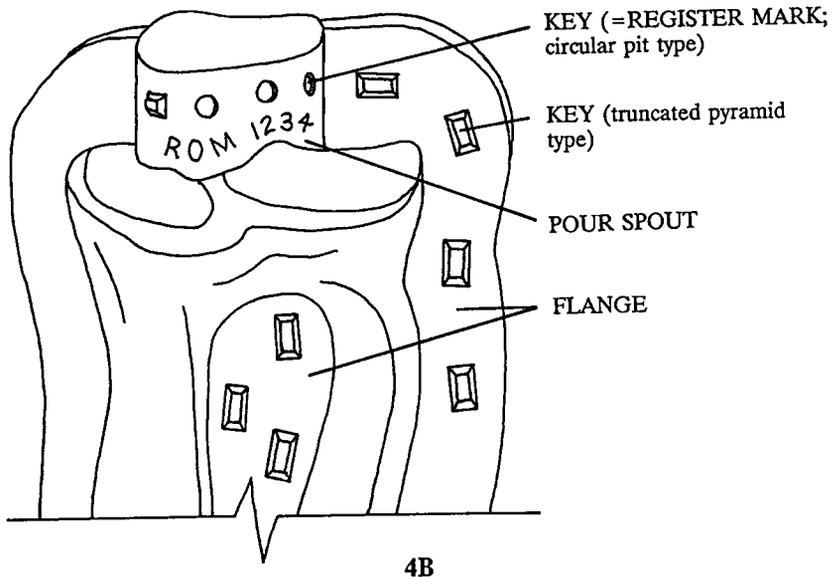
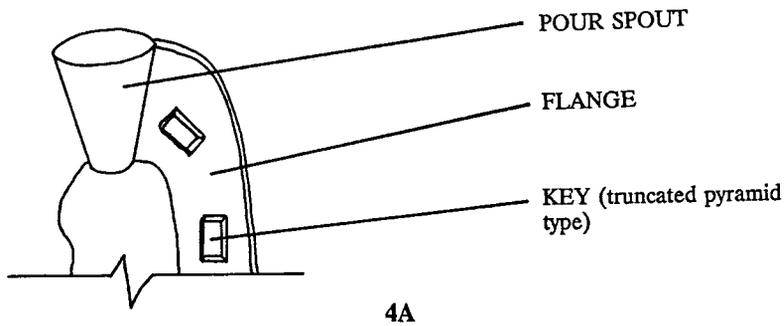


Figure 4. Slightly oblique lateral views of bones with Klean Klay pour spouts and flanges. 4A. The end of a limb bone set up for a traditional funnel-shaped pour spout and flanged for a one-piece (or wrap-around) mold. 4B. An edentate tibia-fibula set up for creating a pour spout with a registered pour spout plug. The bone is flanged for creating a two-piece mold (plus pour spout plug). The catalogue number is engraved in the modelling clay, the flange is not yet fully keyed.

instances of tearing in those parts of the mold subjected to high stress during demolding. This reinforcing also allows the mold to be constructed slightly thinner. Cheese cloth will reduce the flexibility and amount of stretching that the mold will be capable of. The outer surface of the mold should be smooth and without threads or blebs of molding compound sticking out. This prevents the mother

mold from adhering excessively during the initial demolding and allows a close fit of mother mold to mold when they are reassembled.

### MOTHER MOLD

The mother mold, whether made of plaster or fiberglass, should be tight fitting but be easily removable. In order to accomplish this, undercuts and cavities must be filled in with removable plugs. These are made by mixing coarse vermiculite with latex rubber molding compound and packing this mixture in the undercuts and cavities, using plastic food wrap as a separator with the mold. The surfaces should be smoothed to shapes that will allow the mother mold to easily lift away. The plugs in deep cavities, or cavities with constricted access, can be made in several pieces in order to facilitate removal.

Mother molds can also be made in multiple pieces to compensate for complex shapes. If they are of fiberglass, temporary flanges of modelling clay may be used to create flanges for bolting the adjacent pieces of mother mold together. A separator must be used. Damage to the object can result if removal of the mother mold is difficult. Do not use plastic food wrap as a separator with fiberglass mother molds as the heat from the exothermic reaction of the catalyzed resin will cause the plastic food wrap to shrink and deform the mother mold. Aluminum foil is acceptable if it is pressed down to a close form fit. Some people use polyvinyl alcohol as the separator. Toilet paper makes a good separator for plaster mother molds.

Once the mother mold has set and cured, carefully drill bolt holes along the mid-line of the flanges so as to avoid the possibility of damaging the object with the drill bit. Insert a bolt and nut finger tight in each hole as you drill them. This prevents the whole mold from inadvertently coming apart as you work on it. Trim the edges of the mother mold back to the edges of the mold. Remove the mother mold and trim off a small amount of the edges of the rubber mold's flanges. This gives a clean neat edge that aids in spotting misalignments whenever the mold is reassembled, and eliminates overlapping molding compound material at the edges that often binds the halves of the mold together to prevent separation. Check the fit of the mother mold again and trim the edges back again if necessary. Print the catalogue number and identity on the pieces of the mother mold.

The finished edges of the mother mold should not extend beyond the finished edges of the mold flanges. The mother mold flanges will act as a vice when the pieces of the mother mold are bolted, clamped or bound together with elastics. This will cut down on leakage or unnecessary flash. This will also allow the person casting to observe whether there is any leakage along any of the flanges and to clamp it as necessary. In the event of a leak, if the edges of the flanges are not encased by the mother mold the casting compound can run off and will not build up so readily between the mold and the mother mold. A buildup of material between the mold and mother mold will prevent a proper close fit when the whole mold is reassembled.

Demolding of the object is to be done very gently. Apply gentle to moderate tension and let the mold separate at its own pace. First separate the halves of the flanges, then demold the object in those areas where the mold separates easily.

Leave those areas where the surface detail is complex and/or delicate and the stubborn areas for last. This will reduce the possibility of damage to either the mold or the object and will make it easier to demold the difficult areas.

#### PREPARATION FOR CASTING

When reassembling the mold, fit one half of the mold accurately in its portion of the mother mold. Then fit the other pieces of the mold to the supported part. Gently run a finger along the flange to ensure that the keys properly index. Visually inspect the edges of the flanges to check that the sections of the mold are in proper registry (i.e., the trimmed edges line up). If it is a latex rubber mold, liquid rubber cement can be used to glue the mold together. Do not use contact cement, as the mold sections must come apart, undamaged, when demolding the cast. The careful use of rubber cement on latex rubber molds will cut down on leakage and unsightly flash.

Fit the rest of the mother mold in place and bolt, clamp or hold the mother mold together with heavy duty rubber bands. Rubber bands work well on small molds with plaster mother molds; clamps and/or bolts work well on medium size molds; bolts work best on the very large molds. Visually inspect the edges of the flanges to ensure that the bolts are not so tight that they force the flange halves out of alignment. The mold is now ready for casting.

The advice given for demolding the original object is equally applicable to demolding the casts.

#### ACKNOWLEDGEMENTS

The author wishes to thank the following people (in alphabetical order) for sharing their knowledge and for their support and assistance: Maggie Dickson, Gord Edmund, Catherine Hollett, Anne MacLaughlin, Peter May, and Chris McGowan.

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### APPENDIX 1: GLOSSARY OF TERMS USED

- air lock:** during the casting process, an air bubble trap in the mold created by any feature of the mold that does not allow the air to be fully displaced by the casting compound when it is poured into the mold.
- air vent:** a small open passage that allows air and excess casting compound to escape from the mold during casting in order to eliminate air locks, and thus eliminate the presence of unsightly air bubbles (and the associated loss of detail in the area of the bubble) in the casts; usually interchangeable with the term "riser."
- casting sprue:** a reproduction of the pour spout on the casts, formed from the excess of casting compound entering the pour spout; must be removed by careful cutting and carving as its presence on a cast is not desirable.
- consolidant:** a compound applied in a liquid form to an object, to penetrate the surface and preferably soak into the interior to strengthen it. The compound is either in solution or melted form for application, and hardens either through the evaporation of the solvent or through cooling. Application of a consolidant is intended to arrest further physical deterioration and stabilize the object in its current state, reinforcing the object's physical strength.
- demolding:** the act of removing a mold from either the original object or a cast.
- flange:** an artificially created flat feature of a mold, perpendicular to the surface of the object, along which the mold opens to allow demolding. It is not reproduced in the cast.
- flash:** a thin, irregular projection of casting material on the surface of a cast; found on a cast where flanges of the mold were located, and created by the seepage of casting material into the flange area.
- keys:** a constructed feature of a mold. Keys are interlocking, regular geometric shapes, located regularly spaced along the inside faces of mold flanges. They are of positive relief on one flange with the complementary negative relief on the counterpart flange face. Keys provide for repetitive precise reassembly of mold halves. Sometimes keys are also constructed on the outer surface of a mold to provide for the precise reassembly of the mother mold to the mold. The term is interchangeable with the term "register marks."
- molding artifact:** any feature found in a mold and reproduced on the casts that is not originally present on the original object. Examples are flash, seam lines, brush marks, and projecting spheres (air bubbles in the mold).
- mother mold:** a close fitting, exterior reinforcing jacket for the mold. The mother mold keeps the pieces of a mold together and maintains the mold in its proper shape and dimensions during casting.
- pour casting:** casting by pouring the casting compound into the mold.
- pour spout:** an opening into the inside of the mold that allows casting compounds to be poured in; often funnel-shaped.
- pour spout plug:** an individual piece of a mold, fabricated during construction of the mold, that fits precisely (keyed) into the pour spout during casting to fully close the mold. The pour spout plug reproduces on the cast the detail found on the original object in the pour spout area (usually lost on casts) and eliminates the casting sprue.
- riser:** a small tubular passage in a mold, best located in a flange, leading from a feature or area of the mold that would trap air when casting compounds are poured into the mold. It allows air to escape from the air lock, ensuring that this feature or area of the mold is reproduced in the cast. It should exit at the top of the mold at the same altitude as the pour spout so that it does not act as a drain.
- separator:** a substance applied to the surface of objects or molds in order to prevent adhesion in areas upon which molding or casting compounds are applied.
- shrinkage factor:** the degree to which either a mold or a cast made out of a particular material is smaller or larger than the original object in the former, than the mold in the latter; expressed as a percentage.
- slush casting:** producing a hollow cast by pouring only a fraction of the casting compound that would be needed to fill the mold, closing the mold and then rotating the mold along all three axes until the casting compound has set.

undercut: an area of negative relief on an object into which the mold will project, such as to make the mold difficult to remove from this feature and stress both the mold and the object (original or cast) in the demolding.

## APPENDIX 2: SUPPLIERS OF MENTIONED MATERIALS

### MODELLING CLAY

KLEAN KLAY #20, Neutral

Art Chemical Products, P.O. Box 678, Huntington, IN 46750, U.S.A.

### PREVULCANIZED LATEX RUBBER

MOLD-ALL 61-1000 LATEX MOLDING COMPOUND

Chemionics Corporation, 390 Munroe Falls Road, Tallmadge, OH 44276, U.S.A.

MOLDLENE

Deep Flex Plastic Molds, Inc., 1218 Haley Road, Murfreesboro, TN 37129-2309, U.S.A.

### R.T.V. SILICONE MOLDING COMPOUNDS

GENERAL ELECTRIC R.T.V. 700 with BETA 2 or BETA 5 catalyst; G.E. II SILICONE SEALANT  
Silchem Inc., 546 Gordon Baker Road, Willowdale, ON M2H 3B4

or

General Electric Co., Silicone Product Division, Waterford, New York 12188.

or

any local distributor of G.E. products

STAUFFER WACKER R.T.V. SWS 04478 with catalyst CX

Henley Chemical, 420 Finchdene Square, Scarborough, ON M1X 1C2

or

Wacker Silicones Corporation, 3301 Sutton Road, Adrian, MI 49221-9397

### CONSOLIDANT

VINAC B15 (Polyvinyl acetate)

Air Products and Chemicals Inc., Chemicals Customer Service, P.O. Box 2662, Allentown, PA 18001, U.S.A.

ACRYLOID B-67 and ACRYLOID B-72

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## BOOK REVIEWS

**THE CARE AND CONSERVATION OF GEOLOGICAL MATERIALS: MINERALS, ROCKS, METEORITES AND LUNAR FINDS, 1992, Frank M. Howie, ed.** (Butterworth-Heinemann, Boston, 138 pp.) The durability of rocks and minerals is so widely appreciated (e.g., "diamonds are forever") that all of us have a tendency to forget that collections of geological materials do require proper care and that some specimens require active conservation measures. This volume of nine chapters and four appendices fills a critical need for a single authoritative source that explains basic standards of care for geological collections, describes the physical causes of conservation problems, recommends solutions, and provides a guide to the literature.

Monica Price introduces mineral stabilities in Chapter 1, makes the case for conservation of geological collections, and describes how the basic principles of conservation should be applied by collectors and curators. Kurt Nassau explains in Chapter 2 the physics of color and how light can induce color changes as well as accelerate surface reactions or induce decomposition. Robert Waller describes in Chapter 3 the physical chemistry of conservation problems attending temperature- and humidity-sensitive minerals. Frank Howie addresses the care of elements and alloys in Chapter 4 and sulfides and related species in Chapter 5. Chapter 6 he devotes exclusively to pyrite and marcasite, the dimorphs of  $\text{FeS}_2$  which are the greatest villains (or victims) in our specimen drawers. Alex Bevan offers a primer on meteorites and their preservation in Chapter 7. Charles Meyers describes in Chapter 8 the curation of NASA's lunar sample collection with its elaborate technologies and exacting protocols. Howie discusses hazards that the collector, conservator, and curator might encounter in Chapter 9. Appendix 1 lists construction materials and their possible deleterious effects to collections. Appendices 2, 3, and 4 by Bob King discuss collecting, cleaning, and repairing specimens. The book is indexed and well-illustrated with both black and white and color photographs. All of the chapters include reference lists and typically species lists detailing stabilities, susceptibilities, or recommendations for care.

This is well balanced presentation of theory underlying many conservation problems and practical guidance to address those problems. It demonstrates that much can be done inexpensively and without recourse to conservation consultants to improve the condition of geological collections. The discussion of the lunar sample collections is of particular relevance because it illustrates the extremes possible in collections care. Also, it is clear that investigating the causes of specimen deterioration is a potentially fruitful avenue for research.

Most importantly, I found myself reassessing my own attitudes toward collections care and conservation as I read the book. If keepers of other geological collections respond similarly and we all implement whatever appropriate measures we can, then this book will have served its purpose magnificently.—*Carl A. Francis, Harvard Mineralogical Museum, 24 Oxford St., Cambridge, Massachusetts 02138.*

**GUIDE TO ENVIRONMENTAL PROTECTION OF COLLECTIONS, 1991, B. Appelbaum.** (Sound View Press, Madison, CT, 270 pp.) Much of the recent work in conservation research reflects a philosophical shift away from emphasis

on restoration techniques and toward preventive conservation. This has, in turn, focused attention on the critical role that environmental factors play in the deterioration. Barbara Appelbaum has written a guide intended to serve as a practical handbook for understanding and managing the environment of both public and private collections in the United States.

Ms. Appelbaum suggests methods and materials which can be used by collections professionals without formal conservation training. Her approach focuses on simple, practical, and affordable strategies for environmental monitoring and control. She states that "more expensive and more complex is not necessarily better," an adage to take to heart and to purchasing sessions.

Part I discusses five major issues (or factors) in environmental protection: temperature and relative humidity, light, air quality, mold and pest control, and preventing physical damage. Part II focuses on the needs of collections of specific materials or composition. From the point of view of natural history conservation, the former section is the more useful. Ms. Appelbaum is familiar with a wide range of approaches and materials, and discusses them without jargon or obfuscation.

Ms. Appelbaum's recommendation that the natural properties of different spaces in a building be used for differentially tolerant collections is interesting, though her statement that "[d]usty spaces can be used for . . . boxed collections of arrowheads" is not a better solution than would be eliminating the source of particulate pollution. Her recommendations for light levels are expressed in foot-candles, a unit of measurement less in favor than the more internationally accepted lux.

This book is intended for a North American audience, but Ms. Appelbaum's familiarity with the climate of the northeastern United States overrides any consideration of the extremely varied and diverse climates of the majority of the country. Collections in arid, sub-tropical, or montane climates will encounter a wider range of fluctuations and problems than are addressed in this book. Ms. Appelbaum's central thesis, that relative humidity should be managed to shift gradually throughout the year when it cannot be strictly controlled, is still a sound practical approach.

Some questionable statements occur in the book. Ms. Appelbaum recommends Duco as an adhesive for mending ceramics, even though she recognizes its problems with discoloration. She uses the term "crystal" as a synonym for "salt" (which it is not) in a discussion of Byne's disease. In the single paragraph allotted to amber, she makes no recommendations for its care.

It is obvious that Ms. Appelbaum is not comfortable with the needs of natural history collections or with the materials encountered in these collections. Minerals, pyrite disease, and fossils each receive a single paragraph of discussion, although the problems associated with these certainly justify a better treatment. As many private collectors maintain large collections of these materials, the brevity and lack of useful information in these sections is a positive disservice. After she discusses wood, bark, ivory, leather, furs, shells, feathers, and amber as separate subjects, she introduces a section on natural history specimens as if they are somehow different in composition or behavior from objects made from natural history materials. Bone as a material is never mentioned, even though its characteristics are problematic and unique. It would have been better and more ef-

fective to integrate the discussion of natural history materials, rather than to isolate it.

This book is not the definitive guide to environmental protection of collections, though it contains much useful information. A natural history museum professional lacking conservation training could not rely on this book alone for good information on managing environmental factors. Finally, it is disturbing that a book for this audience should be riddled with typographical errors, misspellings and run-ons.—*Sally Y. Shelton, Natural History Conservation Laboratory, Texas Memorial Museum, The University of Texas, 2400 Trinity, Austin, Texas 78705.*

## PREPARATION OF MANUSCRIPTS

*General.*—It is strongly recommended that, before submitting a paper, the author ask qualified persons to appraise it. The author should submit three copies of the manuscript either typewritten or printed on letter quality printers. **All parts of the manuscript must be double spaced** with pica or elite type on 8½ × 11 inch (21.6 by 27.9 cm) or A4 paper and at least one inch (2.5 cm) margins on all sides. Manuscripts should not be right justified, and manuscripts produced on low-quality dot matrix printers are not acceptable.

Each page of the manuscript should be numbered. Do not hyphenate words at the right-hand margin. Each table and figure should be on a separate page. The ratio of tables plus figures to text pages should generally not exceed 1:2.

The first page includes the title of the article, names of authors, affiliations and addresses of authors, and the abstract if present. In the top left-hand corner of the first page, indicate the name and mailing address for the author to whom correspondence and proofs should be addressed. All subsequent pages should have the last names of the authors in the upper left-hand corner.

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*Literature cited.*—This section includes only references cited in the manuscript and should be typed double spaced. References are listed alphabetically by authors' names and take these forms:

Jones, E. M., and R. D. Owen. 1987. Fluid preservation of specimens. Pp. 51–64 in *Mammal Collection Management* (H. H. Genoways, C. Jones, and O. L. Rossolimo, eds.). Texas Tech University Press, Lubbock, 219 pp.

Sarasan, L. 1987. What to look for in an automated collections management system. *Museum Studies Journal*, 3:82–93.

Thomson, G. 1986. *The Museum Environment*, 2nd ed. Butterworths, London, 293 pp.

*Tables and illustrations.*—Tables and illustrations should not repeat data contained in the text. Each table should be numbered with arabic numerals, include a short legend, and be referred to in the text. Column headings and descriptive matter in tables should be brief. Vertical rules should not be used. Tables should be placed one to a page, after the references.

All figures must be of professional quality as they will not be redrawn by the editorial staff. They may include line drawings, graphs or black and white photographs. All figures should be of sufficient size and clarity to permit reduction to an appropriate size; ordinarily they should be no more than twice the size of intended reductions and whenever possible should be no greater than a manuscript page size for ease of handling.

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*Evaluation of a manuscript.*—Authors should be aware that the following points are among those considered by the editorial staff when evaluating manuscripts: 1) Is the content appropriate to the purpose of the journal and society? 2) Are the contents clearly and logically presented and the paper well organized? 3) Is the methodology technically and logically sound? 4) Does the paper contribute to the body of knowledge and literature? 5) Is the study integrated with existing knowledge and literature? Is the literature cited appropriate for the study? 6) Are the conclusions supported by sufficient data? 7) Does the title reflect the thrust and limitations of the study? 8) Are the tables and figures clearly presented? Are they necessary to support the text?

## SUBMISSION PROCEDURE

Manuscripts intended either as feature articles or general notes should be submitted in triplicate (original and two copies) to the Managing Editor. Letters to the Editor and correspondence relating to manuscripts should be directed to the Managing Editor. Books for review should be sent to the Associate Editor for Book Reviews.

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