

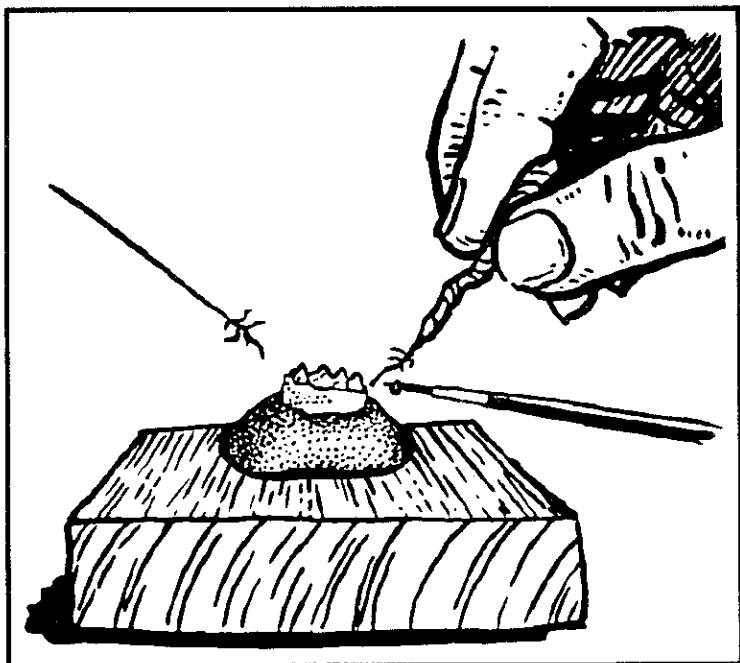


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Techniques for Recovery and Preparation of Microvertebrate Fossils

Richard L. Cifelli
Editor





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**Oklahoma Geological Survey
Charles J. Mankin, *Director***

**The University of Oklahoma
Norman, Oklahoma**

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Front Cover

Positioning and reattachment of tooth cusp of a Mesozoic mammal (dryolestid). The main part of the specimen is embedded in modeling clay affixed to a wooden base. (Illustration is from p. 31 of this volume). *Drawing by C. D. McCallister.*

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PREFACE

Most living terrestrial vertebrates are small animals (e.g., Eisenberg, 1981); as fossils, they are important not only in constituting a major fraction of the biota but also in providing important data for biochronologic control and paleoenvironmental reconstruction (e.g., Graham and others, 1987). Microvertebrate fossils are not commonly encountered through standard prospecting methods, however, and application of specialized recovery techniques is generally required to obtain a diverse, well-represented sample of such taxa. Paleontologists have long employed the technique of underwater screening, called "screen-washing" (e.g., Hibbard, 1949; McKenna, 1962, 1965), and a variety of other techniques to recover microvertebrate fossils, as a growing body of literature on the subject attests (see, e.g., references in Hannibal, 1989). In recent years, design changes and development of new materials and approaches have permitted increased efficiency and effectiveness of microvertebrate recovery operations, provided alternatives to some of the hazardous materials commonly used, and facilitated preparation, conservation, and display of microvertebrate specimens. In addition, mechanical preparation of microscopic fossil vertebrates has become both increasingly sophisticated and more widespread, as research interests have turned to diminutive elements of paleofaunas.

A number of contributions to microvertebrate recovery and preparation have appeared in recent years, most notably those contained in the compendia of Feldmann and others (1989) and Leiggi and May (1994). The papers contained herein are designed to supplement existing accounts, with particular reference to concentration and preparation techniques. The first paper reviews microvertebrate recovery techniques using underwater screenwashing and associated concentration methods, emphasizing variation according to lithology and local conditions; the second paper describes methods for manual preparation, repair, and storage of microvertebrate specimens. The main purpose of both is to present the various methods now available, their logistical and material requirements, and the conditions under which they are applicable.

Our experience stems mainly from the collection and preparation of Mesozoic microvertebrates, with particular emphasis on mammals, and is thus based on situations in which fossils occur in consolidated to partly indurated rock and are generally small, scarce, and fragile. Although some

of the advocated procedures may require modification or may be unwarranted under other conditions, our underlying theme is that the effectiveness and efficiency of a microvertebrate recovery program can be enhanced by judicious application of available techniques. In this sense, at least, we hope that this review will be useful beyond the bounds of the Mesozoic. Indeed, the impetus to produce this compendium arose from the fact that many existing references on the topic deal with specialized circumstances and prescribed methods that are not readily translated to other situations—as our own experiences, as well as those of many colleagues and acquaintances, attest. Because this contribution is directed at a wide audience, including students as well as seasoned professionals, we have included descriptions of many procedures that seem obvious. In so doing, we hope to prevent repetition of the many mistakes we have either witnessed or have made ourselves: many of the most "common sense" methods are discovered in hindsight.

Richard L. Cifelli, *Editor*

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CONTENTS

Preface	iii
---------------	-----

Screenwashing and Associated Techniques for the Recovery of Microvertebrate Fossils

Richard L. Cifelli, Scott K. Madsen, and Elizabeth M. Larson

Abstract	1
Introduction	2
Fossil Occurrence and Sample Collection	2
Primary Screenwashing Equipment and Methods	4
Location of Operation: Field or Laboratory	4
Screen-Box Design	5
Setup for Washing	6
Washing Procedure	8
Drying the Concentrate	12
Shipment Preparations	13
Secondary Matrix Reduction	13
Kerosene Washing	13
Acid Treatment	14
Rock Composition and Strategies for Screenwashing	14
Indurated Samples	14
Siltstones	15
Fine-Grained Rocks	15
Concentration Techniques	16
Interfacial Concentration Method	17
Concentration Techniques Utilizing Differences in Specific Gravity	17
Brominated Hydrocarbons	17
Sodium Polytungstate	17
Zinc Bromide	18
Setup and Concentration Procedures	18
Fossil Extraction	20
Acknowledgments	22
References Cited	22

Some Techniques and Procedures for Microvertebrate Preparation

Scott K. Madsen

Abstract	25
Introduction	25
Definitions	25
Glues, Preservatives, and Conservation Philosophy	26
Equipment, Tools, Accessories, and Materials	27
Microscope	27
Illuminator	28
Flexible-Shaft Power Tool	28
Tungsten Carbide Rod	28
Superglue	29
Polyethylene Glycol (PEG)	29
Small, Adjustable Blower	29
Modeling Clay	29
Superfine-Point Forceps	29
Miscellaneous Tools and Materials	29
Preparation of Microvertebrates	29
Field Considerations	29
Determination of Best Laboratory Procedures	30
Application of Glue	30
Repair of Small Bones	31
The Use of Carbowax in Microprep	32
Picking, Sorting, and Storing Microfossils	34
Vials and Vial Trays	34
Sorting Bone	35
Mounting Small Teeth and Bone	35
Acknowledgments	35
References Cited	36

Screenwashing and Associated Techniques for the Recovery of Microvertebrate Fossils

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ABSTRACT.—Underwater screening (“screenwashing”) and related concentration techniques constitute an important means of sampling fossil vertebrate faunas, particularly microvertebrates, and can yield diverse assemblages from rock units in which preservation of complete specimens is rare. We describe various methods and equipment needed for collecting and processing rock samples using these techniques. A field-based screenwashing operation—using a pump system, nested coarse and fine screen boxes, and portable washing tanks—is often the most efficient means of processing large samples, especially if it is impractical to transport large volumes of rock back to a laboratory. Secondary processing techniques, which cannot generally be employed in the field, are commonly needed to further reduce rock volume. The most common and useful secondary technique involves washing in combination with kerosene or other suitable petroleum distillate, which lacks the surface tension of water and which is therefore often effective at disaggregating fine-grained rock. Coarse-grained rock, on the other hand, is often indurated with calcium carbonate, in which case bathing in dilute acetic acid can aid in disaggregating samples prior to final screenwashing.

Screenwashing strategies are largely dictated by rock composition. Extraction of intact specimens from coarse-grained rock cemented with carbonate is laborious and expensive; because it is not generally feasible to process large samples, sites that are either highly significant, fossiliferous, or both should be targeted. The ease of disaggregation of siltstone in water is highly variable, although kerosene is generally an effective technique for secondary proc-

essing; test samples should always be processed, because it may be necessary to transport a significant fraction of the original volume of rock to a laboratory situation where kerosene treatment can be done safely. The behavior of claystone during screenwashing varies according to the mineral composition of the clay itself, diagenesis, and other considerations; test washing of such samples is also recommended. Claystone or mudstone with a high illite content will generally reduce quickly and thoroughly under most conditions. On the other hand, claystone or mudstone with a high montmorillonite content can be virtually unwashable under certain conditions: low salinity, warm temperature, and long soaking time are generally needed to deflocculate the clay flakes.

If a large proportion of unwanted residues remain in samples after screenwashing, it may be desirable to employ further concentration techniques. The most widespread and generally effective concentration method, heavy-liquid separation, exploits the difference in specific gravity between fossils and most of the unwanted residues; because vertebrate fossils tend to be relatively heavy, this method is most useful where the residues have a specific gravity of less than 2.6. Brominated hydrocarbons (e.g., di-, tri-, and tetrabromoethane), traditionally employed for heavy-liquid separation by micropaleontologists, pose considerable health risks, and their use is discouraged. Sodium polytungstate, widely promoted as being a safe heavy liquid (although its health risks remain unknown), is effective for heavy-liquid separation of vertebrate microfossils, but may not be practical for large samples because of its relatively high cost; for a large-scale operation, the salt zinc

bromide is recommended. We describe a setup that uses standard laboratory equipment to manage heavy-liquid separation and recovery of vertebrate fossils.

Except for the coarsest concentrate, which is separated by dry-screening, fossil extraction should be done with the aid of a binocular microscope at a magnification of 10 to 14 \times . Concentrate is spread thinly and evenly in a sorting tray that is marked with a grid system; fossils are removed with fine forceps or a paintbrush.

INTRODUCTION

Concerted collecting and concentration-based fossil recovery efforts can yield impressively diverse, well-represented vertebrate microfaunas (e.g., Clemens, 1963; Lillegraven, 1969), even where rocks appear to be sparsely fossiliferous (McKenna, 1965). Thus, application of these methods has become important in development of relatively long, continuous faunal sequences useful for biostratigraphic, paleoenvironmental, and paleobiogeographic studies (e.g., Barry and others, 1990; Jacobs and others, 1990). On the other hand, it has long been recognized that screenwashing (i.e., underwater screening) and associated concentration techniques are inherently destructive procedures (e.g., McKenna, 1962; Waters, 1978), particularly when applied to small, fragile fossils. Indeed, although practical considerations rule out controlled experiments,

our experience suggests that, of the mammal fossils originally present in a given Mesozoic sample, a very small fraction (perhaps less than 20%) is actually recovered intact. Thus, if fossils are fragile and their utility is dependent on completeness, application of concentration techniques should be considered a course of last resort. In many cases, however, a few, broken fossils are better than none at all, and large-scale efforts can result in well-represented faunas despite attrition caused by the process itself. In virtually all cases, results can be significantly improved by eliminating unnecessary steps and by always treating samples with the utmost care.

FOSSIL OCCURRENCE AND SAMPLE COLLECTION

Although it is possible to recover vertebrate microfossils from horizons that appear to be barren (McKenna, 1965), this is rarely a worthwhile enterprise. Fossiliferous horizons are usually discovered through surface accumulation of small bone (Fig. 1), which will vary in composition according to age, location, and depositional environment (Clemens, 1965, fig. 2, provides a useful depiction of the commonly encountered elements of a North American Late Cretaceous microvertebrate assemblage). Although it is not necessary to discover fossils of the desired taxa (e.g., mammals) on the surface—an accumulation of "other" bone is



Figure 1. Surface lag at Late Cretaceous vertebrate locality, Utah. The assemblage includes "typical" elements such as dinosaur bones and teeth, fish teeth, bones, and scales, and other assorted materials. Except for the dinosaur remains, most of the included taxa are euryhaline-tolerant aquatic taxa; the desired fossil mammals were absent from this locality. For scale, length of vial is 55 mm.



Figure 2. Lag of bone and other coarse clastic material in a fluvial system, John Henry Member, Straight Cliffs Formation (Upper Cretaceous, ?Santonian), Utah. Such sites may be very fossiliferous, though specimens are often poorly preserved because of the high-energy depositional environment. In addition, a large proportion of coarse sedimentary particles at such sites are often cemented with calcium carbonate or other agent, so that disaggregation of the matrix is difficult.

sufficient to justify sampling—it is useful to carefully consider the taxonomic constituents of the surface assemblage. If all elements appear to belong to one, undesired taxon or if most are marine or euryhaline-tolerant species, for example, the desired terrestrial taxa may be rare or absent altogether. In Mesozoic rocks of the Western Interior, microvertebrate assemblages commonly occur as lag concentrations at paleochannel margins (Fig. 2), in crevasse splays or other overbank deposits (Fig. 3), and at the base of ash beds, although in some cases the cause of accumulation or concentration is not immediately apparent from the lithology.

The surface of a locality should be carefully picked for fossils prior to sampling. If the surface matrix is collected for screenwashing, it should be kept segregated from rock collected in situ, because its precise stratigraphic provenance may be in doubt and the surface accumulation will, in any case, give a misleading impression of the productivity of the site. The producing horizon is often but not invariably marked by lithologic discontinuity; if doubt exists, it can be located through examination of rock samples from a trench or stratigraphic profile.

A test sample should be collected to determine site productivity. The size of the test sample will vary according to lithology, significance and rareness of desired fossils, and practical considerations (e.g., distance to motorized trans-

port). In general, rock indurated with a cementing agent is not collected unless it appears to be highly productive (because of the effort required to extract fossils from it); an initial sample of 50 to 150 kg is sufficient. For rock that will disaggregate in water, a larger sample is usually required: mammals and other terrestrial vertebrates are generally rare in Mesozoic rock units, and a test sample should include at least 400 kg of rock. For the test sample, at least, rock should be quarried with hand tools, broken into chunks, and examined for fossil content before being collected (Fig. 4).

Whether a locality is deemed sufficiently productive to merit intensive work depends on the significance of the fossils, ease of matrix reduction, and other considerations. For North American Late Cretaceous mammal sites, a productivity in excess of two mammal specimens per 100 kg of rock is a worthwhile yield (Clemens, 1965); on the other hand, Early Cretaceous mammals from the Antlers Formation, Texas, were deemed sufficiently important that a yield of less than 0.03 mammal specimens per 100 kg of rock (Clemens and others, 1979) was acceptable!

Likewise, quarrying techniques for large-scale operations will vary. Where fossils are fragile (and thus susceptible to considerable damage during concentration) but relatively complete, highly significant, and sufficiently concentrated, every effort should be made to recover them

during quarrying (Fig. 5). Rock is broken into almond-sized chunks (or even brought back to the lab, in large blocks, for controlled preparation), and the "backdirt" is saved for screenwashing. If, on the other hand, the fossils are not particularly concentrated, complete, or associated, it may be more efficient to emphasize fossil recovery through concentration techniques: matrix is collected as rapidly as possible—even to the extent of using heavy equipment—and broken into larger (golf-ball- to baseball-sized) chunks for screenwashing.

Burlap or synthetic-material grain bags, locally available at modest cost, are used for samples. Each has its advantages; we prefer burlap because it withstands physical abuse better (Fig. 6). The quantity placed in each bag will depend on the abilities of the labor force. However, it is important to obtain an estimated average weight per bag (so that the total size of the sample can be estimated), because later sampling decisions are often judged on the basis of productivity. If the locality is laterally or stratigraphically extensive, it may be useful to segregate individual subsamples from different levels or places. For large-scale collecting, however, separate labeling and processing of individually bagged samples from any single locality, which has sometimes proven useful in reassociating broken specimens (Waters, 1978), is generally unwarranted. This is because the number of recovered fragments that can be reassociated is generally small, and many of these fragments can be reassociated anyway by judicious sorting to type and taxon. In addition, given locality samples are generally large, and processing involves a number of individual steps, so that segregation of individual bag samples poses serious logistical problems and slows the operation considerably.

The most effective means of securing individual bags is with small sections of stiff parachute cord, whose ends have been melted to prevent unraveling. Ties fastened with a looped square knot can be quickly removed and reused. Each bag should be individually tagged (inside and out) with locality and other relevant collecting data. Because we advocate keeping tags with samples through the matrix-reduction process, the tags and markings should be relatively impervious to water, acid, and other commonly used agents. For this purpose, we use sheets of aluminum,¹ from which tags are cut with scissors. Holes are made with a paper



Figure 3. Microvertebrate locality in an overbank deposit underlying a channel sandstone of a fluvial system, Wahweap Formation (Upper Cretaceous, lower Campanian), Utah. A large sample of siltstone and claystone is being collected for underwater screenwashing.

punch, and each tag is fitted with a loop of wound, waxed, sewing-awl thread. Data can be etched into the tags with an awl, firmly pressed ballpoint pen, or similar object; alternatively, a permanent felt-tip marker can be used, in which case the tag can be recycled after the old marking is removed with acetone or other solvent. The tags are simply looped through the woven fabric at the rim of the bag, for easy removal.

PRIMARY SCREENWASHING EQUIPMENT AND METHODS

Location of Operation: Field or Laboratory

The location of a screenwashing operation (field- or laboratory-based) will depend on a number of considerations, including nature of the rock sample and methods required to effectively reduce it, cli-

¹Sheet aluminum can be purchased at nominal cost from a local newspaper; prefabricated aluminum or impregnated paper tags are commercially available at somewhat higher cost.



Figure 4. Microvertebrate locality in the Aguja Formation (Upper Cretaceous, upper Campanian), Texas. The site is in a paleo-coastal-plain channel deposit overlying a lignite bed; the fauna (which includes both terrestrial and marine taxa), together with sedimentological evidence, indicates an estuarine environment.

matic conditions, logistics of matrix transport, distance from home base, availability and nature of water in the field, and so forth. If conditions permit, on-site screenwashing is recommended for several reasons. First, it reduces or altogether alleviates problems associated with transport of large rock samples. Second, many samples can be fully reduced in the field, so that no further washing or concentration is required; field reduction minimizes the need for establishing a large-scale screenwashing operation at home base, which can be impractical because of space constraints or because weather does not permit washing during the off-season. Finally, screenwashing in the field usually is dramatically more efficient and cost-effective in terms of labor. A field crew is generally a "captive audience," and, free of the distractions in town or at an institution, the crew can focus its efforts in a manner not otherwise possible. On the other hand, some rock types require reducing agents such as kerosene and acid, whose use is rarely practical in a field setting because of environmental and safety concerns. In other cases, however, the local water source may be unsuitable for effective rock disaggregation. The large-scale, field-based screenwashing operation advocated herein requires three or four persons, two or more metal tanks, a gas-powered pump, 50 to 100 screen boxes, and other equipment and materials according to local conditions (Table 1). The portable field operation fits readily into the bed of a large pickup truck, although a trailer (5 × 8 feet or larger) is useful for this purpose.

Screen-Box Design

A screen-box design is shown in Figure 7. This box differs from previously described versions (e.g., McKenna, 1962, 1965; Clemens, 1965; Waters, 1978) in being much smaller, in lacking a cross-piece handle on top, and, most important, in being composed of two separate screening elements, coarse and fine. Each sieving screen is supported by ¼-inch-mesh hardware cloth, which provides durability when large rock clasts are routinely washed. The coarse screen is window-screen gauge (18 mesh); the gauge of the fine screen will depend on the minimum dimensions of desired fossils and on rock type. If a very high mesh screen is used, it will tend to clog readily with rock particles. We find 30 mesh to be most suitable for recovery of Mesozoic mammals; the tooth fragments that pass through it are generally too small to be of use. (Many important specimens do, however, pass readily through window screen, so that the fine fraction often contains more significant material than the coarse fraction. Indeed, the largest collection of North American Symmetrodonta, for instance, was recovered almost exclusively from 30-mesh screens.) On the other hand, if one wishes to recover smaller biologic remains, such as ostracodes, then use of a finer screen is warranted. In situations where it is unnecessary to recover fossils smaller than the openings in window screen, the fine-screen box can be simply omitted from the process. Both screens are aluminum; in cases where screen boxes are to be used in conjunction with acid or other agents, use



Figure 5. Microvertebrate quarry site in the Cedar Mountain Formation (Lower Cretaceous, upper Albian), Utah. Fossils occur in a bentonitic mudstone underlying an ash horizon (visible as a light band at approximately head height to the individuals in the photo). Because the fossils are both relatively complete and significant, an effort is made to recover them through quarrying: rock is split into small fragments and examined with a hand lens before being collected for later screenwashing.

of stainless steel screen (and other appropriate box parts, such as supporting screen), although more expensive, will be necessary. Drywall or deck screws are preferred as fasteners because they hold much better than nails or staples and can be readily removed, without damage to other box parts, in the event repairs are necessary (pre-drilling of the screen cleats is necessary to prevent splitting). The screen is secured on all of its margins; on the box sides, metal strapping prevents leakage of matrix and supports the broad wood pieces that form the sides of the box in the event repeated soaking and drying causes them to split. The spacing of the bottom cleats is such that boxes nest when stacked (Fig. 8), so that individual stacks are relatively stable.

Some investigators have successfully sieved matrix by using bags, either of burlap or mosquito netting (Grady, 1979; Tokaryk, 1986), in lieu of screen boxes. However portable and inexpensive, the utility of such bags in conjunction with claystone or consolidated rock is limited; their usefulness is further constrained by the diminutive size and fragile nature of many microvertebrates (particularly Mesozoic mammals). Kühne (1971) described a portable apparatus for screenwashing by the "Henkel process." This device has not achieved widespread use, perhaps because of the relatively small samples it is capable of

processing and because its success is dependent on matrix being weathered and relatively unconsolidated. Because the Henkel process utilizes a high-pressure spray to disaggregate rock, we are concerned about possible breakage of fragile fossils. In our view, the screen box remains the most useful tool for underwater sieving, and its versatility is broadened by use of a nested coarse-screen and fine-screen system. Whether the design presented herein is adopted or not, a standard pattern should be used so that box parts are interchangeable.

Setup for Washing

Traditionally, field-based screenwashing has been accomplished in locally available water bodies, such as streams or ponds (e.g., McKenna, 1962; Lillegraven, 1969). An advantage to this approach is that minimal auxiliary equipment is required. Additionally, if the water body is sufficiently large, concurrent soaking of matrix in all available screen boxes is permitted. Such water sources are not universally available, however (particularly in the arid West), and a number of practical considerations make this approach undesirable in many cases. The process of loading, unloading, and transporting boxes to and from water of sufficient depth requires considerable effort, and resultant lower-back stress—in many cases severe—makes this



Figure 6. Collection of rock matrix, for underwater screenwashing, from a fluvial overbank deposit, Smoky Hollow Member, Straight Cliffs Formation (Upper Cretaceous, Turonian), Utah. The site is poorly fossiliferous but was deemed important because of the stratigraphic interval represented. Though fossils are scarce, the matrix is an illitic mudstone that washes easily and is amenable to volume processing. Poor site accessibility dictated that sample bags be skidded downslope, a situation in which burlap is superior to synthetic material.

technique labor intensive (see McKenna, 1962, figs. 2, 4). Many fluvial sources fluctuate dramatically—in some cases catastrophically—in flow level, posing a hazard to equipment, samples, and personnel and requiring constant vigilance or special precautions (e.g., Lillegraven, 1969). Screenwashing in water-filled containers is generally a preferable alternative, because it reduces labor and lower-back stress and is adaptable to a far broader variety of local conditions and circumstances (Fig. 9).

Waters (1978) described a screenwashing operation based in bisected 55-gallon metal drums. Potential disadvantages to this system

are container availability (discarded drums are not now widely available because many contained toxic substances), the limited capacity of individual drums, and the fact that such a setup is not readily transported. Galvanized cattle tanks, widely available at moderate cost,² are generally satisfactory on each count. Tanks should be long and narrow (not round), permitting unrestricted screen-box access and tank elevation to working height. Dimensions may vary, but tank size should be chosen to make maximum use of available space for boxes. Although soaking time will vary according to rock type, two or three tanks with a collective capacity for 20 to 30 boxes will generally be adequate for the large-scale operation described below. The tanks should be fitted with large drains (approximately 1½-inch diameter; stoppers or threaded drain plugs work equally well) to permit draining of water-suspended clastic particles. A set of matching tanks is shown in Figures 10 and 11. The large tank can soak 16 screen boxes (double-stacked); the small tank, 8 screen boxes. The two tanks are fastened together with buckles for transportation and storage; when assembled in this fashion, they hold 32 screen boxes.

Although the use of metal tanks allows great flexibility in the location of the screenwashing setup, it necessitates some type of water-transfer system. The recommended solution is a portable, gas-powered "trash" pump, which is capable of passing particulate matter. Most such pumps are centrifugal, which means that they push water much better than they pull it. The pump itself will need to be located near the level of the water source. Most 3-horsepower centrifugal pumps are capable of pushing a 90-foot head of water, which gives great flexibility in selection of the screenwashing site. In addition to the pump itself, an intake hose of 20 feet and a minimum of 50 feet (and possibly much more) of exhaust hose are needed. The exhaust hose, which is collapsible and is available in 25-foot sections, is relatively inexpensive and takes little space; thus, it is advisable to have several extra sections (with a total length of 100 feet) in the event the water source proves to be more distant than anticipated. A foot valve (which prevents backflow), fitted over the end of the intake hose, is a worthwhile investment because it obviates the necessity for repriming the pump each time it is used.

As stated above, the use of the pump and metal-tank system permits great flexibility in water source and location of the screenwashing

²Tanks can be custom-made, at prices competitive with those of factory-produced models, by sheet-metal shops.

TABLE 1.—EQUIPMENT AND MATERIALS USED IN PORTABLE SCREENWASHING OPERATION

Item(s)	Use(s)
Galvanized cattle tanks (2 or 3, with total capacity of 20–30 screen boxes)	Screenwashing
Sawhorse brackets	Sawhorses to support screenwashing tanks at working height
Lumber: size (in inches), nominal 2 x 10 or 2 x 12; 2 x 4	Sawhorses, tank support, screen-box drying, water diversion, removal of vehicles from quicksand
Gas-powered, centrifugal trash pump	Filling wash tanks, buckets, water reservoirs
Pump accessories: foot valve, 20 feet of intake hose, 100 feet of exhaust hose (in 25-foot sections)	Pump operation
Sheet metal (medium gauge; 8 sheets, 4 feet x 4 feet or equivalent)	Drying washed concentrate, vapor shield and/or reflector under screen boxes, covering samples, miscellaneous
Plastic buckets (10–30, with capacity of 3–5 gallons)	Soaking matrix, rock-reduction experiments, pump priming, miscellaneous
Bed sheets (20, torn in half or quarters)	Drying washed concentrate
Duct tape	Miscellaneous
Cardboard boxes (20–100, approximately 6 x 10 x 12 inches)	Packing concentrate for shipment to lab
Heavy-duty paper tape, Ziploc bags, plastic trash bags	Assembly of boxes, packing concentrate for shipment to lab
Garden hoses and spray nozzles	Disaggregating wet clay lumps by spraying
Drum(s) or comparable containers (1–2, with 55-gallon capacity)	Water reservoir(s) for siphon-fed, field spraying system

operation (Figs. 9, 11). It is possible, for example, to exploit sources such as shallow cattle ponds (which may not be desirable because the water is commonly both fouled and highly ephemeral), very small yet nonetheless perennial streams (many stream beds, although dry at the surface, will produce a usable volume of water if a hole 1 to 3 m deep is dug), fluvial sources that are otherwise inaccessible because they are located in deep ravines, and streams that are susceptible to flash flooding but may serve as a source for a site above the high-water line, and so forth.

The screenwashing operation itself should be set on relatively level ground that is clear of brush and has a substrate low in clay (which tends to cause problems when wet). Smooth, bare rock is an ideal substrate, if a large enough level area can be found (Fig. 11). Vehicular access is required so that equipment, materials, and samples may be readily transported; if possible, the area should be at least 150 m², so that sufficient space is available for tanks, equipment, bagged samples, tarps with drying matrix, and drying screen boxes. The tanks should be set up adjacent to one another, so that boxes can be readily transferred from one to the other, and should have their drains facing downslope and away from the remainder of the operation, so that they can be readily cleaned. If necessary, a dike and

trench system can be dug to encourage outflow in the desired direction, and splash guards can be fashioned from scraps of lumber, metal, or flat rock. The tanks should be set to working height on sawhorses; rocks set under the legs will prevent their sinking into the ground under the tanks' weight. Because of the great weight involved when the tanks are full, care must be taken to assure that they are set on a planar surface, slightly tilted toward the drain; nominal 2 x 10 or 2 x 12 lumber (standard dimensions, in inches) should be used to support the tank bottoms. If integrity of the tank seams is violated, repair can be made with silicon caulk or duct tape, applied to the inside.

Washing Procedure

Rock should be thoroughly dried prior to washing. Waters (1978) described a method of drying on racks, which may be practical under semicivilized conditions. Unless individual bag samples must be kept separate (Waters, 1978), the most practical field approach is to simply spread samples on tarps (oil- or wax-impregnated canvas, although more expensive than the blue, green, or brown plastic variety, is far more durable and will not degrade in sunlight). Some consideration should be given to location of the various elements of the operation, because the matrix, like the screen boxes, will need to be placed near the

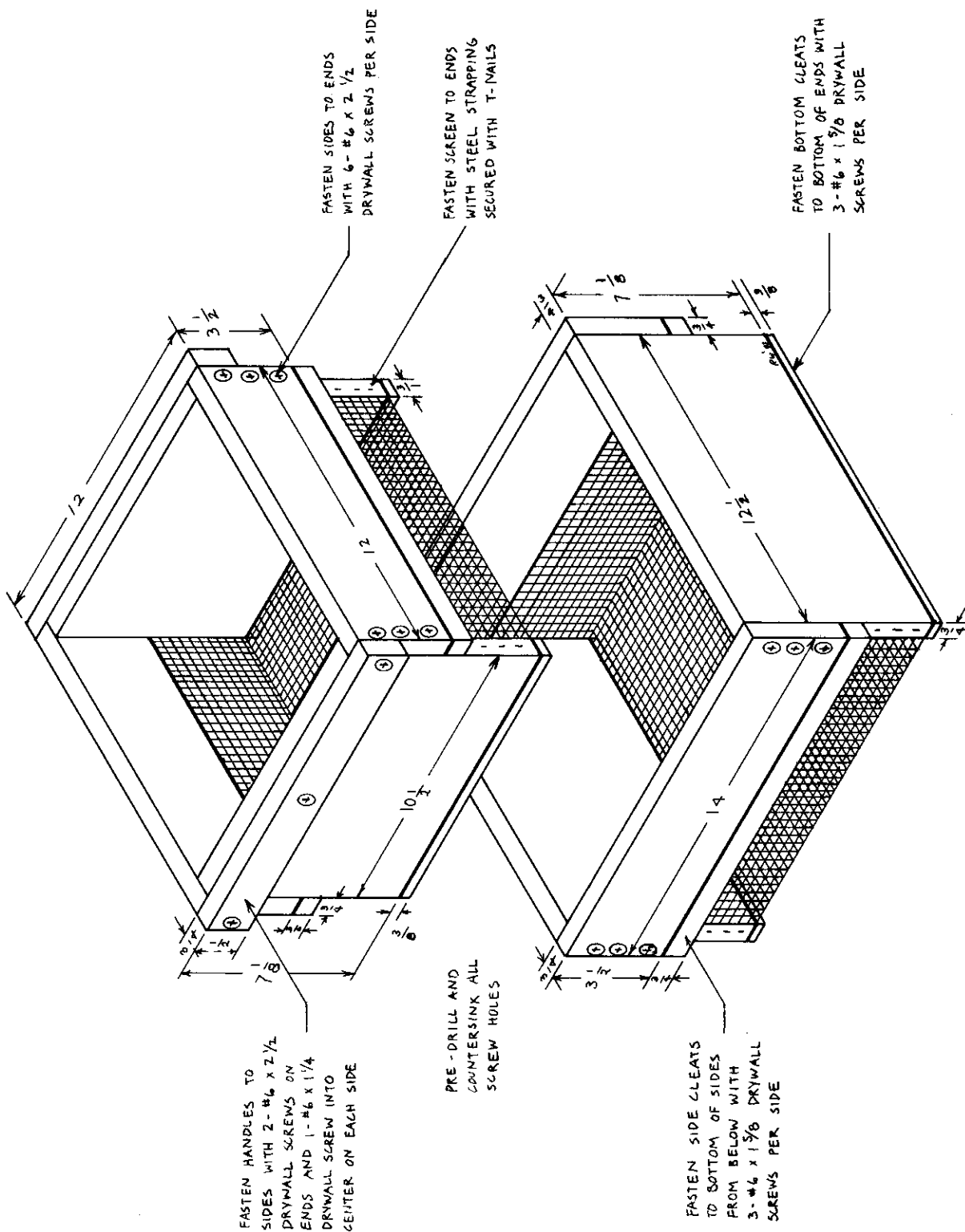


Figure 7. Plans for nested coarse-screen and fine-screen box system (shown with supporting 1/4-inch hardware cloth only). Hardware cloth and screen ends are folded and enclosed between box sides and side cleats. Boxes should be made of clear pine. Measurements are in inches.

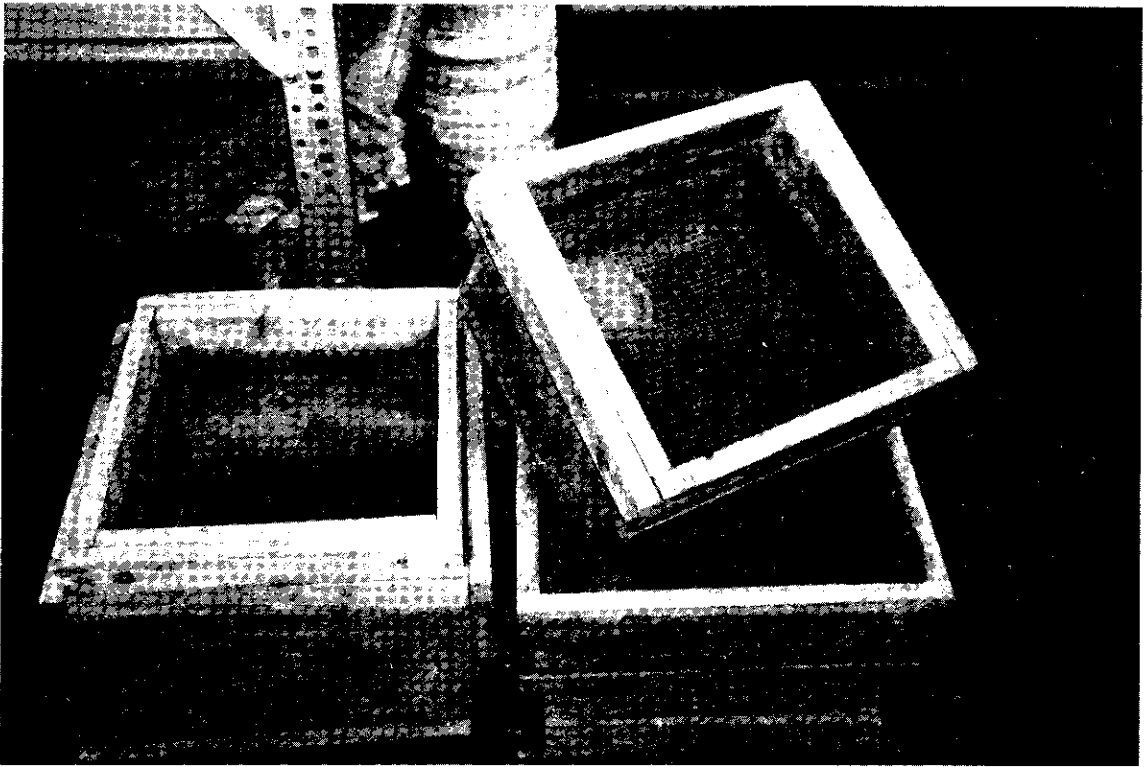


Figure 8. Stacked, nested screen boxes. Cleats on the bottom of the fine-screen (bottom) box fit underlying coarse-screen box, perpendicular to the handles.

tanks in order to minimize labor. Rock should be spread as thinly as practical; in general, 500 to 600 kg should be considered a maximum for a 10 × 12 ft tarp. The rock should be spread and dispensed into screen boxes either by hand or with an entrenching tool, to minimize potential damage to specimens; personnel should avoid stepping on the matrix. The sample tags on each sack of matrix are removed and simply placed with the rock itself. These tags will remain with the sample through the washing process and can be important in establishing identity of concentrated residue if, for some reason, locality information is improperly transcribed (or not recorded at all) when the samples are packed for shipping. The rock must be protected from moisture prior to washing, because prior disaggregation will greatly increase specimen damage as the rock is handled.

The amount of matrix placed in each box will vary according to rock type. For the boxes described herein, capacity ranges from 1.5 kg (for matrix high in expandable clays) to 5 kg. Similarly, soaking time required for disaggregation varies tremendously according to rock type. For consolidated samples, many illitic mudstones placed in warm water will require only 15 to 20 minutes; some siltstones may require 2 to 4 hours, and rock high in montmorillonite, which will disaggregate only under certain conditions (see below), may take 2 to 5 days. Although a few techniques are available to coax rock into disaggregating more rapidly, this high variability dictates application of

different strategies in order to maximize efficiency and minimize specimen damage.

If any doubt exists as to the "washability" of rock from a given locality, tests should be performed on small samples. For claystones, it is useful to have some means of testing water temperature, pH, and salinity. In addition, a scale will prove useful in measuring the reduction in weight through various trials, so that the success of alternative methods can be judged quantitatively. Disaggregation of different rock types, and strategies for efficient processing, are discussed in a separate section, below.

If prolonged soaking impedes the operation by tying up screen boxes and tanks (as commonly happens with fine-grained rocks), matrix can be soaked in plastic buckets (which, because of the relatively high surface-area-to-volume relationship, will permit more rapid heating under solar radiation) prior to washing, although this extra step increases the chances for breakage.

As with all steps in the operation, screen-box agitation should be done gently. Washing time can be greatly decreased by putting less rock in each box (this approach requires the use of more boxes for a given amount of matrix but, by the same token, the washed concentrate dries much more quickly). Movement of particles against each other and the screen should be minimized; as a general rule, if the washing is audible, it is too rough. A successful tactic for obstinate clumps of rock is to fully submerge the box and pull it swiftly upward without moving particles,

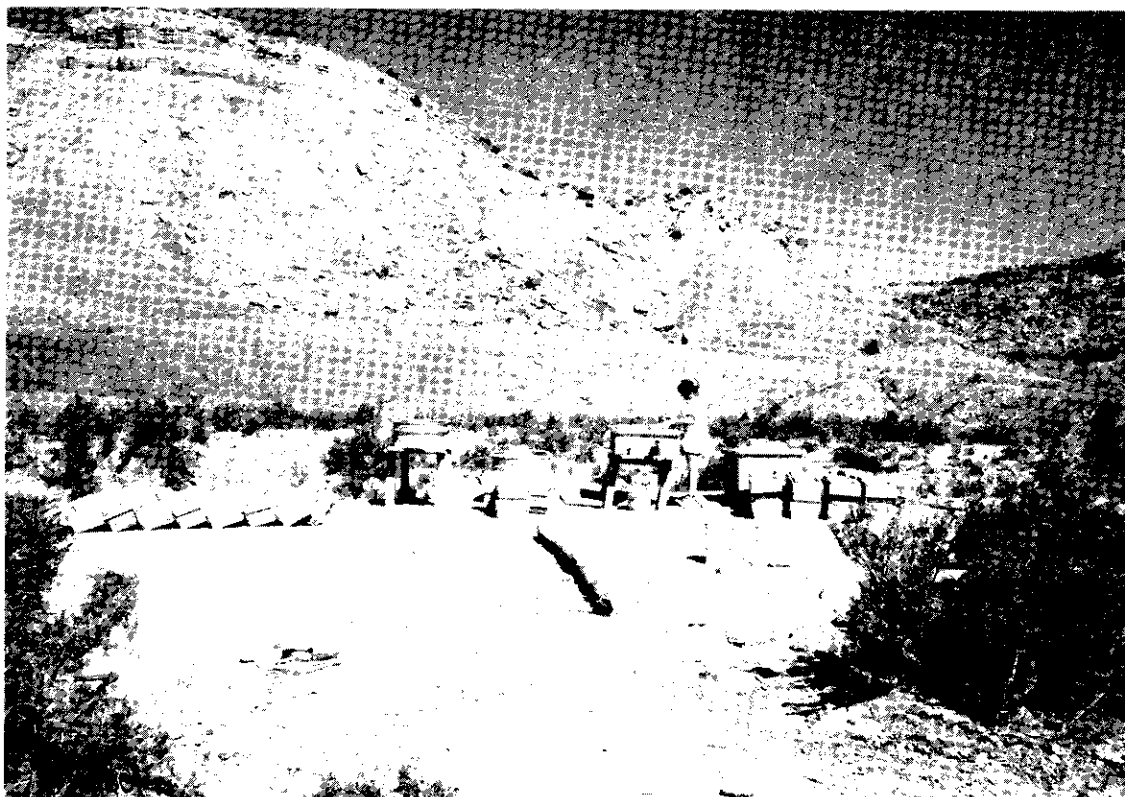


Figure 9. Field-based screenwashing operation, located adjacent to an ephemeral stream in central Utah. The apparatus is set up on a bench 4 m above the stream cut, keeping it away from the danger of flash flood, and water is brought up through a gas-powered pump. When the stream is dry, water is obtained from a hole dug into the streambed. Elevation of holding tanks permits washing at a comfortable height; after washing, boxes are propped against timbers, facing the sun, for drying.

thus disaggregating the mud with hydraulic action. Large, insoluble particles (concretions, crystals, rocks, macroscopic fossils, and so forth) should be removed as they are encountered, in order to lessen the likelihood of their breaking delicate microfossils. If nodules appear to be fossiliferous, they should be saved for further examination. Microfossils can be extremely fragile when wet and, for this reason, Waters (1978) advocated leaving them in the screen boxes. We believe that the risk posed by potential loss or breakage during screening and subsequent recovery operations outweighs this consideration, and we recommend immediate removal of significant fossils (with brush or forceps, if warranted). Vials and/or gel caps, together with other materials for treating fossils, should be available at the wash site, so that useful macroscopic fossils can be removed and placed in labeled containers (Madsen, 1996).

When the coarse fraction appears to be finished, the insert is removed, and the fine-screen box alone is agitated to finish screening the fine fraction. For the fines, repeated rocking motion of a tilted, partly submerged box produces a gentle yet effective wave action. Because the fine particles will often lodge partly in the fine screen or otherwise stick to it, the fines should be gently swished to the middle of the box prior to drying.

Claystones will often form muddy, almost gelatinous lumps at the bottom of screen boxes. Lumps should not be disaggregated manually, because of the detrimental effect hands have on delicate, wet microfossils. In general, this problem is greatly eased by putting less matrix in each screen box. If box agitation alone is insufficient to dissolve clay lumps, then the box may be raised and cups of water—dipped from the tank—may be poured over them. If clay lumps are a continuing problem, then it may be advantageous to set up a spraying system. The portable pump is far too powerful for this purpose; if running tap water is not available, then the most suitable substitute is a siphon system (Fig. 11). Water can be pumped into a holding container, such as a small, metal cattle tank or 55-gallon drum, and siphoned through garden hoses outfitted with spray nozzles set to a fine mist. A 1–2 m head is generally sufficient to produce adequate water flow. If continued spraying is needed, one of the wash tanks can be drained for this purpose, while initial box agitation is done concurrently in the other tank.

Periodically (after 10–15 cm of sediment has accumulated), the washing tanks will need to be cleaned. Unless water must be recycled, the most effective means of cleaning the tanks is to stir the sediment into suspension



Figure 10. Custom-made portable washing tanks. These tanks have a collective soaking capacity of 24 boxes; when fitted together for shipment, 32 boxes can be accommodated.

manually, so that all water and sediment can be expelled through the drain. When the tank is nearly empty, one end can be lifted to promote complete draining and cleaning.

Drying the Concentrate

The screen-box drying area should be located adjacent to the wash tanks in order to avoid excessive walking back and forth; smooth, bare rock is an ideal substrate for drying because it contains negligible moisture. Relatively straight, long timbers or similar objects are useful for leaning the boxes against, so that they are kept away from potentially adherent substrate particles and air flows freely beneath them. Ideally, each coarse-screen insert should be placed in its respective fine-screen box for drying, because particles will continue to rain from the coarse-screen box as it dries. Nesting the box pairs is seldom practical, however, because it greatly prolongs drying time. The boxes will be most stable if the fine-screen box is leaned against a propping timber, open-screen-side down (to promote runoff), and the coarse-screen insert stacked against it, with the screen cleat on the edge of the fine-screen box. In this fashion, four or more sets of boxes may be set for drying in series (Figs. 9, 11). This arrangement lends itself well to covering partially dry matrix in the event of inclement weather. If sufficient sheet metal is available, it can be placed under the boxes to promote rapid drying, because the metal acts as both a solar reflector and a vapor shield to substrate moisture.

Concentrate is transferred from screen boxes to quartered, cloth bed sheets.³ Boxes should not be emptied until the contents have dried as much as possible, so that adherence of particles (particularly the fine fraction, but also the coarse fraction in the case of many siltstones) is avoided. Coarse and fine fractions are emptied onto different sheets; care must be exercised in moving coarse-screen boxes so that fossils do not drop through the screen before the box is dumped. While working samples from a given locality, it is not necessary to completely clean each box; indeed, it is better to leave recalcitrant particles in boxes rather than risk destruction by sweeping them out. To avoid contamination, screen boxes must be thoroughly cleaned when a new site is being processed. Boxes can be swept clean with a whisk broom (the plastic variety is far more durable than that made from natural materials).

Screenwashed concentrate must be thoroughly dried prior to secondary processing or packing for shipment. In a field situation, the most rapid and effective means of drying washed samples is on sheet metal, of which several sheets 4 × 4 feet in size should be available for the purpose. The matrix-covered cloth sheets are laid in sunlight on the sheet metal, and the washed concentrate spread gently by hand with a plowing (not smearing) motion. Washed concentrate should not be spread unless adequate sunlight will permit drying the same day, so that repeated

³Available at nominal cost from second-hand stores.



Figure 11. Screenwashing operation in central Utah. Water is drawn from a plunge pool—in this otherwise dry setting—by a gas-powered pump (left in center distance) and transferred to portable tanks (center) and metal drums (upper right). The drums act as reservoirs for siphon-fed spray systems. Water is exhausted into the plunge pool and therefore is recycled. Boxes are set to dry on smooth, bare rock (center, foreground); sheet metal (right) is used for drying washed concentrate, covering matrix and boxes during inclement weather, and miscellaneous purposes.

spreading of the same sample is avoided. One corner of a cloth sheet may be tied in an overhand knot around the remaining three corners, thus forming a bag, so that it can be conveniently carried to overnight shelter or transported to another location for packing. Wetting of washed and dried samples must be avoided at all cost, and so they should be packed immediately, unless a second water wash in the field is contemplated.

Shipment Preparations

Although the fine fraction is packed for shipping “as is,” the coarse fraction should be dry screened prior to shipping. This procedure will reduce volume and microfossil breakage. We recommend a nested set of three sieves: ¼-inch hardware cloth, ⅜-inch hardware cloth, and 30-mesh aluminum screen. The coarsest fraction can be visually scanned in the field and discarded after fossils have been removed; the remaining two coarse fractions are packed separately. The method of packing will vary according to sample size; however, all samples should be placed in rigid containers and packed so as to minimize intraparticle movement. It is often possible to procure plastic buckets with tightly fitted lids, which serve as useful containers because they are both solid and watertight. However, a full bucket can weigh 40–50 kg, and if many are to be used,

they make inefficient use of space. An alternative is to use cardboard boxes whose dimensions are approximately 6 × 10 × 12 inches. These can be purchased, in volume (100 or more may be needed), from local paper supply companies; uniformity of size will facilitate shipping. Boxes can be stored flat and assembled as needed; they can be used repeatedly. Heavy paper tape is preferred over plastic or duct tape because it is both easier to use and more durable in field situations. Boxes are lined with plastic trash bags of appropriate size (small samples can be stored in Ziploc bags) and should be filled to the top, if possible. Identifying tags remain with the matrix itself; the exterior of each box is labeled with locality, date, particle size, processing data, and other relevant information. As filled boxes accumulate, they must be kept in a cool, dry place, out of the weather and direct sunlight.

SECONDARY MATRIX REDUCTION

Kerosene Washing

Kerosene and related petroleum distillates (such as diesel fuel, which is a more widely available alternative to kerosene) tend to be especially effective on fine-grained clastic rocks because they lack the surface-tension characteristic of water and thus readily penetrate even the small-

est interstices within clasts. Immersion of kerosene-soaked matrix causes rapid displacement of kerosene by water, resulting in disaggregation of the rock, provided that it is absolutely dry to begin with; samples can be dried in an oven if necessary (J. A. Lillegraven, personal communication, 1993). A kerosene operation must generally be set up at home base or under circumstances that otherwise provide for logistical requirements and environmental safety. A kerosene operation was described by Waters (1978); we add only a few points regarding kerosene soaking and recovery. Although kerosene is among the more innocuous of petroleum distillates, we recommend use of rubber gloves throughout the operation.

If kerosene soaking is employed as a secondary (rather than primary) method, as advocated herein, coarse and fine concentrate will already be separated. In general, far less matrix is added to each box than in an initial wash, because prewashed matrix will tend to be more expandable and colloidal than the original rock itself. The coarse fraction will require usage of nested screen boxes, whereas the fine-screen box alone is used for the fine fraction. Waters (1978) reported a kerosene soaking time of 15 to 30 minutes; our experience indicates that 30 seconds to 2 minutes is generally adequate. Prior to washing, the kerosene should be drained thoroughly from each screen box to prevent excessive buildup in the washing tank. Following matrix reduction through a combination of gentle box agitation and spraying, the box should be placed in a separate, water-filled container so that remaining kerosene, bits of vegetation, dead insects, and other debris can be separated from the concentrate (Waters, 1978). A plastic trash container of a size such that the screen box barely fits inside will allow it to be jammed in a submerged position for a short time. A hose providing a slow but continual influx of water to the trash can will cause most of the vegetation and residual kerosene to simply float off of its own accord; remaining detritus can be expelled with a swirling motion of the hand, just above the screen bottom.

As with a primary wash, drying is done in boxes; because a secondary wash with kerosene generally results in almost total reduction, drying time is usually negligible. Coarse and fine concentrate fractions are dumped onto cloth bed sheets; the coarse fraction should be dry screened, if warranted. Utmost care must be exercised in handling all concentrate: particles should be gently rolled or poured; they should not be allowed to drop from appreciable heights. The separate fractions are then transferred to suitable storage containers (coffee cans, Ziploc bags, etc.), upon which is recorded relevant field and sample data.

Acid Treatment

If rock to be acid-bathed has undergone an initial water wash, the coarse residue should be dry-screened through ¼-inch mesh. The different fractions are placed in plastic buckets⁴; fine matrix should not be more than 10 cm deep

because the acid will not penetrate well. Each bucket is filled with sufficient 10 to 15% acetic acid (Rixon, 1976) to cover all of the rock. Industrial-grade acid, which is adequate for this purpose, is considerably cheaper than laboratory-grade. The rock should be acid treated in a well-ventilated area (preferably outside, if many buckets are involved) and should be kept out of direct sunlight. The acid should be changed every few days; in any case, rock should not be left to sit for prolonged periods in degraded acid because crystallization of by-products (mainly salts) may cause fossils to shatter. After sufficient fine particles have accumulated to justify washing, the buckets are repeatedly flushed with fresh water and left to stand. All acid should be removed from the rock, to ensure that salts do not build up and the screen boxes do not have their iron-based screens rusted. If after several bathings the acid no longer is effective yet the particles are insufficiently disaggregated, accumulation of calcium or some other buffering agent is the likely culprit. Extended flushing in fresh water, followed by drying, will often facilitate further acid treatment.

ROCK COMPOSITION AND STRATEGIES FOR SCREENWASHING

Poorly consolidated rock, particularly when composed of silt- to sand-sized particles, will generally disaggregate readily when immersed in water. A primary concern for more consolidated matrix is sample hydration: the degree and speed of rock disaggregation is dependent on the speed and completeness of water penetration, which is inhibited by preexisting water content. Thus, most rock samples should be dried completely before washing. (Excessive humidity can rehydrate previously dried samples and impede washing, a factor that should be considered when contemplating removal of samples from an arid field area to a humid home base.) Except for sites that are being quarried to recover intact specimens manually, samples can be collected far more quickly than they can be washed. Thus, for a long-term project, it is advantageous to collect extra samples at the end of a given field season. These can often be stored locally, so that dry samples are immediately available at the beginning of the next field season, and washing can begin forthwith.

Indurated Samples

Rock composed of relatively coarse particles (sand-sized and larger) may be indurated with a cementing agent such as CaCO₃ (for discussion of treatment for other cementing agents, see references in Hannibal, 1989). The presence of carbonates can be judged with acid testing (HCl); preferably, a small sample can be placed in acid to judge its effectiveness on disaggregation. Because the effort and expense required to extract intact specimens from such matrix can be considerable, the importance and relative abundance of the contained fossils should be carefully considered. On the other hand, such matrix is sometimes tremendously fossiliferous, so that the effort required to extract specimens may be well worthwhile—particularly if the stratigraphic horizon being sampled is an important one. In terrigenous Upper Cretaceous units of the Western Inte-

⁴Three- to five-gallon buckets can be obtained free or at nominal cost from bakeries, grocery stores, and restaurants.

rior, for instance, microvertebrates may be locally abundant in partly indurated channel lag deposits. Depending on the degree of induration and the abundance of clayballs in the matrix, an initial water wash may serve to disaggregate rock and reduce its volume somewhat. However, it is generally not worthwhile to undertake this in the field if reduction by weight is less than 40%. This is because the slight savings in weight is greatly offset by the breakage that occurs as samples are handled and packed; because acid will, in any event, be required for reduction, the samples will generally be small. For partly indurated samples cemented with CaCO_3 , a combination of initial water washing, acid treatment, and kerosene treatment (especially if clayballs are an abundant rock constituent) should be used.

Siltstones

Many siltstones, although relatively free of cementing agents, are partly indurated, and underwater screening—even when matrix is broken into relatively small chunks and dry—results in insufficient reduction of volume. For instance, most siltstone samples from the Upper Cretaceous Kaiparowits Formation, southern Utah, lose only 40 to 60% of their original dry weight through a first water wash. In some cases, a second water washing (after thorough drying) is effective, particularly if clay content is high; however, in many cases, kerosene treatment is necessary. Whether a kerosene wash can simply replace (rather than supplement) an initial water wash varies according to unknown factors (although we suspect that particle size and clay content are involved). Waters (1978) described an effective method of kerosene treatment that bypassed an initial water wash. However, we have conducted controlled experiments on several Cretaceous siltstone samples and found that kerosene reduction, unless preceded by a water wash, produced no significant difference in ease of washing or in speed or volume of matrix reduction. Detergents and other wetting agents have apparently been successfully used in facilitating matrix reduction during underwater screenwashing (e.g., Clemens, 1965). We have undertaken controlled experiments using several wetting agents (e.g., Photo-Flo, Alconox, laundry and dish detergents) on a variety of rock types and observed no significant differences from straight water washing. The use of petroleum distillates and water additives, even where effective, pose logistical and environmental concerns, especially in field situations; thus, for a typical 1,800 kg rock sample, it may prove necessary to transport 800 to 1,000 kg to a site where kerosene may be used safely.

Fine-Grained Rocks

Clay Characteristics and Effects

The behavior of rocks composed predominantly of clays (e.g., claystone, mudstone, shale) will, when screen-washed, vary considerably according to the specific clay minerals, diagenetic alteration of sediments, and local conditions involved. Some mudstones high in illites, for example, will disaggregate readily, whereas bentonites (high in montmorillonites) usually will transform into unwash-

able, doughy masses when immersed in water. Maximizing efficiency of a screenwashing operation and obtaining reasonably complete vertebrate microfossils from such rock types depend on an understanding of clay structure and the conditions necessary for clay deflocculation. Useful information on clay properties is available in standard textbooks (e.g., Blatt, 1992).

Most of the clays encountered in terrigenous sedimentary rocks are three-sheeted aluminosilicates, composed of two layers of silicate tetrahedra sandwiching an aluminum-bearing octahedral layer. In montmorillonites (smectites), cation substitutions (mainly Mg^{2+} , Fe^{2+} , Fe^{3+}) occur in this octahedral layer, creating charge deficiencies in the center of each flake; in illites, on the other hand, cation substitutions (Al^{3+}) occur in the outer, tetrahedral layers. Individual clay flakes are bonded together by electrostatic forces: when charge deficiencies occur in the center of the flake, as in montmorillonites, the flake has less attraction to adjacent flakes; the opposite is true of illites. In addition, because of their numerous cation substitutions, individual montmorillonite flakes are more "defective" and tend to be much smaller than illite flakes. As a result of these attributes, montmorillonite clays are characterized by extreme colloidal behavior, hydrophilic tendencies, expandability, and impermeability. These features of montmorillonites—which render this clay type so useful for some commercial purposes (e.g., drilling mud, kitty litter) and which anyone who has prospected bentonitic horizons on a rainy day can appreciate—cause problems for the micropaleontologist. As a practical consideration, the large flakes of illites will allow a higher, more rapid degree of water penetration into rock than will those of montmorillonites.

Montmorillonites

If conditions are unsuitable for deflocculation of individual montmorillonite flakes, rocks containing these clays in appreciable quantities are practically unwashable. We recently encountered this situation in a bentonite sample from the Lower Cretaceous Cedar Mountain Formation in Utah. Our field-based washing operation, including four persons and about 100 screen boxes, is generally able to process 250 to 540 kg of dry claystone per day, with soaking time averaging 15 minutes to 2 hours. Larger clasts of this rock sample, however, would not disaggregate when soaked: those soaked even for several days still retained hard (and quite dry) lumps in the middle. Smaller clasts, and the outsides of larger clasts, transformed into gelatinous to doughy lumps, which required much agitation and spraying to reduce. Productivity for this site averaged a scant 35 to 40 kg per day. Furthermore, the increased level of energy needed to successfully break down the matrix, coupled with the fact that fossils from this unit are fragile and suffer much damage from swelling action of the clays alone, resulted in a very low yield of morphologically informative specimens because of breakage.

Fortunately, the flocculating behavior of clay is well understood, and, armed with proper strategies, the screen-washer can successfully tackle even the most obstinate bentonite. Clay flocculation is dramatically influenced by salinity, which increases the electrostatic charges of adher-

ing flakes: salinity above 2,000 ppm will assure flocculation. Clay flocculation is also affected by temperature: with increasing temperature, water becomes less viscous and penetrates better; electrostatic bonds of adhering particles are reduced. Under certain conditions, pH can also affect clay flocculation, because free hydroxide ions (OH^-) will bond with various cations (noted above) present in clays. We have found that addition of calcium hydroxide (lime) or potassium hydroxide to a soaking solution facilitates disaggregation of some claystones; however, if effective, it generally results in precipitation of unwanted by-products.⁵

Temperature and salinity, at least, can be important factors in a field or laboratory screenwashing operation. In the example cited above, the water source was a highly saline, cool plunge pool in an ephemeral stream—conditions unfavorable for deflocculation. The remainder of the sample was transported to home base, where a screenwashing operation was set up in a local pond. The lack of salinity and the availability of warm water resulted in deflocculation of all clay flakes and complete disaggregation of the rock, which “washed itself”—no agitation or spraying whatsoever was required—provided that it was soaked for a sufficient time. Soaking time varied according to water temperature: at 24°C, complete matrix reduction took 5 days, whereas at temperatures approaching 30°C, reduction occurred in 2½ to 3 days, or half to 60% of the time required at the cooler temperature. In this case, the problems and expense posed by long-distance transportation of bulk rock samples were more than counterbalanced by the dramatic reduction in both specimen breakage and labor investment, because agitation, spraying, and secondary water or kerosene washes were unnecessary.

The expandability of montmorillonites and the special conditions required to disaggregate rocks composed of such clays have important implications for screenwashing strategy. The prolonged soaking period implies that a large number of screen boxes must be used to process any appreciable quantity of matrix; soaking in buckets is not a satisfactory alternative in this case, because of the additional specimen breakage involved and because, with the rock touching the bottom of the bucket, the rock's wettable surface area is reduced. A washing area meeting temperature and salinity conditions must be large enough to accommodate concurrent soaking of every available screen box, and sufficient time must be available to process the entire sample. It may be possible to meet these conditions

in the field area, but, as in the example given above, it may be most efficient to transport rock to a location where conditions are suitable and the operation can be monitored for an extended period (which may be two or more months for many samples). The logistical problems of reducing montmorillonite-rich rock are somewhat offset by the following factors: full reduction is achieved in a single wash, little or no spraying or agitation is required, secondary concentration techniques generally need not be used, and very little labor is involved in the processing itself.

Illites

Most illitic claystones are far easier to process: initial water washes generally result in reduction of 60 to 95% or more by weight, so that washed samples can be transported without difficulty, and soaking time is usually negligible, even if the water is cold. In general, claystones will respond to a second wash in plain water far better than will siltstones. The effectiveness of a second wash can be tested with a small sample (if circumstances permit, a similar sample can be processed with kerosene, and the results compared). If a second water wash is effective, it is usually extremely effective; for reduction of less than 80%, the concentrate should probably be set aside for kerosene treatment.

Although it has been established that diagenetic processes result in the eventual conversion of montmorillonite clays to illites, the specific mechanisms and processes involved, and the subsequent history of some of the daughter products, are poorly understood (e.g., Blatt, 1992). The conversion involves addition of K (possibly from alteration of feldspars) and $\text{Al}(\text{OH})_3$ to montmorillonite, which yields illite, SiO_2 , Na, Ca, H_2O , Fe, and Mg. We point this out because silicified nodules are often encountered when washing illitic claystones, and we suspect that these nodules are the result of diagenetic conversion of montmorillonites to illites and the localized concentration of one of the daughter products, SiO_2 . Whatever the source of these nodules, they cannot be disaggregated by conventional means, and it is likely that any effective agent, such as hydrofluoric acid, would destroy the contained fossils. We recommend extraction of these nodules manually and/or through dry screening. If they are deemed worthy of further examination, they should be transported to a laboratory setting, where they can be split (as necessary) and scanned under a magnifier; significant contained fossils should be manually prepared.

CONCENTRATION TECHNIQUES

Many samples, even if thoroughly washed, will still contain a high proportion of inorganic residues and non-vertebrate fossils. If a sample is relatively large and its fossil content correspondingly low, it may not be cost-effective to pick it as is. If the sample contains small clasts of consolidated rock, it is well worth attempting to find means of disaggregating these, prior to implementing separation techniques. This situation is commonly encountered with siltstone, even after it has been washed and treated with kerosene. Often, the rock particles are cemented with CaCO_3 , in which case acid treatment, followed by rinsing

⁵We have conducted recent experiments with two additional agents commonly used by potters to deflocculate clays. The composition of the first, Darvan 7, is unknown to us, although it behaves somewhat like a wetting agent. We found it ineffective in deflocculating montmorillonite. The second, soda ash (Na_2CO_3 ; a salt commonly used to adjust pH in swimming pools and widely available, at moderate cost, at pool-supply stores), worked astonishingly well on montmorillonite. The pH of working solutions appears to be about 11, so that it appears to be relatively safe when used in conjunction with rubber gloves and other protective clothing. This agent appears to show great promise for reducing bentonitic claystones, and experimentation with it is highly recommended.

and washing, can dramatically reduce sample volume. In other cases, hydrogen peroxide (Carpenter, 1981) at concentrations up to 10% will disaggregate otherwise indurated and insoluble rock particles.

Several techniques, which take advantage of the unusual characteristics of fossil bone or of most unwanted residues, are available to further concentrate samples. Whether these procedures are implemented, and which method to use, depends on a number of factors including overall sample size, cost, nature of the residues to be removed, and availability of proper lab equipment, facilities, and trained personnel. All available concentration techniques add extra steps to the process of fossil extraction and therefore will result in some specimen attrition through physical damage or loss; some methods are costly, and some are hazardous. Unless these negative factors are offset by a substantial savings in labor costs, concentration techniques should not be employed.

Interfacial Concentration Method

One approach, the "interfacial method" (Freeman, 1982) exploits the tendency of fossil bone and other organic materials composed of calcium phosphates to be lipophilic (Merrill, 1985). Several variants of the technique have been described; in its simplest and most practically applied form (procedure B of Freeman, 1982, p. 472), kerosene, emulsified in a detergent-water solution, coats calcium phosphate particles, which in turn adhere to a paraffin wax substrate for which kerosene is a solvent (Merrill, 1985). Tests of this technique, involving recovery of both microvertebrates and conodonts from concentrates with a variety of undesirable residues (including quartz grains), have produced results that are noteworthy in terms of both the specificity of separation and the ease with which it is accomplished (Freeman, 1982; Merrill, 1985). Unfortunately, our experiments with the technique have not been successful. However, as a potentially inexpensive, precise, and easily implemented technique that is applicable to large samples, the interfacial method merits wide visibility and further experimentation.

Concentration Techniques Utilizing Differences in Specific Gravity

Most of the remaining concentration techniques take advantage of the difference in specific gravity (or density) between bone and most unwanted residues in the sample. Bone and similar hard tissues are largely composed of hydroxyapatite, which has a density of 3.1 to 3.2 g/cm³ and thus is relatively heavy (although most individual fossils are lighter than this because they contain pores and other vacuities). By contrast, many unwanted residues in a microvertebrate concentrate, including lignite (1.0–1.8 g/cm³), gypsum (2.32 g/cm³), and feldspars (2.5–2.6 g/cm³), are relatively light; quartz (2.65 g/cm³) is somewhat heavier.

Samples that contain unusually high proportions of basaltic lava fragments or heavy minerals (e.g., zircon) are not amenable to separation on the basis of specific gravity. However, some heavy minerals may be removed with magnetic separation (Dow, 1960); pyrite may be so sepa-

rated following oxidation (Merrill, 1980).⁶ One density-based technique involves use of a water column that, through adjustment of flow velocity, suspends and floats off lighter particles (Kietzke and others, 1985). We have experimented with this method and have been unable to separate even very light residues such as lignite.

By far the most common method for concentrating fossils is heavy-liquid separation, whereby the specific gravity of a relatively heavy liquid is adjusted so that fossils sink and unwanted residues float, or vice versa. This technique, pioneered by micropaleontologists to recover Foraminifera (Carson, 1933, 1953; Gibson and Walker, 1967), has been successfully applied to recovery of microvertebrates from various rock units (e.g., Kermack and others, 1965; Clemens and Lees, 1971; Murry and Lezak, 1977).

Brominated Hydrocarbons

A number of liquids have been used, including carbon tetrachloride and methylene iodide (the former being extremely hazardous and the latter prohibitively expensive for use in a large-scale operation), but the most commonly used are the brominated hydrocarbons dibromoethane, tribromoethane (bromoform), and tetrabromoethane, either diluted with a solvent or in combination (i.e., dibromoethane with tetrabromoethane; Kermack and others, 1965). Unfortunately, the health and/or fire hazards posed by these liquids, and the solvents commonly used in conjunction with them, are considerable.⁷ In view of the facts that heavy-liquid separation is often a messy process, that accidents are inevitable despite care and precaution, and that such lab work is commonly done by students, temporary assistants, or poorly informed researchers (rather than trained, professional technicians) under less than ideal circumstances, we do not consider use of such chemicals as a generally viable option, and we strongly discourage their use.

Sodium Polytungstate

The most recent heavy liquid to enter the arena is sodium polytungstate, a form of sodium metatungstate. This substance is soluble in water, can be used at densities up to 3.1 g/cm³, is relatively neutral in pH, and is widely represented as posing no known health problems (Chaney, 1986; Krukowski, 1988; Harris and Sweet, 1989). Solubility in water and safety considerations alone make sodium

⁶We have not encountered abundant magnetic minerals in our samples; however, J. A. Lillegraven (personal communication, 1993) reported to us that sideritic particles are common contaminants and that they can be effectively removed by using magnetic separation techniques—often eliminating the necessity of heavy-liquid processing.

⁷Tetrabromoethane, for instance, is listed by a recent materials safety data sheet (MSD) as being highly toxic, with an exposure limit mandated by the U.S. Occupational Safety and Health Administration (OSHA) of 1 ppm (14 mg/m³) over an 8-hour period. Merrill (1985) cited Brem and others (1974) as indicating tetrabromoethane to be a confirmed carcinogen, although it is not officially recognized as such. Nonetheless, MSD sheets indicate that it is tumorigenic and mutagenic.

polytungstate a favorable candidate for heavy-liquid separation, although it should be pointed out that relatively little is known about its health effects.⁸ Thus, despite the reputation of sodium polytungstate as a "safe" heavy liquid (Chaney, 1986; Harris and Sweet, 1989), we urge caution and, as with other heavy liquids, advocate use of a fume hood and protective clothing.

Sodium polytungstate has been highly successful in separating large, platform conodonts (Krukowski, 1988), and our tests have shown it to be very effective for microvertebrates as well. Some researchers (Savage, 1988; Harris and Sweet, 1989) have reported slow separation at high densities, because of increased viscosity. Distilled water should be used, because sodium polytungstate can react with common constituents of tap water, resulting in salt precipitation. By the same token, use of this liquid in conjunction with matrix capable of introducing calcium cations (e.g., incompletely acidized samples of rock cemented with carbonates) into the solution will cause salt precipitation and degradation of sodium polytungstate.

The major shortcoming of this compound is its great expense, which, for large-scale operations, may place it beyond the means of all but the best-funded projects. Moreover, sodium polytungstate is susceptible to dehydration and crystallization if excessive or prolonged heating is used to restore it to working density, and we know of no method to place it back in solution. Vigilance in recovering this liquid is essential: because large volumes are generally used in microvertebrate operations, inattentiveness can lead to the loss of several hundred dollars' worth of sodium polytungstate at one time. The use of this liquid has been discussed by Krukowski (1988; see also Harris and Sweet, 1989, and references therein); adaptation to recovery of microvertebrates is treated below.

Zinc Bromide

Zinc bromide, which is also soluble in water, is a salt that can be used at densities of up to about 3.0 g/cm³. As a relatively inexpensive heavy liquid that poses some health risks but is not nearly as dangerous as the brominated hydrocarbons, this substance is useful for very large samples or where cost otherwise precludes use of sodium polytungstate. The toxicological properties of zinc bromide are poorly known; there are no known chronic (cumulative) effects, and available MSDs include the nebulous disclaimer that its acute effects "may be harmful." Under extreme heat, zinc bromide may yield hydrogen bromide gas as a hazardous decomposition product. Thus, this solution should be kept under a fume hood and carefully monitored when heat is applied to it. Zinc bromide is kept in solution with hydrobromic acid. Although we have encountered no obvious examples of fossil etching or corrosion, the potential effect of the acidic pH of this solution should be considered. By the same token, zinc bromide solution will react

(sometimes violently) with matrix containing CaCO₃. As a result of this reaction, the pH is altered such that zinc bromide will precipitate from solution. There is no practical method to rejuvenating the solution, because calcium acts as a buffering agent; thus, zinc bromide should not be used in conjunction with carbonate-rich matrix. Because the solution is acidic, use of plated or non-stainless steel metal ware should be avoided.

Setup and Concentration Procedures

Heavy-liquids operations designed and described by micropaleontologists (e.g., Gibson and Walker, 1967) generally involve separation in a funnel or flask outfitted with a stem and stopcock or tubing and clamp system, through which the heavy and light fractions are sequentially drained after separation has occurred. This system is not generally practical for recovery of microvertebrates because of the vastly greater quantity of matrix involved, although a scaled-up version has been designed and successfully implemented by Murry and Lezak (1977). For large quantities of matrix to be concentrated with either zinc bromide or sodium polytungstate (but not brominated hydrocarbons), we think that the following system (based on that described by Reynolds, 1983) is simpler and more efficient (equipment and materials are listed in Table 2). Using this system (Fig. 12), an individual can process 30 kg of concentrate in an afternoon, and the operation could be scaled up further if necessary. For all heavy liquids, operations should be conducted in or in front of a fume hood, and protective clothing (rubber gloves, apron) and eye protection should be used. Because it contains bromine, zinc bromide is a hazardous material and should be disposed of as such.

The heavy liquid is adjusted to a working specific gravity by adding or evaporating water to or from it. "Working" specific gravity, which will vary considerably from one fossil locality to the next depending on the residues to be removed, is determined empirically, on the basis of a small sample. For most situations, an initial specific gravity of 2.5 to 2.6 will be appropriate. A sample of the heavy liquid is poured into a graduated cylinder (250 cm³ is a useful size), and specific gravity is checked with a hydrometer (if a hydrometer is unavailable, specific gravity can be estimated by observing the buoyancy of mineral samples or other items of known density). The specific gravity should be checked while the liquid is at working temperature. The test sample should be run as indicated below, and the float checked for fossils. If an unacceptable level of fossils occurs, the specific gravity of the liquid will have to be lowered. "Acceptability" is determined by importance of the sample and by practical considerations. If the sample is extremely large and contains a high proportion of relatively heavy residues, the loss of a few fossils may be more than counterbalanced by the savings in time and the high specimen yield resulting from mass processing. On the other hand, if the sample is relatively small and of exceptional significance, the potential loss of any specimens may be undesirable.

The working heavy liquid is poured into one or more separation containers. These containers should be trans-

⁸There are no OSHA exposure limits, but the American Conference of Government Industrial Hygienists recommends inhalation of no more than 1 mg/m³ during an 8-hour period (see comments on tetrabromoethane, above).

TABLE 2.—EQUIPMENT AND MATERIALS USED IN HEAVY-LIQUID SETUP FOR FOSSIL CONCENTRATION

Item(s)	Use(s)
Equivalent of 5-L heavy liquid (ZnBr ₂ or sodium polytungstate) at density of 2.6 g/cm ³	Separation of fossils from unwanted residues
1,000-mL beakers (6)	Containers for heavy liquid during separation
250-cm ³ graduated cylinder	Container for checking density of heavy liquid
Hydrometer with calibration range of 2.0 to 3.0	Determining density of heavy liquid
Plastic soup ladle	Transferring heavy liquid from casserole dishes to beakers and graduated cylinder
Ring stands (2) and rings	Holding funnels while matrix and fossils are being washed
Ladle fashioned from 30-mesh stainless steel screen	Removal of floating residues from heavy liquid
Heat-resistant casserole dishes (2), 4-L capacity	Recovery of heavy liquid after dilution during washing
Hot plates (2)	Evaporation of excess water from heavy liquid
Large plastic or glass funnels (2)	Washing fossils and residue
Screen (30-mesh stainless steel) funnel liners (2), homemade	Washing fossils and residue
Plastic squeeze bottle	Washing fossils and residue
2-gallon plastic bucket or equivalent	Recovery of diluted heavy liquid after washing
Sieving screen or screen box lined with 30-mesh (or finer) screen	Drying fossils

parent and large enough to permit removal of the float; 1,000-mL beakers are suitable. Matrix is added and gently stirred in. The matrix should be allowed to settle and then stirred again several times, to minimize specimen flotation due to rafting on or adhesion to light particles. If the difference in specific gravity between fossils and most of the residue is great, and if the liquid is of proper density, a clear separation should be apparent in a few minutes. If the difference is slight, however, separation may take several hours, in which case the utility of the method will depend on factors such as sample size, importance, and so forth. Our experience suggests that use of heavy liquids at densities greater than 2.6 g/cm³ is seldom worthwhile, because of the great time required for separation, greater frequency of fossils in the float, and poor separation in general. The float is gently ladled off the surface (a ladle may be fashioned from 30-mesh stainless steel screen) and placed in a funnel lined with a 30-mesh stainless steel screen. In turn, the funnel is supported by a ring stand over another beaker. The heavy liquid should be returned to use prior to washing and recovery of heavy liquid adhering to the particles. As float accumulates in the screen-lined funnel, it is washed with distilled water expelled from a squeeze bottle; the water and heavy liquid drain into a recovery container (such as a plastic bucket; the size and nature of the container will depend on the volume being run). The cleaned float should be occasionally spot-checked for fossils, even after the working specific gravity

of the heavy liquid has been determined, prior to disposal. In most cases, the fossils and other heavy particles will constitute a minor fraction of the sample, so that a number of runs may be done in each separation container before it is necessary to recover the heavy fraction. After removal of the float, the heavy fraction is gently agitated into partial suspension and simply poured through another ring stand-funnel-screen-recovery container system. Particles adhering to the inside of the separation container should be coaxed out with a spray of distilled water, because physical removal with a spatula or other implement will result in specimen damage. In practice, it is most efficient to stockpile diluted heavy liquid and continue running the operation until the supply of heavy liquid at working specific gravity has been exhausted, because evaporation of excess water from the diluted solution is time consuming. The diluted heavy liquid (recovered from washing the matrix) is placed into containers for readjustment to working specific gravity; semitransparent Pyrex casserole dishes of appropriate volume are suitable for this purpose. Water can be evaporated by placing these containers on hot plates within a negative-pressure fume hood. Zinc bromide solution can be boiled, although a timing device should be used to avoid excessive water loss unless the solution is carefully monitored. It is generally preferable to use low heat over an extended period of time (e.g., overnight). As noted by Krukowski (1988), sodium polytungstate is very susceptible to dehydration, so that

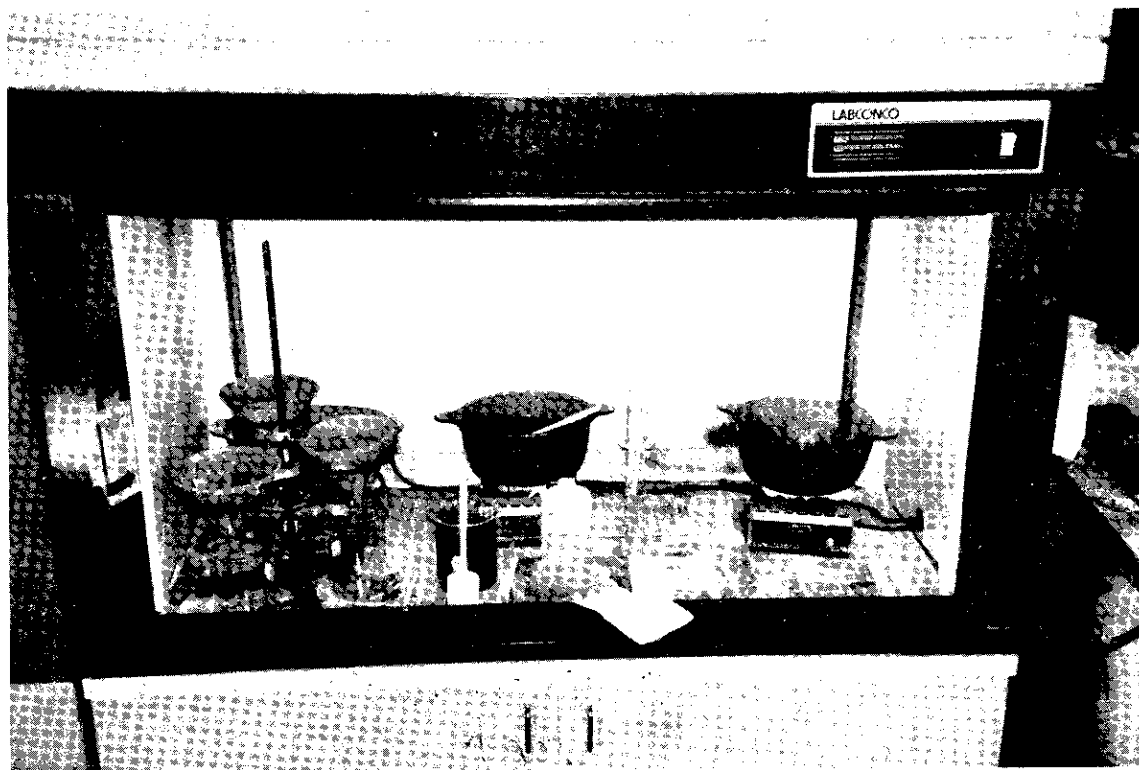


Figure 12. Heavy-liquid setup for fossil concentration. All operations are conducted under a negative-pressure fume hood. In the left foreground, a ring stand holds three plastic funnels, each lined with a filter fashioned from fine (30-mesh) stainless steel screen; heavy liquid is recovered in 1,000-mL beakers, below the funnels. In the background are three hot plates, each with a large, Pyrex casserole dish used for evaporating water from diluted heavy liquid; the dish in the center contains heavy liquid at working specific gravity (note plastic ladle, used for transfer to beakers). In the foreground, left center, a beaker contains heavy liquid at working specific gravity, ready for use; a rubber spatula, leaning against the beaker, is used to stir concentrate. In the center foreground is a plastic squeeze bottle containing distilled water, used for cleaning fossils and "float" after separation in heavy liquid. At the right center, middle ground, is a graduated cylinder containing a hydrometer, used for determining specific gravity of the solution.

low heat should be used and the solution carefully monitored.

Following initial wash, the funnel containing the heavy fraction should be thoroughly washed under a constant, low flow of tap water for one-half hour. The simplest method of drying large samples of the heavy fraction is to place them in a small, low-walled screen box with 30-mesh or finer screen (e.g., the fine-screen box from a set of dry screen boxes, or a standard, brass separation sieve) under a heat lamp.

After repeated use, the heavy liquid will become contaminated with fine particulate matter, especially if the samples contain appreciable quantities of lignite. Much of this material will settle if left undisturbed in the recovery container. After decanting off the clean fraction, the remainder may be gravity-filtered by using paper coffee filters (laboratory filters are generally unsuitable because the finer pores clog readily and an aspirator or filter pump is usually required).

Degradation of sodium polytungstate results in dehydration and the precipitation of salts (Krukowski, 1988), so

that with many runs, a progressively smaller percentage of the original volume is usable. As zinc bromide solution is degraded, it progressively becomes less stable and more apt to precipitate as salt (particularly at high specific gravities) unless kept at high temperatures. As a result, it becomes progressively more difficult to keep the solution at proper working specific gravity, and the solution must ultimately be discarded.

FOSSIL EXTRACTION

Following coarse screening and, where appropriate, concentration of fossiliferous matrix, the separate fractions are scanned visually and the fossils removed. In all cases, a sorting tray marked with a grid should be used, in order to assure uniform coverage. Such trays are available commercially or can be fashioned from other items (cf. Waters, 1978; Harris and Sweet, 1989). We find large trays with low sides to be most versatile (Fig. 13). These are readily made by applying white paint to the inside of an aluminum cake pan, about $11 \times 7 \times 1$ inch. The finish should be matte or flat to reduce glare and to permit easy marking. A



Figure 13. Fossil-sorting tray made from a painted cake pan. Grid lines are drawn every 1 to 2.5 cm inside the pan. Concentrate should be spread as thinly and evenly as possible.

grid system, 1 to 2.5 cm square, should be marked on the inside surface of the pan. The actual dimensions of the grid are not critical, so long as it is possible to see the borders of each square when viewed under magnification. The grid should be keyed with a system of arrows, which permits the scanner to continue work on a tray of matrix after an interruption or intermission. Some individuals scan matrix more comfortably along columns than rows, so each tray may be individually customized. In addition, labeling the rows and columns with an alphanumeric system (such as that commonly provided on road maps) may also prove useful.

The coarsest fraction (that which did not pass through $\frac{1}{4}$ -inch mesh) can be scanned with the naked eye; magnification should be used for all other fractions. An illuminated magnifier works well for particles $>\frac{1}{8}$ inch and $<\frac{1}{4}$ inch in size; smaller fractions should be scanned under a binocular microscope (Fig. 14). The microscope should have a zoom adjustment; picking is generally done at a magnification of $10\times$ to $14\times$. In order to accommodate the large picking tray described above, a boom mount for the microscope will be necessary. Adequate lighting is important; a twin-piped fiber optic light system is most adaptable. As discussed by Waters (1978), a brush (size 0 to 5/0) and watchmaker's forceps (or those used for microsurgical procedures) are the most useful tools for handling fossils. Small containers of water should be available for wetting brushes. Fossils (Fig. 15) are sorted into separate vials as they are picked; the number of sorting categories

will depend largely on the individual locality being picked and the experience of the sorter.

The time invested in training and supervising new assistants is well rewarded by fossil returns. A comparative collection of commonly encountered fossils (and pseudo-fossils—"fools' bone"), together with xerographic copies of figures from the literature, should be available. For Mesozoic mammals, scale models are useful in demonstrating analogues of given fossil specimens and in giving fuller depictions of the taxa in question. In this fashion, assistants with little anatomical background can rapidly become proficient in identifying the bulk of microfossils encountered. A new assistant should be instructed to save the matrix after scanning it; this matrix should be spot-checked frequently by an experienced individual. (For extremely important localities, it is sometimes useful to save all of the matrix for picking a second time; important specimens often have one "bad" side and can readily be overlooked.) An unacceptable level of fossils in the "dump" can result in several ways. The most common of these is the matrix simply being scanned too rapidly and superficially. A second problem is the tendency of many individuals to put too much matrix in the tray. Matrix should be sprinkled uniformly and sparsely throughout the tray; particles should not be piled on top of each other, nor even concentrated too closely together (Figs. 13, 14). Finally, a bad practice that appears to develop convergently in many laboratories is the related habit of stirring matrix with forceps while scanning an overloaded tray, in the mistaken

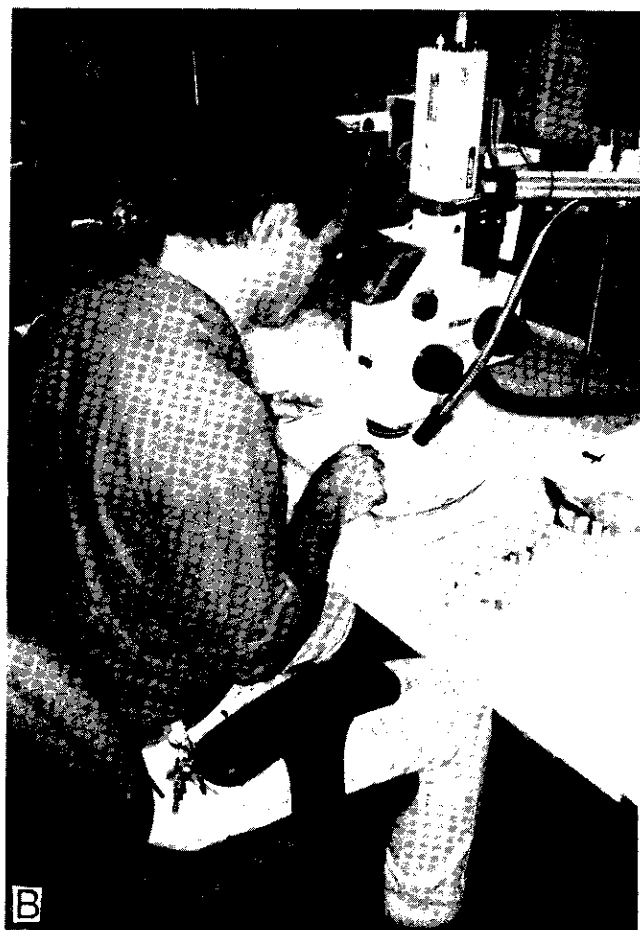


Figure 14. Picking concentrate under a binocular microscope. (A) Adequate light, supplied here by fiber-optic light pipes, is essential. (B) The microscope is mounted on a boom (right) to permit unrestricted tray movement. The tray is scanned systematically by using the grid system in the pan (left); fossils are sorted into vials mounted into a wooden vial tray (right).

belief that this technique will permit recognition of a noteworthy fossil from within a densely packed concentration of particles. If several individuals are picking concurrently, as is common for large-scale operations, it is advisable to monitor the process carefully: enthusiasm in the work is generated by interest on the part of the researcher or professional technician; and bad practices will spread like viruses if they are not immediately corrected.

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Figure 15. Fossiliferous concentrate, viewed under magnification. The concentrate is from the Cedar Mountain Formation (Albian) and shows some of the fossils typically encountered in Cretaceous terrestrial microvertebrate assemblages of North America: a, fish scale; b, crocodile teeth; c, reptile vertebra; d, lizard jaw; e, theropod dinosaur tooth. The lizard jaw (d) is about 3 mm in length.

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Some Techniques and Procedures for Microvertebrate Preparation

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ABSTRACT.—Microvertebrate specimens are generally prepared under a microscope, often under very high magnification; small errors in preparation can be catastrophic and, because procedures are often irreversible, advance planning is important. Herein I describe a micropreparation setup and the various tools, materials, and equipment needed to undertake common procedures. Glues, which are used for both specimen consolidation and repair, constitute an especially important aspect of micropreparation; polyvinyl butyral resins, polyvinyl acetate resins, and cyanoacrylates are recommended.

Field consolidation should be done only if necessary to avoid specimen disintegration, and consolidant should be applied sparingly; often, a consolidant or glue applied to the rock matrix, rather than to the specimen itself, is advisable. In the laboratory, glue can be applied to minute areas by using forceps, a needle, or a piece of fiber; because of the unforgiving nature of microvertebrate fossils, it may be useful to practice the procedures beforehand. For repair of small fossils, pieces can be manipulated with a moistened brush. Bases or pedestals, fashioned from modeling clay, can be extremely useful in positioning small fragments for reassembly.

Some situations (e.g., fossils too delicate to handle or to prepare completely; areas of fossils needing special support) require use of an artificial matrix, for which polyethylene glycol is recommended. This substance can be removed with a needle or by dissolution with water, but care must be taken that the specimen is sufficiently consolidated.

Microvertebrate fossils are commonly stored in vials; because specimens are often mounted on pins embedded in the vial corks, the specimen numbers should appear on the corks. Glue should be used if a semipermanent mount is desired (e.g., for specimens that will be handled frequently); for temporary mounts (e.g., where frequent mounting and dismounting is anticipated, as with individually sorted fragments that may later be assembled), a microcrystalline wax is recommended. In mounting specimens, the pin should be kept short, so as to avoid potential damage when the specimen is removed from and returned to its vial; the specimen can be positioned in a pad of

modeling clay, mounting side up, and picked up with the glue or wax on the pinhead.

INTRODUCTION

Microvertebrate specimens that are obtained via screenwashing (i.e., underwater screening) and associated techniques generally differ from those obtained through quarrying in being less complete, in having their broken parts, if any, disassociated, and in lacking a surrounding rock matrix. Nonetheless, most preparation techniques, including repair and consolidation, are similar. Although there exists a considerable (and growing) literature describing materials and methods used in fossil preparation, very few published accounts deal specifically with the specialized techniques required when working with tiny, fragile bones and teeth of small vertebrates ("microvertebrates"). The present offering is an attempt to combine some of the accumulated wisdom of others with my own observations and experiences in preparing microvertebrates over the course of the past 15 years. The main purpose of the paper is to present the procedures, along with the required tools and materials, most commonly used in micropreparation, including specimen repair, consolidation, mounting, and vial storage. Countless variations can be made on the techniques; experimentation is of great importance in developing an appropriate procedure, given differences among specimens and preparators. I have omitted discussion of removal of rock from bone, whether through mechanical or chemical preparation, because I have assumed that the reader already has a solid background in these aspects of preparation. For further information on relevant preparation techniques, important contributions include Whybrow (1982), Berdan (1989), Amaral (1994), Davidson (1994), and Palmer (1989).

Definitions

What is micropreparation (herein referred to as "microprep")? Microprep can be defined as preparation that would be virtually impossible without the use of a microscope. One of the defining characteristics of microprep is what might be referred to as specimen "forgiveness." Large specimens are relatively forgiving of preparator error

in that small gouges, nicks, and scrapes may go unnoticed or may be restored, preservatives can be applied with some abandon, and mistakes can be more readily reversed (for instance, when large amounts of solvent are used to reverse a gluing procedure on a poorly set bone). Microfossils, on the other hand, can be completely obliterated with one careless slip of a needle; glue must often be applied in very precise quantities to very small areas; and glue and other treatments to a specimen are, practically speaking, irreversible: if a mistake is made, the cure can often be worse than the ill. Microfossils are, in general, very unforgiving of preparator error.

In this paper, the terms "bone," "tooth," "object," and "specimen" are used interchangeably: they refer to whatever is being worked on at the time. Likewise, the terms "glue," "adhesive," "consolidant," and "preservative" are commonly used interchangeably. In most situations, "glue" and "adhesive" refer to a material used to bond two surfaces, whereas "consolidant" or "preservative" refer to the same material, usually in a thinner mixture, used in a less topical application.

Glues, Preservatives, and Conservation Philosophy

Because microprep procedures are often irreversible, it is critical to think ahead. When choosing a preservative, one should always consider the future of a specimen, from excavation to eventual exhibition, storage, or study. Particularly relevant in this context are analytical procedures the specimen might be subjected to after work is finished on it. Will penetration of bones by a consolidant render them useless for isotope analysis? Will a film of glue result in an inaccurate cast or SEM micrograph? Will a consolidant hastily applied in the field present serious problems back in the lab?

The major practical considerations when choosing a glue are setting time, penetration (of both bone and matrix), hardness, and reversibility. Other considerations include "softening point," technically termed glass transition temperature (T_g), long-term reversibility, toxicity of solvent systems, pH, reactivity, and physical or chemical stability. Discussion of these factors is provided by Wolberg (1989; see comments by Shelton and Chaney, 1994), Johnson (1994), and Shelton and Chaney (1994). In addition, the reader is encouraged to request product information packets and material safety data sheets from manufacturers. The pros and cons of various glue types are numerous and complex; the following discussion is a brief overview of the use and characteristics of the three most commonly used glues.

The two most studied (see, e.g., Johnson, 1994; Shelton and Chaney, 1994) and widely used glues are currently Butvar (polyvinyl butyral resins; Monsanto's B-76 is recommended) and PVA (polyvinyl acetate resins). Both are available in various molecular weights and are dissolved in alcohol or acetone (or both), with approximately 6% water added. I have found great variation in the penetration, ultimate hardness, and setting time of both glues, depending on the type and ratio of solvents used; the reader is encouraged to experiment with these glues, using drops of

glue in a sand table to simulate bone and matrix (or, if scraps sufficiently similar to the specimen can be sacrificed, real bone and matrix). Because of their versatility and reversibility, both glues are recommended.

Cyanoacrylates (referred to here as "superglues") have a special place in the preparator's repertoire of materials because of their great setting speed and adhesion. Information on long-term properties of superglues is not yet available. There is clearly a need for more study of these glues, although they have been used extensively in microprep for at least 20 years with few apparent problems. Superglues are available under many labels, with various setting times and viscosities. The brand Paleobond is especially formulated for paleontological applications and is highly recommended. Superglue is best used as a contact cement. Because of low surface tension, the least viscous types will disperse on a surface or penetrate into cracks with astonishing speed, a property that can be used to the preparator's advantage. Although superglue will penetrate and fill the smallest of spaces, it only coats a given surface, as can be seen under the microscope: superglue will not truly be absorbed into and through a bone surface in the same fashion as dilute PVA or Butvar. This can be a major concern when a tooth or bone is later studied or photographed with the SEM, or when it is cast. In such circumstances, it is important that surface details be true to life and not artifacts of preparation. Superglues can be used in conjunction with accelerators. A possible concern with these products is that they can sometimes form a vivid malachite-green or blue stain on a specimen. Although this stain barely penetrates the surface, its removal can be problematic.

Epoxy glues, extraordinarily useful for repairing large specimens because of their superior strength, are sometimes used in microprep if a prolonged working time is needed (W. W. Amaral, personal communication, 1995). For extremely small specimens, epoxy is not generally recommended as an adhesive because it is relatively viscous, making it difficult to register contacts precisely, and because it is very difficult to remove, even with specialized solvents.

Glue Reversibility

In a sense, any treatment of glue on bone should be regarded as "irreversible." Strictly speaking, most techniques used to remove glue, either mechanical or chemical, will leave traces, even if they are invisible to the eye. Strategies for glue application will depend on the often conflicting demands of specimen use vs. research applications and archival considerations. Many researchers prefer, when possible, to see a specimen "dry-prepped," with as little applied consolidant as possible (see Amaral, 1989, 1994). This view is shared by some conservators, who feel that a specimen should be maintained in as pristine a condition as possible throughout its treatment, from discovery to collection case (see discussions by Shelton, 1994; Shelton and Chaney, 1994). On the other hand, if a specimen is to be handled and moved about a great deal, it may be advisable to treat it enough to be "bombproof" (D. S. Chaney, personal communication, 1992). Whatever the

decision, it should be reached, in consultation with conservators and curators, with full awareness of the consequences and an eye to the future.

For all its strength, it can be seen under the microscope that superglue always remains slightly gummy and flexible, so that it can be trimmed off with a sharp needle. A carbide needle can even be used to cause a thin coat of superglue to bend under pressure, so that it can be peeled off a smooth surface. The danger with this technique, however, is that if the glue has penetrated hidden cracks, one can inadvertently peel off bone fragments as well. With microfossils this is a very risky procedure.

Superglue can also be dissolved chemically with a "supersolvent," sold by most manufacturers, or with acetone. However, it generally takes a large quantity of any solvent to do the job, and the result is often a gummy mess that is hard to clean off the specimen. There is the added risk of getting solvent where you don't want it and, through capillary action, weakening the rest of the specimen. This potential problem should be considered when dissolving any type of glue.

Sometimes different stages of preparation of the same specimen require different tactics. When I glue a minute cusp back onto a 1-mm-long dryolestid tooth, for example, I generally intend to do it right on the first try, and I want it to be permanent. When mounting that same tooth on a pin, however, it may be desirable to use an impermanent wax, so that the tooth can later be removed for casting or SEM work.

EQUIPMENT, TOOLS, ACCESSORIES, AND MATERIALS

The following annotated list of tools and materials includes those that are most essential for microprep (see Table 1 for sources).

Microscope

A high-quality stereo zoom microscope (Fig. 1) is essential. The quality of the work depends largely on the quality of the equipment used, and the microscope is the primary tool. Distortion-free optics, a wide and deep field of view, and high zoom range will enhance comfort and quality of work. For some work (e.g., picking concentrate), a zoom range of 0.7 \times to 3 \times , with 10 \times eyepieces (as in most budget-priced dissecting scopes), is acceptable, but for really close work, much greater magnification is required: in excess of 200 \times is not uncommon. Less powerful scopes can be upgraded by adding 15 \times , 20 \times , or 30 \times eyepieces or stronger objective lenses. It is important to remember that adding stronger objective lenses will sacrifice working room (because of decreased focal distance), will reduce depth of field, will reduce light gathering, and thus will make it more difficult to focus light on the subject. A working distance of 30–40 mm is fairly satisfactory; closer distances become very awkward. If possible, a trinocular head configuration is very useful for the microscope, as it permits mounting of photographic or video equipment in the event that demonstration or specimen documentation is required.

A fully adjustable boom stand is also essential. The base

TABLE 1.—SOURCES OF MATERIALS AND SUPPLIES

Vendor and/or Manufacturer	Product(s)
Air Products and Chemicals, Inc. Chemical Customer Service P.O. Box 2662 Allentown, PA 18001 (215) 481-3210 (800) 345-3148 (product info., MSDs)	PVA (polyvinyl acetate resin)
Baxter Scientific 201 Great Southwest Parkway McGraw Park, IL 60085 (800) 444-6464	Vials
Carolina Biological Supply 2700 York Road Burlington, NC 27215 (919) 584-0381	Corks for vials
Conservation Materials 1165 Marietta Way P.O. Box 2884 Sparks, NV 89431 (702) 331-0582	Butvar, PVA, Carbowax (polyethylene glycol), Farcolina (plasticine), microcrystalline waxes; forceps, grinders, bits, brushes, etc.
Dolan-Jenner Industries, Inc. P.O. Box 1020 Woburn, MA 01801 (800) 833-4237	Fiber-optic illuminators
Foredom Electric Tool Company 6153 N. Flint Road Milwaukee, WI 53209-3715 (414) 351-1775	Flexible-shaft power tools, bits, and accessories
Industrial Tool and Supply 1177 N. 15th St. San Jose, CA 95115 (408) 292-8853	Tungsten and carbide rod
Lectro-Stik Company 3721 N. Broadway St. Chicago, IL 60613 (312) 528-8860	Microcrystalline paste-up waxes
Monsanto Chemicals 800 N. Lindbergh Ave. St. Louis, MO 63167 (413) 730-3238 (technical information) (800) 325-4330 (sales, MSDs)	Monsanto B-76 (Butvar)
MSC Industrial Supply 6700 Discovery Blvd. Mableton, GA 30037 (800) 645-7270	Tungsten carbide rod, grinders, bits, etc.
Satellite City P.O. Box 836 Simi, CA 93062 (805) 583-0994	Cyanoacrylate glues (superglues), superglue accelerators and solvents etc.
Uncommon Conglomerates, Inc. 287 E. 6th Street St. Paul, MN 55101 (800) 323-4545 (612) 227-6526 (fax)	Paleobond cyanoacrylic glues

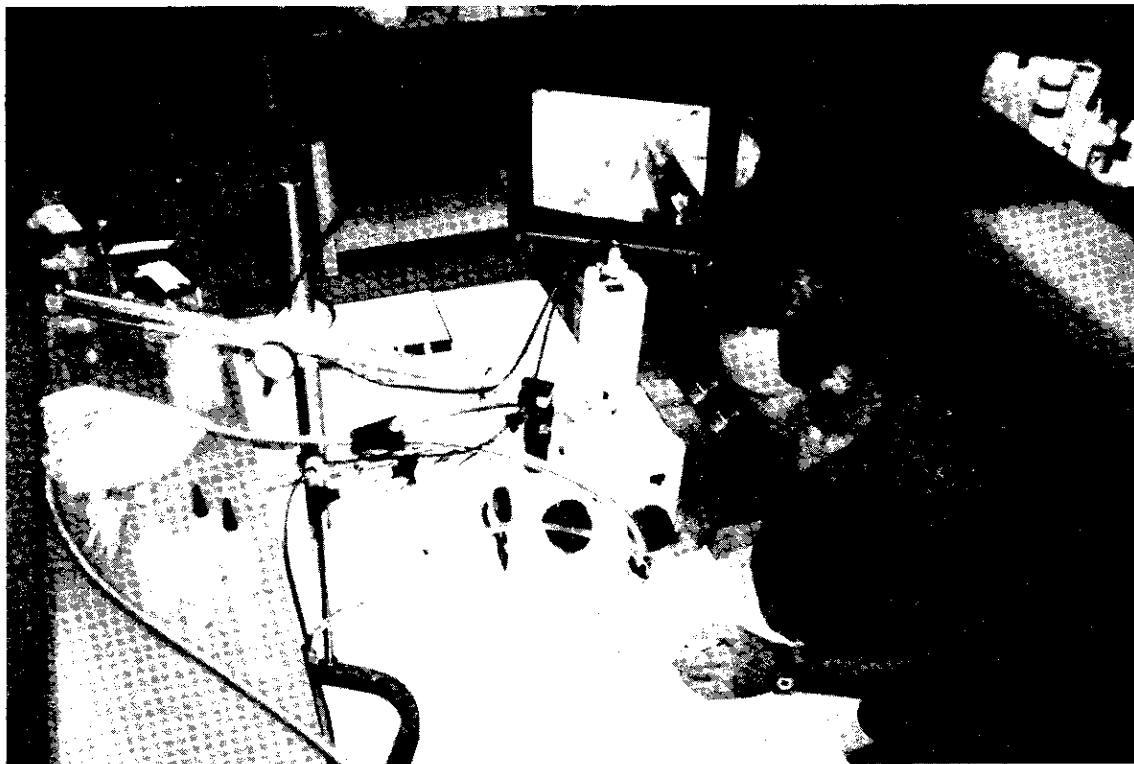


Figure 1. Binocular microscope configured for micropreparation. The scope is mounted on a long boom, permitting a wide range of movement of specimens, materials, and equipment; the boom is supported on a heavy stand for stability. The light source is a twin-pipe fiber-optic system with a long basal pipe, so that the light source itself is placed well out of the way; a clear plastic air tube, for blowing dust and small particles, is affixed to the left pipe. This microscope is configured with a trinocular head, to which a video camera is mounted. The image can be viewed via a monitor (background, center). The camera and monitor are useful for teaching preparation techniques, as well as for consultation for the study or conservation of specimens, exhibition, and for other purposes.

must be isolated from vibrations and should be heavy enough to support the microscope and all of its accessories without the risk of capsizing. For microprep on large blocks, a floor stand with adjustable scope mount may be needed.

Illuminator

A fiber-optic illumination system is vastly superior to any other type of lighting for microprep; one is well advised to get the highest quality and most versatile system that can be afforded. Highly adjustable illuminators are available with twin arm pipes or ring lights. Light pipes and focus lenses can be mounted to the microscope body for convenience (see, e.g., Amaral, 1994, fig. 6.7). The power source should be placed so that vibrations from the fan are not transmitted to either the specimen or the scope.

Flexible-Shaft Power Tool

These tools (e.g., Foredom, Dremel) are indispensable in any preparation lab. They can be fitted with hundreds of types of burrs, wheels, and bits. They are useful for trimming away rock. For rock removal, fine- to coarse-grain tungsten carbide burrs and points are most useful (as are diamond wheels), although they may sometimes transmit

vibrations hazardous to the specimen, and expensive bits can wear out quickly, even on soft rock.

One of the most useful purposes of a flexible-shaft power tool is in grinding super-sharp edges on carbide needles. Diamond disks are best for this, the most useful being the $\frac{1}{8}$ inch \times $\frac{3}{8}$ inch diamond head. Sintered points, though more expensive, are preferable because diamonds are incorporated throughout the head instead of plated on the surface, as they are on cheaper heads, where they will eventually grind off. Diamond wheels are also useful for notching carbide rod where a break is to be made.

Tungsten Carbide Rod

Carbide is blessed for being incredibly hard and cursed for being very brittle. Carbide will keep a sharp point longer than any other material—until it is stressed laterally, at which time it will snap. Unfortunately, this usually happens to the fine tip one has worked so carefully to produce.

Carbide is available in many diameters and can be cut to length. Most useful for microprep is the 1-mm-diameter rod. Points of incredible sharpness can be ground under a microscope. The Foredom handpiece can be attached to a holder or braced on a pad or sandbag. The carbide should

be ground slowly: do not apply great pressure; rather, let the tool do the work. Remove the bulk of the carbide from the end of the rod by rotating it as the tip is moved in and out along the diamond surface. The final edge is attained by placing the rod at a low angle to the wheel, with the wheel rotating away from the point. I have a dozen or more carbide needles handy when I work, each with a slightly different point. I seldom use a true conical point, but prefer a beveled or spade edge for the vast majority of my work (see examples in Amaral, 1994, fig. 6.8). Ground very fine, they can be used for scraping, peeling, probing, poking, or teasing off the tiniest rock particles, one at a time. The most important things to remember when using carbide are to keep it sharp and to refrain from stressing the tip or shaft laterally.

Many preparators seem to like fitting the needles into a pin vise. This approach is fine for many types of preparation, but for the high-magnification, precision work, the user is well advised to get accustomed to holding the needle by the index finger and thumb alone. This method generally permits much greater control of the carbide and greater sensitivity to the subtle differences in resistance of the matrix. Sometimes it may be slightly uncomfortable, but any discomfort generally goes away when calluses form in the right places.

Superglue

This amazing adhesive was developed during the Vietnam War, as a first aid skin bond for field use. There is now a wide variety of superglues, with different properties, available. Dealers sell sample kits if experimentation is called for; however, most dealers will provide product information packets on request, and these will generally include sufficient data to make an informed purchase.

Two-ounce bottles are most convenient for field and lab use. Unopened stock can be stored in a freezer to double shelf life (over 2 years for a 2-ounce bottle); opened stock should not be refrigerated because condensed moisture will reduce shelf life. Superglue will cure much more slowly when cold than at room temperature.

Curing time for superglue ranges from 6 minutes to 30 seconds or less. Generally, the slower the set time, the more viscous the fluid. This property can be used to your advantage. Accelerators are available to speed curing time. These are usually applied to the specimen first (they contain agents that clean the surface and speed curing time, even at low temperature). Accelerators dry instantly but remain effective from 3 to 12 minutes after application. It is important to use superglue sparingly and precisely: get it right the first time so you won't have to reverse it!

Polyethylene Glycol (PEG)

Generally referred to as Carbowax (a trade name of the Union Carbide Corporation), this waxy material has the useful properties of being water soluble and having a low melting point. It comes in several molecular weights, including PEG-1500 (molecular weight, 500-600) and PEG-3350 (molecular weight, 300-3700), the latter being the most satisfactory for most microprep applications. Carbowax comes in flake form, which is melted in a small con-

tainer at low temperatures on a hot plate, under a heat lamp, or in a microwave; it is flammable, so that heating with an open flame is discouraged. In a liquid state, Carbowax is transparent; it becomes opaque when solid.

Techniques for the use of Carbowax are similar to those in molding small fossils; hence the entire procedure should be thought out from start to finish. Possible hazards to the fossil include thermal extremes suffered during application or removal of hot wax, mechanical- or water-induced damage during wax removal, and post-prep lack of support to the specimen once wax is removed.

Small, Adjustable Blower

This is useful in providing a gentle stream of air, directed at the immediate work area, to remove dust. The best arrangement involves running a line (with regulator, to adjust pressure) off an air compressor (see Amaral, 1994). Thin metal or plastic lines can be fastened to the scope or light pipes (Fig. 1). A cheap and versatile system can be rigged to the work area with parts from any hardware store. Lacking this, lung power or the ubiquitous rubber, squeeze-type enema syringe will do. It is essential to maintain a clean work area while using compressed air, in order to prevent loss of tiny bone fragments that may be picked up by the air. The use of aprons or partial enclosures around the table can also help prevent loss of fragments.

Modeling Clay

Modeling clay is useful for building dams to contain Carbowax and for supporting or manipulating small bones. The best types are nongreasy and nonspringy. Once moved, even slightly, they should retain their shape. The best I have found is Farcolina plasticine.

Superfine-Point Forceps

These forceps are used for manipulating bones, lifting bits of matrix, or applying glue. Many varieties are available; those requiring only light pressure to occlude are most suitable for microprep. Dumont makes the best forceps I have found.

Miscellaneous Tools and Materials

Other useful materials and tools include the following: assorted sand bags and pads for specimen support; assorted soft, fine-point brushes for applying PVA, Butvar, etc. (but not superglues) for removing Carbowax, or for picking up and holding extremely small objects; assorted dental tools for specimen preparation (although the metal is flexible and far softer than carbide, they can easily be bent or shaped with a grinder to get into those hard-to-reach areas); and a heat lamp and/or hot plate for melting Carbowax.

PREPARATION OF MICROVERTEBRATES

Field Considerations

Microprep starts in the field: once a microfossil has been discovered and the decision has been to save it, the preparation process begins. Commonly, fossils are given initial

treatment of preservative as a matter of course, a practice that is inadvisable for reasons given above. If consolidation is essential to avoid specimen disintegration, coatings should be applied evenly and sparingly, so as not to obscure detail; also, coating matrix and bone together may reduce the natural separation of matrix from bone during later mechanical preparation. If the bone appears to be intact, well consolidated, and in little danger of breaking, then glue should not be applied. The specimen should be wrapped thoroughly and tightly in toilet paper, taped, and labeled, together with any counterparts that may have been found with it. Where the fit of counterpart pieces is complex, or where the fossil is not immediately obvious, it is helpful to make registration or indication marks on the rock matrix. If the rock is badly cracked, or, as is the case with many mudstones (particularly bentonites), is in serious danger of fracturing as it dries, then a consolidant should be applied to the rock. If time is a factor and one is hurried, superglue is very useful for this purpose, but an effort should be made to keep the glue off the bone itself. If the bone needs to be stabilized, then PVA or Butvar is preferable to superglue because it will be much easier to remove in the lab.

Determination of Best Laboratory Procedures

A preparator must make the same evaluations and decisions with microvertebrates as those made with large bones, in order to decide the correct approach. These questions should be asked: What should the end result be? Is it desirable to end up with a free-standing specimen (if possible), or should it remain partially embedded in the matrix? Are there unstable cracks or loose pieces of matrix and bone that should be glued in place immediately, or can they be safely parted from the block, cleaned, and reglued later? Will any procedure you envision damage the specimen or its scientific value? Can the procedures be reversed if necessary? What exposure or presentation will maximize scientific usefulness?

The best situation, of course, is when the specimen is strong enough to be simply set on a pad under the microscope and the work begun. This is rarely the case. Often the rock and bone are fractured, little bone fragments are loose in cracks, visible bone is a mere black speck in the rock, and the object is yet to be identified. The following are a number of procedures and techniques that can be applied to a variety of commonly encountered situations in microprep.

Application of Glue

As noted elsewhere, glue may be applied to either repair a specimen or to stabilize the matrix that encloses it. Where separate elements are to be bonded, it is essential to dry-fit the contacts first, in order to determine how the fragments contact each other and where the adhesive should be applied. After application, excess glue should be cleaned off before it dries.

PVA or Butvar

If PVA, Butvar, or similar resins are to be applied, then fine (00, 000, or smaller) paint brushes with soft hair can

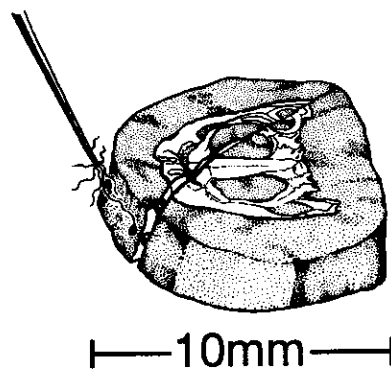


Figure 2. Microvertebrate specimen (frog skull) embedded in matrix. The crack is stabilized by application of microdroplets of superglue, using fiber, to form adherent buttresses or gap fillers.

be used. For more precise applications, drops of glue may be picked up with forceps. One should always be aware that these slower-acting fluids can temporarily weaken a specimen before the polymers bind. Caution should be used when attempting to stabilize loose or overhanging projections.

Superglue

Cyanoacrylates can be applied with a variety of materials depending on the size of the object. For larger cracks in matrix, superglue can be applied directly from the spout of a 2-ounce bottle. Again, use it sparingly! It is not necessary to fill the whole crack; a spacer wall or gap filler (e.g., Fig. 2) will usually be sufficient. For wider cracks (e.g., 1–3 mm), I prefer the more viscous glue (e.g., Super-T or Special-T). To be effective, the glue must contact both sides of the crack. Accelerator can be applied first for a quick set near the surface, or applied after the glue, which allows for greater penetration.

For application of superglue to smaller areas, use a fine pair of forceps. Pick up a small drop of glue with the tips and just touch them to the crack or surface, and the fluid will be drawn in. This technique requires a bit of speed and finesse and works best with the thinner glues. A jar of acetone should be kept handy to rinse the forceps after use, to keep the tips from sticking together. More precision can be obtained by filing the forceps tips so that one extends slightly beyond the other, the longer point delivering the fluid.

For truly minute applications of superglue (e.g., filling tiny cracks [Fig. 2] or making bone-bone contacts [Fig. 3]), a piece of fiber works best. The objects to be glued should first be positioned under the scope and made ready for any manipulations. A useful technique is to tear off a small shred of tissue paper and roll one end between the thumb and index finger for a handle. The business end should appear pointed and slightly fuzzy. This fibrous tip should be barely touched to a drop of superglue and quickly inspected under the microscope. What you hope to see is a fiber out at the end with a microdroplet of glue at its tip

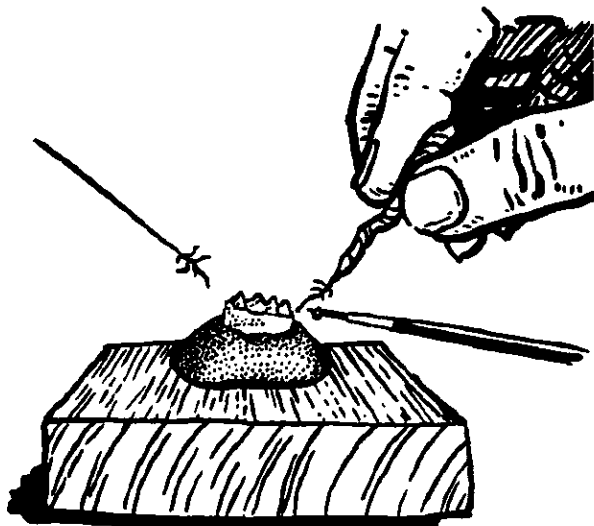


Figure 3. Positioning and reattachment of tooth cusp of a Mesozoic mammal (dryolestid). The main part of the specimen is embedded in modeling clay affixed to a wooden base.

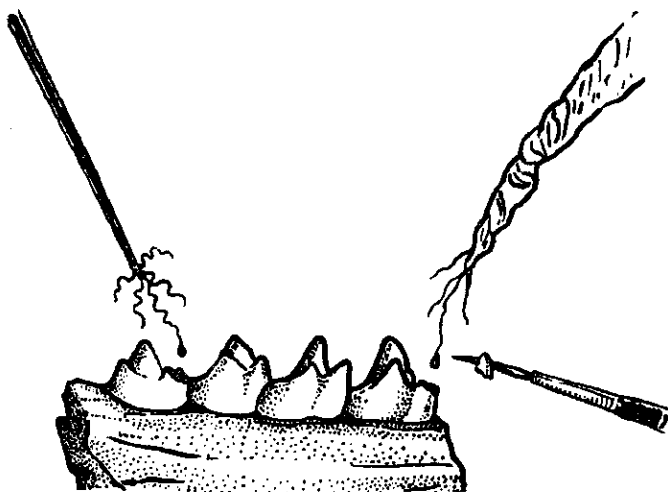


Figure 4. Repair of Mesozoic mammal (dryolestid) specimen. The fragment, held and manipulated with a slightly moistened, fine brush, is affixed with a microdroplet of superglue, applied with fibers adhering to a needle (left) or projecting from a torn and rolled piece of tissue (right).

(Fig. 4, right). It takes some practice to get this technique right, and often it will take more than one try to get exactly the right sized drop just where you can use it best. If a crack is to be filled, simply touch the drop to the crack and the fluid will be drawn in. Bone-bone contacts are discussed below.

Another technique (Amaral, 1994) is to scrape a sharp needle across a piece of cardboard wetted with superglue. The idea is to scrape off a small bundle of fibers which can

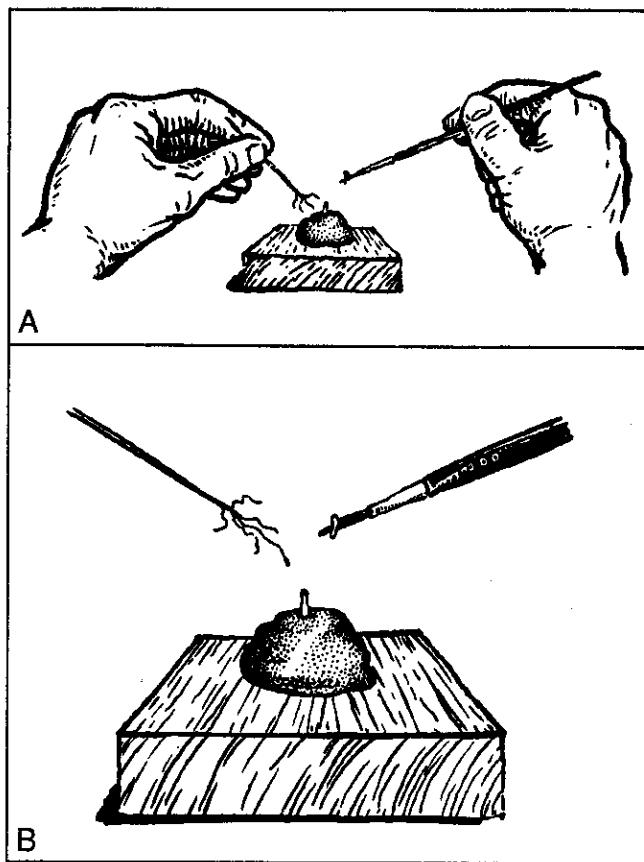


Figure 5. Repair of a small limb bone: positioning. One part of the specimen is embedded, contact up, in modeling clay affixed to a wooden base; the other is manipulated into position with a moistened, fine brush.

be used as described above (Fig. 4, left). This method has the advantage that the needle provides a rigid tool for better control.

Repair of Small Bones

Gluing small, loose fragments back together can be an extremely delicate and precise operation. If a fragment of bone or tooth (a cusp, for instance) is to be reattached, one faces the problem of lifting the fragment to its correct position and then letting go of it. A minute object can be lifted by touching a slightly moistened 000 (or smaller) brush or needle to its side and then raising it to position (Fig. 5). If the glue is already in place on the fixed target (as described above, using fiber), the fragment need only be touched to the glue drop and it will usually be pulled in and away from the needle or brush. If there is a chance that the fragment will need readjusting, then a slower-acting glue is desirable. The moves should be practiced beforehand to insure accuracy.

Modeling clay is extremely useful for positioning small bone fragments so that they can be reassembled. Depending on the situation, a clay base or clay pedestal can be used for this purpose; it may also be possible to manipulate small bones with a vacuum forceps pickup, although I

have had little success with this: the airflow and handpiece are difficult to control during complex operations.

Clay Bases

Sometimes it is necessary to reassemble small, broken long bones (limb elements, for instance) that are free of matrix. If there is a clean, relatively flat contact (i.e., broken surface), it may be practical to embed the heavier fragment contact up in a soft clay bed, and then test-fit the loose piece to be sure it will balance on the lower piece. Generally, it is advisable to mount the clay on a small wooden block so that the specimen can be rotated to visually inspect for proper alignment. If you are sure that the loose piece can be attached with no readjustments, then apply the glue to the fixed piece and attach the loose piece as described above. If a sure fit is questionable, bring the loose piece into position and then apply a tiny glue drop to the side of the contact where it will be drawn in most effectively (Fig. 6). Extra working time can be gained by using a slower setting superglue.

Clay Pedestals

If the pieces are too awkward to manipulate, or the contacts are too poor to attach by the above means, pedestals may be used effectively. Cut two tiny pedestals from a quality, nonspringy clay (e.g., Farcolina) and fix them to a clay base. Rest the bone fragments on either pedestal with the contacts close together. Use a pair of modeling tools to ease the pedestals toward each other (Fig. 7A) until the bones touch; sometimes this movement can be done by flexing the base itself. Rotate the wooden mounting block and inspect the work from all angles, making small adjustments, as necessary, until the bones are in proper alignment. Before touching the glue drop to the contact (Fig. 7B,C), make sure that the clay pedestals have not shifted apart.

The Use of Carbowax in Microprep

In some cases, a fossil is too small and delicate to handle by normal means. If a fragile bone is already free of the matrix but preparation is incomplete (as is often the case with screenwashed material), if a specimen needs to be prepared on all sides but is too fragile to be worked on while it is resting on a sand bag (Fig. 8A), or if some support is needed for another reason, then an artificial and temporary matrix may be in order. The idea behind using Carbowax is to create a moldlike, perfectly form-fitted bed that can support the fossil while it is being worked on and that can be later removed with no damage to the specimen itself. Before proceeding, the specimen should be carefully examined and the whole process thought out to be sure the bone will survive this treatment.

Use of Carbowax with Loose Bone

1. Inspect the specimen to see if it needs protection from wax or water. If later use of water will disintegrate rock or penetrate cracks, then make sure all endangered surfaces are well sealed with consolidant. It should be borne in mind that water can enter uncoated areas and loosen resin coats.

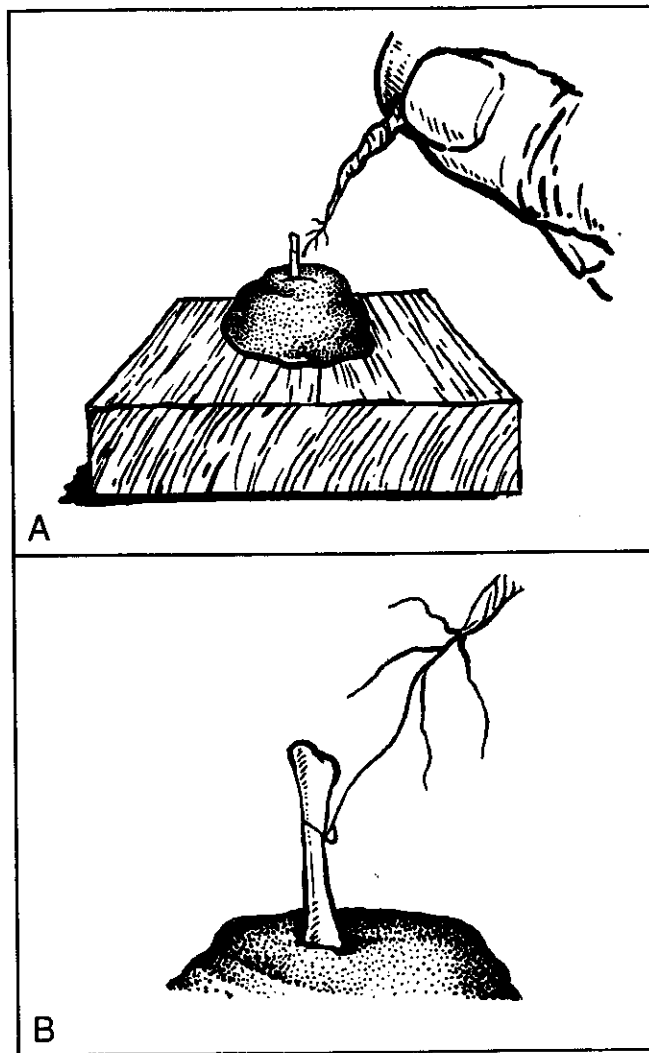


Figure 6. Repair of a small limb bone: gluing. If doubt exists as to whether the parts can be positioned correctly after gluing, the pieces should be positioned first and examined carefully. A microdroplet of superglue is then applied with fiber to an appropriate part of the joint; it will be drawn into the crack through capillary action.

2. Cut a piece of wood large enough to brace with your fingers and hold the specimen within a clay dam. A square or oblong piece is usually best, with the dam positioned at one end. The wood surface at this end should be roughened, as needed, to give the clay and wax purchase.

3. Roll out a piece of clay long enough to enclose the specimen and wax filler. The clay won't need to be more than about 5 mm from the specimen. Cut the clay down the middle to form the dam.

4. Fix the clay dam tightly to the wood surface, roughly in the shape of the specimen. Plan for an orientation that gives you maximum visual and mechanical access.

5. Make a diagram of the specimen so you can later be sure where everything is.

6. A thin layer of Carbowax allowed to harden in the

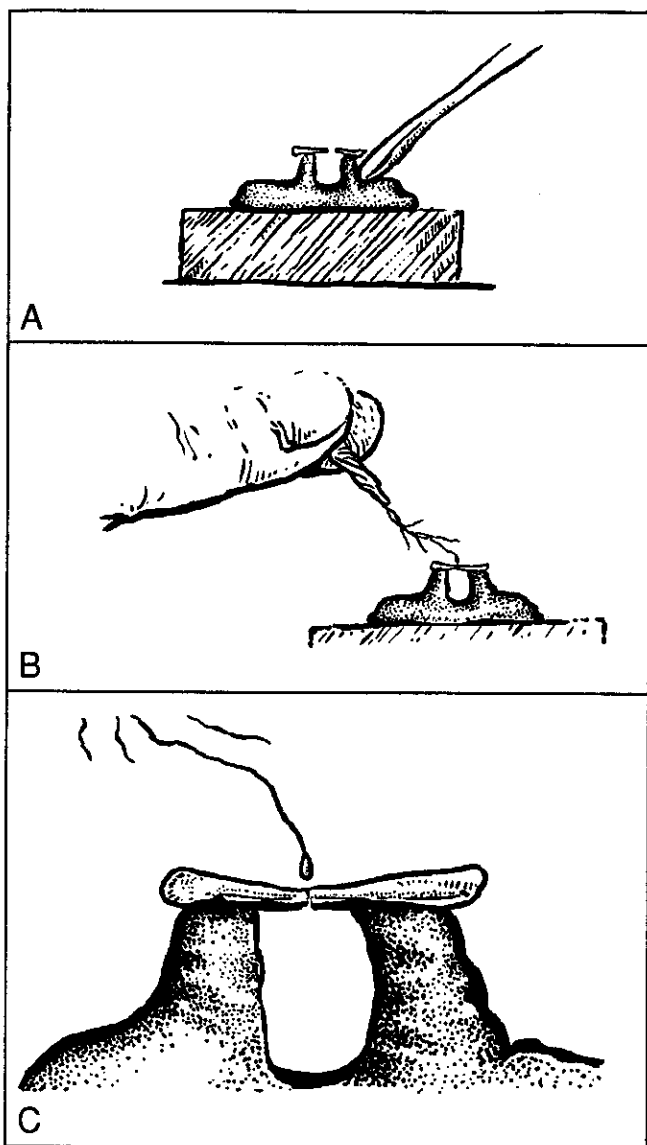


Figure 7. Repair of small bone with limited contact. Where it is not feasible to balance one fragment on top of another, each can be placed atop a pedestal of modeling clay; both pedestals, in turn, are affixed to a clay and wooden base. The separate elements can be positioned by moving the pedestals or flexing the clay base; once in correct position, superglue is applied, using fiber, to the joint.

bottom of the basin prior to positioning the specimen will facilitate its subsequent removal. Position the specimen within the dam (Fig. 8B). If the specimen has a complicated shape and has gaps underneath, it may be advisable to apply a drop or two of Carbowax to these areas beforehand, in order to avoid trapping large air bubbles, adjacent to the underside of the specimen, in the Carbowax. A small clay plug is sometimes useful for orienting the specimen.

7. Heat the wax, pour it in the dam, and allow it to harden completely. Use as little wax as you can.

8. Remove the dam and prepare the specimen, remov-

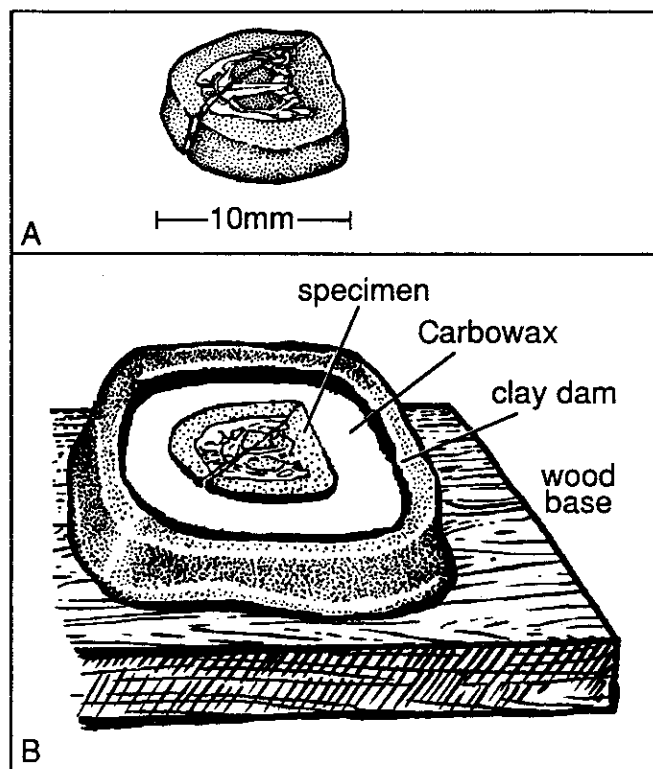


Figure 8. Embedding in Carbowax. Carbowax is useful as a temporary matrix for unstable specimens, such as this frog skull embedded in a cracked rock matrix. A clay dam is affixed to a wooden block; after positioning the specimen, filling gaps underneath as necessary, the liquid wax is poured in.

ing wax as necessary. When preparation is complete, any newly exposed surfaces vulnerable to water should be sealed, as in Step 1.

9. Remove specimen from Carbowax. The bulk of this can be accomplished with a sharp, beveled needle. Care should be used when undercutting: know where the bone is hidden underneath, and work your way in gradually.

10. Turn the specimen over, if necessary, and repeat the procedure, starting with Step 3.

Final Removal of Carbowax

After the preparation, most of the Carbowax can be removed with a needle. It will often separate from the bone in the same way a soft matrix will part from a fossil. When water is used, always watch carefully for any loose bone fragments. If instability is detected, then let the specimen dry and consolidate it by any means necessary. Any wax residue can be removed by one or more of the following procedures.

1. If the specimen is robust enough, immerse it in a beaker of warm water.

2. Rest the specimen on several layers of soft, absorbent paper. Using a very soft brush, carefully dissolve away the wax with warm water, cleaning the brush regularly with warm water.

3. Rest the specimen on absorbent paper under a heat lamp and allow the wax to melt. As it melts, use a soft brush or fragment of tissue paper to absorb wax residue. Care should be used in applying heat, which can soften PVA or Butvar.

When the specimen is free of wax, let it dry completely and inspect it to be sure there is no water damage or wax residue remaining. Pay particular attention to teeth and other critical areas. Usually a thin coat of wax will give the specimen an unnatural sheen or a hazy, milky appearance. If water has seeped under a surface coat of consolidant, it usually appears as white, weblike strands. These can be removed with a needle or dissolved with acetone.

Use of Carbowax on Specimen Still Embedded in Rock

If the specimen is still resting in the matrix, the job will generally be easier. The specimen should be prepared, in situ, as much as possible according to the steps listed above. The specimen can then be stabilized with a consolidant and/or Carbowax, so that the fossil can be undercut and removed from the rock. To prepare the other side, simply turn the specimen over and follow the procedures described above.

Carbowax can also be used for spot jobs on isolated parts of bones, big or small. It is particularly useful on delicate overhangs, where any pressure could collapse unsupported bones. Simply drip a little wax around the area where support is required or, as needed, construct a small clay dam and fill with wax.

PICKING, SORTING, AND STORING MICROFOSSILS

Many vertebrate microfossils are recovered as isolated specimens (e.g., tooth, jaw fragment) through screenwashing and associated procedures described by Cifelli and others (1996). Other vertebrate microfossils, recovered through manual or chemical preparation, are often mounted and stored in a fashion similar to that for screenwashed fossils, depending on size and physical characteristics. In this section I describe procedures for sorting and reassociating screenwashed microfossils and for mounting and storing such specimens.

Vials and Vial Trays

Most microvertebrate fossils are well-suited to vial storage, whether as individual specimens (e.g., significant dentulous jaw or tooth) or specimen lots (e.g., highly redundant materials such as fish scales, lizard osteoderms, or teeth of many lower vertebrates). The most versatile and commonly used vial size is ½ dram, for which fitted corks must be ordered separately; other, larger, vials (e.g., 4 drams, 7 drams) are useful for large specimen lots or individual fossils. The tops of corks should be painted with white acrylic paint so that locality and specimen number can be written on them. Even if a label including specimen data is to be ultimately placed in vials, it is important to include the data on top of the cork, because many specimens will be mounted to pins affixed to individual corks

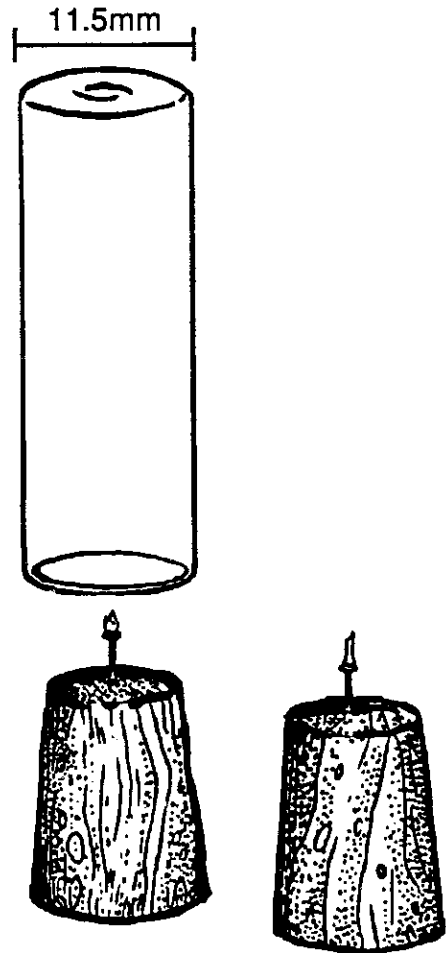


Figure 9. Typical storage for microvertebrate fossils. Specimens are mounted onto pins, which in turn are embedded in corks that are fitted into vials. The pin should be as short as possible to avoid specimen damage when the cork is removed from or inserted into the vial. Paint the bottom of the vial to avoid accidentally trying to insert the cork into the bottom and damaging the specimen.

(Fig. 9). Cork labeling will therefore assure that specimens do not become mixed if a number of them have been removed from their vials (e.g., for study or identification). One of the greatest hazards to specimens so mounted is posed by people trying to return the cork to the wrong end of the vial and crushing a specimen against the glass. This hazard can be reduced by painting the vial bottoms with an obvious color (e.g., red).

Vial boards are needed for both sorting and storing the small (½-dram) vials. These can be made from ¾-inch-thick wood (see Cifelli and others, 1996, fig. 14 [p. 22, this volume]), cast from acrylic or other resin, or fashioned from some other material (e.g., grid panel from lens of a fluorescent light fixture). The vials should fit the holes snugly but not tightly (½-inch holes work well for ½-dram vials) and should fit deeply enough so that they cannot fall

out if the tray is jarred. For sorting, a tray should have holes spaced far enough apart to permit labeling (e.g., with pieces of tape), if desired, of individual holes. I find a 3½ × 12 inch piece of pine to be a convenient size for holding 60 ½-dram vials (4 rows of 15). For specimen storage, vials can be spaced closer together; several sizes should be made, so that vials can be grouped appropriately in the collection (e.g., by element represented, taxon, or locality). The actual dimensions of the trays are not critical, but standards should be adopted so that they fit properly in cardboard trays, specimen drawers, and so forth. Larger vials (e.g., 4 or 7 drams) are often stored on their sides. Such vials should be shimmed into cardboard specimen trays with polypropylene blocks or some other material to keep them from rolling around and bumping each other when the specimen drawer is opened or closed.

Sorting Bone

While picking screenwashed concentrate, I generally sort the bone into broad categories as I go, separating vertebrates from invertebrates, limb elements from vertebrae, teeth according to major taxon, and so forth. Most important to my work (and most rare) are mammal teeth, so I pay particular attention to them. Because screenwashed material is generally fragmentary, one should always be mentally mixing and matching parts.

After a batch of concentrate has been picked, the true sorting process begins. If I have a group of mammal teeth from a given sample, I will sort them by taxon and element (e.g., tooth locus). When this is done, incomplete fragments possibly belonging together are arranged onto a piece of clay and systematically scanned for matches. A single tooth can easily have been broken into many fragments, so this can be a tedious procedure. For large samples, it is sometimes convenient to mount fragments individually by using a temporary medium such as wax. Individual fragments can then be sorted into fine categories (e.g., pieces of left-lower molars), and the potential fits can be examined closely by juxtaposing fragments under the microscope. Fragments with contacts of which I am certain are set aside for reconstruction, as described earlier.

Mounting Small Teeth and Bone

Vertebrate microfossils having individual significance are commonly mounted on pinheads (or, in the case of complex specimens, soft wire that can be formed to fit an internal or external contour) embedded in corks and stored in vials, which prevents them from moving about and provides a ready "handle" so that they can be manipulated, without damage, for study or identification. A word of caution, however, is in order. Potential damage resulting from return of the specimen to the wrong end of the vial has been noted above; damage is even more commonly inflicted when specimen users neglect to pull or push the cork straight from or to the vial, so that the specimen is either crushed against the inside of the vial or knocked off its pin. This danger can be reduced somewhat by using larger vials, as appropriate, or by positioning the pinhead as close to the cork as possible.

Various media are available for mounting specimens to pinheads. PVA or Butvar is appropriate if a more permanent mount is desired. Because these glues result in a relatively secure mount, they may be preferable if frequent specimen handling or transportation (e.g., specimen loan or exchange involving postal delivery) is anticipated. However, glue mounts may present problems if the specimens need to be removed for any reason (e.g., casting, study under SEM). Application of or immersion in a solvent may smear glue on a specimen or, worse, loosen bonds where a specimen has been glued together from various fragments.

Various types of microcrystalline waxes can be used, in lieu of glue, for mounting. These are particularly useful for temporary mounts, or where frequent mounting and dismounting are anticipated. A disadvantage with waxes is that they may not hold a specimen strongly enough to withstand jarring; additionally, temperature extremes may weaken the bond. Many petroleum-derived microcrystalline waxes tend to be messy to handle and hard to remove from the specimen. Beeswax tends to be difficult to remove from specimens; the best waxes I have found are "paste-up" waxes used in the printing industry. These are dry, positionable, and nontacky; they generally do not adhere to specimens, and removal, if necessary, can be done with needles. Carbowax has also been reportedly used as a mounting medium; in which case, the pinhead is dipped lightly into melted Carbowax before affixing the specimen, as described below (W. W. Amaral, personal communication, 1994).

Pin-Mounting Fossils by Using Glue

Position the object on a pad of clay with the surface to be glued facing up. Using a pair of needle-nosed pliers, insert a pin into the bottom of a cork. Pick up a small drop of glue with the pinhead. The glue should be slightly viscous and tacky to the touch. Touch the glue drop to the bone surface (Fig. 10, right). It will usually pick up the bone as you lift it away. If the object is a tooth, touch only the root, if a root is present. Turn the cork right side up and, if necessary, adjust the position of the bone with a needle before the glue dries; gas bubbles often form in the drop, distorting its shape.

Pin-Mounting Fossils by Using Wax

Position the specimen, pin, and cork as described above. With a fingernail, pull off a small dab of wax and form it around the pinhead, making a small point or pedestal at the tip (Fig. 10, left). Press the wax gently to the bone and lift the bone up. Often, it may be necessary to use a needle to work the wax around the bone surface a little, so that good purchase is achieved; however, assure that no important features of the fossil are obscured in the process.

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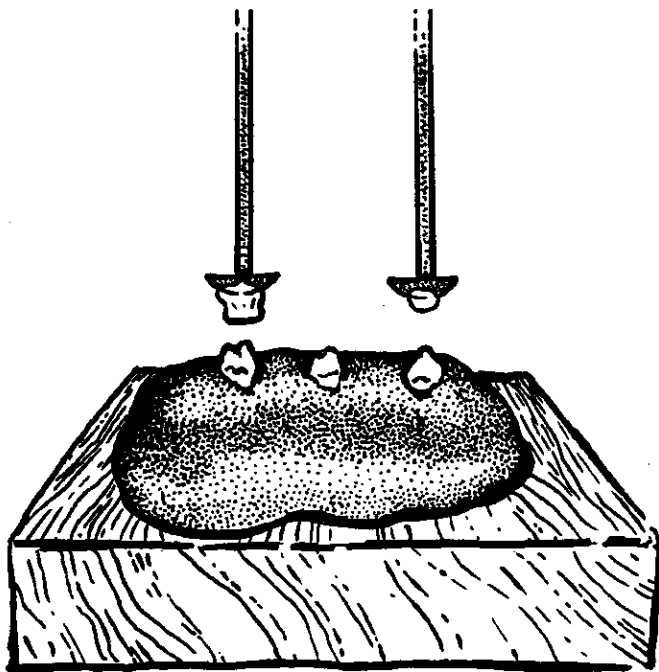


Figure 10. Mounting microvertebrate specimens. Fossils are placed on modeling clay, morphologically informative side down, and picked up with cork-mounted pins whose heads bear drops of glue (Butvar or PVA, right) or, if a temporary mount is desired, globs of wax, which can be custom-formed (left).

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