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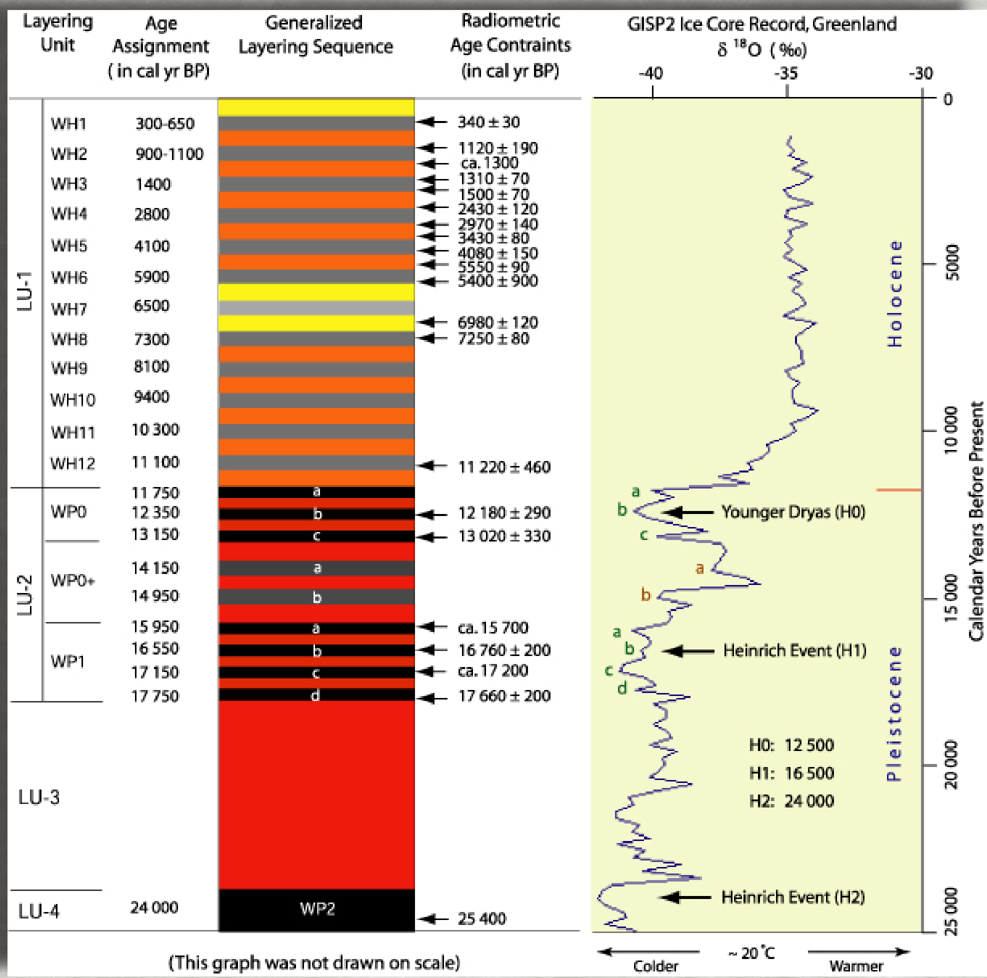

Dating Techniques for Piedmont Landforms in Maricopa County

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ARIZONA GEOLOGICAL SURVEY

Executive Summary

This dating technique assessment demonstrates how landform surface age estimates can be used in the evaluation of alluvial fan flood hazards in Maricopa County, Arizona. Detailed geomorphic mapping of alluvial fan surfaces combined with surface age estimates reveal the degree of flood hazards by identifying the most recently active active flooding areas. Geomorphic mapping and application of relative dating methods (surface morphology, degree of soil and desert pavement development, vegetation type and density, carbonate content and structure) should be performed prior to applying any numerical dating techniques. However, by themselves, relative dating techniques do not provide direct age estimates for Holocene surfaces. OSL and AMS radiocarbon dating methods are the most applicable numerical dating methods for dating alluvial fan sediments on fan landforms in Maricopa County. Cosmogenic nuclide dating and varnish microlamination correlation are the most favorable methods for estimating surface ages. Varnish microlamination (VML) is a correlative method and should be evaluated further in Maricopa County. The types of dating techniques and their resolution and age ranges are shown in Table E-1.

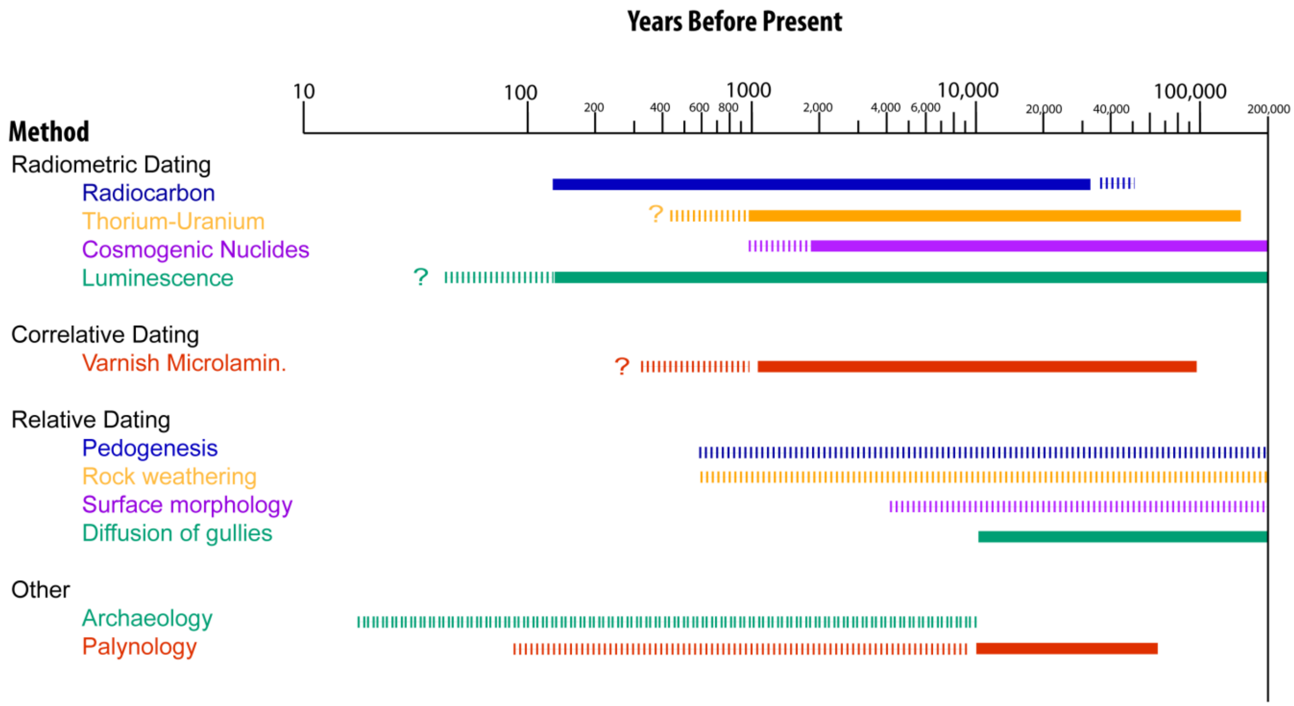

Table E-1. Dating techniques and age-resolution available for use on alluvial fans in Maricopa County.

This study recommends that a combination of relative and numerical methods be applied to most accurately determine surface age on alluvial fans in Maricopa County. It is further recommended that a regional chronology be constructed so that more cost-effective relative dating techniques can be used to determine correlative ages.

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Acknowledgment:

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Introduction

The objective of this dating technique assessment is to demonstrate how surface age informs on piedmont landform flood hazards, and outline how surface age estimates can be used in the evaluation of alluvial fan flood hazards in Maricopa County, Arizona. This report describes the types of absolute and relative dating techniques applicable to Holocene-aged landforms in Maricopa County, the limitations of specific dating techniques, and how surficial dating has been applied in previous alluvial fan flood hazard assessments.

Types of Dating Methods

Surficial dating methods can be categorized into the following three types:

- Relative dating methods
- Numerical dating methods
- Correlative dating methods.

Relative Dating Methods. Geomorphic surfaces can be dated using a relative order of age by evaluating the degree or intensity of weathering features observed on a particular surface and comparing them to those observed on other surfaces. The physical characteristics of a landform provide clues as to its age, as well as its depositional history, existing level of stability, and future flood potential. If a portion of the landform becomes isolated from its original watershed and watercourse, it ceases to receive new deposits and its surface will begin to develop specific physical characteristics indicative of its age. These physical characteristics include soil profile development, an integrated tributary drainage network, rock varnish, desert pavement, topographic relief, rounding of surface margins, color, and distinctive vegetative suites. Relative dating provides a first-order approximation of the age range of surfaces, and is often used to estimate ages of alluvial landforms in the southwest.

Numerical Dating Methods. Numerical dating methods are rooted in radiometric dating techniques, such as radiocarbon and cosmogenic nuclide dating, but also include other measurable techniques such as Optically Stimulated Luminescence (OSL). Numerical dating methods usually provide specific age estimates from measuring the physical properties of fan constituents, including organic material, sand grains, or gravel.

Correlative Dating Methods. Correlative dating methods are sometimes referred to as age-equivalence dating, and involve correlating physical attributes of a surface or deposit with similar physical attributes that have been constrained with numerical dating methods, such as the correlation of desert varnish microstratigraphy from one region to another.

Dating Holocene Alluvial Fan Landforms

Alluvial fans are complex and dynamic geomorphic systems that alternate between deposition and erosion both spatially and temporally. Numerical age estimates of deposits and their associated alluvial surfaces, in conjunction with geomorphic mapping of alluvial fan deposits, could provide a detailed record of shifting depositional patterns on alluvial fans over the past few hundreds to tens of thousands of years. This information could then be used to identify active and potentially active alluvial fan areas, and could potentially be used to assess the frequency and character of major channel pattern avulsions and associated areas of deposition.

Several features of an alluvial fan landform may be datable. However, selection of datable material must be done judiciously and within the geomorphic context of the alluvial fan as a system. Datable features may include fan surfaces, lobes of deposits, and deposits from channel avulsions. Numerous dating methods have been tested on geologically young deposits in various parts of the world. Only a few of these methods are applicable to alluvial fans in arid environments such as that of Maricopa County, and only the most applicable methods are discussed in this report.

The "Dating Techniques" section of this work discusses the subtleties of dating alluvial fan deposits and associated alluvial surfaces in arid environments, describe numerical and relative dating techniques applicable to Holocene alluvial fans and their limitations, and discuss how dating techniques have been applied to other alluvial fan systems.

Limitations of Dating

Deciding which dating method is appropriate depends on site specific conditions and what it is that you actually want to date. For example, if you wanted to know the age of a particular fan surface, you could use surface dating methods, such as cosmogenic nuclide dating, or varnish microlamination dating. One might also find dateable material in the deposit beneath the surface that would provide constraints on the estimated age of the surface. Because of the unavoidable uncertainties in any dating method, using multiple methods is always advisable.

There are several inherent geologic processes to consider: flooding, scouring and sedimentation. Flooding, scouring and sedimentation occur when a part of a fan is the locus of floodwater and sediment flux. The water and sediment flux may shift abruptly to another part of the fan, resulting in the abandonment of part of the fan. Equally, and perhaps more likely, however, is that some water and sediment may continue to enter the "abandoned" part of the fan in large floods, perhaps only in topographically low areas. Even if parts of fans are completely isolated from flood flow, local processes of erosion and deposition will continue to alter the original fan surface, albeit at a much slower rate. Alluvial fans are typically composed of nested channel deposits that can be derived from different flooding events even though they are part of the same alluvial fan. In some situations these nested deposits might be very similar in age, but in other situations they might differ in age by thousands of years. This would result in different age estimates for those sediments. It is important to note that the dating of a surface or deposit does not include the dating of subsequent floods over that surface. That is, the mere presence of surface age does not necessarily preclude potential future flooding. For example, geologically old surfaces may not have enough relief between them and surrounding channels to confine water and sediment. These older surfaces may experience aggradation, flooding and erosion.

Dating of specific floods on a particular surface is difficult unless special conditions exist, such as the burial of a historic artifact of known age. Dating past avulsion events can be done if sediment from the initial event still exists, or a correlation can be made from abandoned surfaces related to the initial avulsion event. Detailed geomorphic mapping could elucidate the relative chronology of deposits so that deposits from subsequent flow along an avulsion channel can be distinguished from deposits from the initial avulsion event.

It should be noted that estimating the age of a landform from numerical dating methods may not provide greater resolution than can be determined with relative dating techniques, and determining a numerical age of a Holocene surface may not necessarily improve hazard assessments. Errors associated with each numerical dating method and imperfect conditions, such as re-transported organic material, could lead to incorrect ages, even when care is taken in sample selection.

Dating Techniques Applicable to Alluvial Fans in Maricopa County

Potential dating methods were narrowed down to those may be useful in the age determination of Holocene alluvial fans in semi-arid environments like those found in Maricopa County (Figure 1). Not all of these methods have been applied to fans within Maricopa County. However, they may prove useful in the future, since they have been used in other arid environments to date alluvial fan systems. The methods most applicable to Maricopa County include the following, which are described in the following paragraphs:

1. Optically Stimulated Luminescence (Numerical)
2. Radiocarbon (Numerical)
3. Cosmogenic Nuclides (Numerical)
4. Thorium-Uranium (Numerical)
5. Varnish Micro-Lamination (Correlative)
6. Pedogenesis (Relative)
7. Rock weathering (Relative)
8. Surface Morphology (Relative)
9. Gully diffusion (Relative/Correlative)
10. Palynology (Correlative)
11. Archaeology (Correlative)

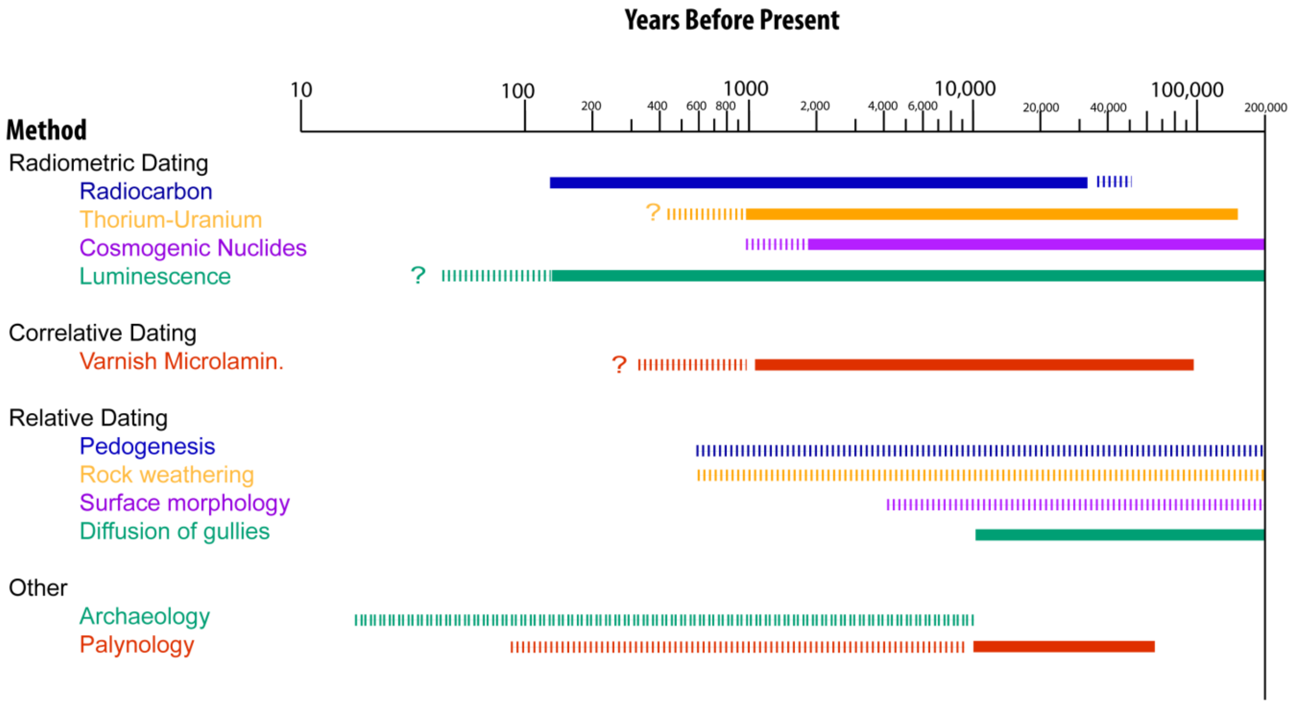

Figure 1: Numerical and relative dating methods that are appropriate to use in arid, alluvial fan environments; Age ranges possible per each method type is shown with corresponding color bars; age scale is logarithmic and in Years Before Present (YBP).

A number of numerical dating techniques have been applied to Quaternary sediments, soils, lavas and ice, such as electron spin resonance, paleomagnetism, amino-acid diagenesis, potassium-argon/argon-argon dating. However, only a few are applicable to alluvial fans in arid environments such as that of Maricopa County. Notable Quaternary dating methods that are not applicable to dating Holocene alluvial fan sediments include electron spin resonance, paleomagnetism, amino-acid racemisation, and Argon-Argon dating. Electron spin resonance (ESR) is often used to date bone and tooth enamel found in sediment greater than 40,000 years old, although some success has been made in dating quartz-rich sediment. ESR dating requires a full re-zeroing of the electron clock, which is problematic for geologically young sediments, such as those deposited in the Holocene. Paleomagnetism as a dating technique generally relies on periodic reversals of the earth's magnetic field that are recorded in magnetic minerals in volcanic rocks and sediments. The most recent magnetic reversal occurred about 780,000 years ago, so this technique only works for sediments that are hundreds of thousands to millions of years old. Amino-acid racemisation measures chemical changes in organisms following their death. This technique is limited to mollusks and animals with skeletal carbonate matrices, and thus is not useful in alluvial fan settings. Potassium-argon and argon-argon dating methods are generally limited to igneous rocks. Even with the exclusion of the above mentioned dating methods, there are still several Quaternary dating methods that are applicable to dating Holocene alluvial fan deposits in arid environments like that found in Maricopa County.

A combination of applicable techniques listed above would result in better age constraints. A combination of at least two field or relative dating methods should always be combined with one or more numerical methods. This will ensure that the numerical dates obtained would be in the correct context of the geomorphic system, and provides an independent check that the numerical value is not erroneous. For example, a suspicious radiocarbon age could actually be much older than the sediment in which the sample was taken since most radiocarbon samples found in alluvial fan sediments are detrital in nature, (not *in situ*). If the soil appears geomorphically young, and the surface morphology indicates a relatively young fan surface, but the radiocarbon age suggests a much older age, then that radiocarbon age should be excluded from the age estimate.

Optically Stimulated Luminescence (OSL)

Description. OSL dating works on the principle that sediments containing sources of naturally occurring radioactive isotopes, such as uranium, thorium, or potassium-40 are subject to low levels of radiation (Walker, 2005). Mineral grains exposed to radiation in the soils become ionized and release electrons that consequently become trapped in defects in the mineral grains. When sediment samples with these mineral grains are heated up, the electrons are released and can be counted to quantify how long the sediment has been exposed to the low level radiation, ideally after deposition. The amount of released electrons is proportional to the amount of time the sediment has been buried (Figure 2). This process of heating and measuring the amount of electrons that are released is called Thermoluminescence (TL). The sediment can also be exposed to a beam of light to release electrons in a process called Optically Stimulated Luminescence (OSL). OSL dating has essentially replaced TL dating in the dating of sediment (Walker, 2005), so this section will focus on OSL dating only.

The sample age is determined when the amount of radiation in the grains (dose equivalent) is measured and divided by the amount of radiation dose per unit of time absorbed by the mineral of interest since the zeroing of the luminescence clock by exposure to sunlight (dose rate). Because thermally stable traps cannot be pre-selected in OSL samples, sample aliquots are heated after exposure to laboratory radiation, but before final measurement. This “pre-heating” method empties all of the unstable traps that were filled with laboratory radiation, but it also leads to the transfer of some electrons, which will result in an erroneous error if not accounted for (Aitken, 1998; Huntley, 1985; Huntley et al, 1993b). The pre-heating error can be accounted for by constructing a dose-response curve from aliquots that have been given various lab doses and then given a long bleach (Walker, 2007; Huntley et al., 1993b). The dose equivalent is proportional to the point where two dose-response curves intersect over the dose axis. The environmental dose rate must account for the radiation absorbed by a mineral grain from itself and from surrounding minerals. Concentrations of uranium, thorium, potassium-40 for example, in the sample and its surrounding must be measured and converted to known formulae for this step. Cosmic rays, organic matter and water can infiltrate the sample and its surroundings and also must be accounted for in the dose rate.

OSL dating has been used to date Holocene sediments derived from fluvial, eolian, and alluvial systems. Dating of individual grains (single-grain OSL) of quartz has yielded late Holocene ages for alluvial sands in the Cuyama Valley near the central coast of California. Several samples from alluvial fans and fluvial terrace deposits were dated using OSL, radiocarbon methods and cosmogenic nuclides. Sand and silt deposited in a known flood event in 1998 were dated using the single-grain OSL method and yielded an age of 10 years (DeLong and Arnold, 2006). The U.S. Geological Survey's Luminescence Geochronology Laboratory successfully dated sands from alluvial fans located in the northeastern Mojave Desert (Mahan et al., 2007). They reevaluated geomorphic surfaces that had been previously dated with accelerator mass spectrometry (AMS) radiocarbon methods so that they could refine their OSL dating methodology and evaluate the applicability of dating alluvial fans. They refined Holocene and Pleistocene dates from multiple deposits from Valjean Valley, Silurian Lake Playa, Red Pass and California Valley using OSL and found that the dates were in agreement with previous AMS dating and mapping results.

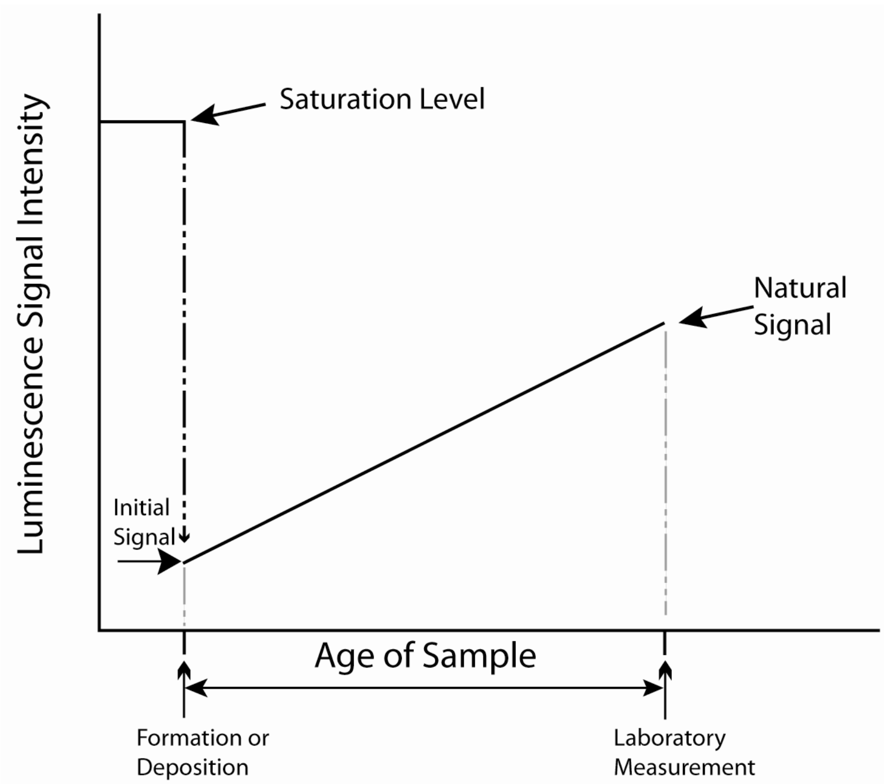

Figure 2: Schematic plot representing luminescence dating principles as applied to sediment; The "Initial Signal" represents the bleaching or erasing of low level radiation by exposure to light during erosion, transport or deposition; the "Natural Signal" represents the buildup of radiation after the sediment has been buried; modified from Walker, 2005 and Aitken, 1998).

Sampling Techniques. OSL sampling protocols have been determined by the U.S. Geological Survey, and by individual laboratories that perform OSL analysis, such as the laboratory at Utah State University. This section gives a generalized description of sampling protocols, but specific protocols set forth by the laboratory that will process the samples should supersede this description. OSL samples should be targeted around sandy deposits, preferably deposits that contain bedding structures, such as laminae, cross-bedding or grading. Eolian deposits are especially preferred since they are quartz-rich and have had adequate exposure to sunlight. Fire can reset the luminescence clock and if sediments are suspected to have experienced a fire, they cannot be sampled for OSL dating. OSL sampling requires one tube sample, one bulk sample and one moisture sample per each lens or bed of silty sand or sand layer to be dated. The exposure is cleaned off by removing about 8 inches to a foot deep of sediment. An inch diameter and 8 inch long aluminum (or thick pvc) tube is driven perpendicularly into the exposure after it has been cleaned off. A moisture sample should be collected using a small cylinder that has an air-tight cap, such as a film canister. The aluminum or pvc tube should be capped on the exposed end to prevent light from entering into the tube. To prevent mixing of sediment when the tube is driven into the exposure, the Utah State OSL Laboratory suggests adding a 1 inch thick disk of Styrofoam to the tube at the open end prior to driving the tube into the exposure. For the bulk sample, the sediment around the tube should be collected in a 1 quart Ziplock-type plastic bag. Collection of the bulk sample will also aid in the removal of the tube sample. Upon removing the tube sample from the exposure, the tube should be pulled out gently and tipped upward on the open end. Once the tube is removed, it should be quickly capped and taped to prevent exposure to light. The precise location of the sample should be noted, along with the depth from the surface and orientation of the exposure with respect to north. It is strongly recommended that prior to OSL sampling, a working relationship be developed with the laboratory operators and scientists because most academic laboratories, like the Utah State OSL Laboratory, do not do outside contract work.

Limitations. OSL dating requires that the radiation clock in the grains has been completely reset by adequate exposure to sunlight prior to deposition and that they are not exposed to intermittent sunlight after deposition. For example, if sediment was removed from another landform and then transported rapidly and deposited after a storm, it may not have received adequate sunlight to zero the luminescence clock (residual OSL). Moreover, if the sediment had been densely burrowed by roots and animals, it may receive intermittent sunlight. Deposition in alluvial fan settings may mix grains with differing amounts of residual OSL, resulting in different age estimates. The rate of bleaching or zeroing is less rapid for quartz than say for feldspar minerals, thus quartz samples may have more residual OSL than feldspar and give different ages. Young sediments in particular, are thought to be problematic because of the rate of bleaching associated with them (Aitken, 1998; Walker, 2007); however, very young sediments were dated in the recent study by DeLong and Arnold (2006). Although the bleaching rate is controlled by site conditions, such as fire, transport history, and grain types, the results from the DeLong and

Arnold (2006) study suggest that bleaching may occur during grain transport within an individual flood event.

Radiocarbon Dating of Organic Material

Description. The radiocarbon dating method was first developed in the 1950's (Libby, 1952) and has been applied to a wide variety of geological and archaeological studies. Organic material and charcoal found in alluvial fan sediments have been dated over the last several decades with meaningful results. Dating organic debris or charcoal in deposits dates those deposits, and would generally provide a maximum age constraint for the overlying alluvial surface.

The radiocarbon dating method relies on the principle that terrestrial organisms bind up carbon isotopes from the atmosphere until they die. After death, the carbon isotopes decay at a known rate and can be analyzed to obtain the time since death of the organism. The isotope of carbon, ^{14}C is not stable and decays to a stable form of nitrogen via the release of a beta particle. ^{14}C becomes part of the global carbon cycle when it interacts with the atmosphere and forms $^{14}CO_2$ which is used in plant photosynthesis and ingested by animals when they eat plant tissue. Once an animal or plant dies, the organism no longer replenishes itself with ^{14}C and the ^{14}C begins to decay. The half-life of a ^{14}C atom has been determined and is 5730 years. By comparing how much ^{14}C remains to a modern standard amount, the age of death of the organism can be estimated. Accelerator Mass Spectrometry (AMS) techniques are now commonly applied by dating laboratories and can be used to date 1/10 of a milligram of material. AMS dating measures the amount of ^{14}C directly by accelerating the sample atoms as ions to high energies with a particle accelerator and then detecting the amount of particles in a nuclear particle detector.

In a depositional setting, such as an alluvial fan, the organic material usually has been transported by water and is often referred to as "detrital". The length of time between death and transport and final deposition can vary, resulting in varying reliability of the age estimate. For example, if a desert tree dies and parts of it are entrained in a flood, it may be deposited relatively quickly with respect to the time since its death. If that same part of a tree is transported and re-deposited several times, it may not yield a meaningful age for the deposits it ends up in. Radiocarbon dating of situ dead trees may also provide constraints on the age of alluvial fan deposits (Pearthree et al, 2000).

Sampling Techniques. In order for radiocarbon dates to effectively date alluvial fan deposits and surfaces, the stratigraphic or geomorphic position of the sample must be documented. Radiocarbon dating plant debris or charcoal in alluvial fan sediments requires that the sample be taken at a particular stratigraphic interval. In other words, the sample must be taken from an identifiable sedimentary or pedogenic unit. Alluvial fan sediments can contain decaying plant debris or pieces of charcoal. If such material is identifiable with the naked eye, it is likely large enough for AMS radiocarbon dating. The sample should be collected with tweezers and wrapped in foil, taped and bagged with a label. Bulk sediments can be selected and dated. One-gallon air-tight plastic bags, like Ziplock Freezer bags can be used to collect bulk samples. Organic material can be separated from the bulk sediments via floatation and can be identified by an AMS laboratory or palynologist for selection of datable plant debris. The bulk age will represent the age obtained by combining the small fraction of floated plant debris and will not represent the date on a specific piece of organic material. Bulk sample dates may provide an idea of the age of the sediments, but can also have so much detrital plant material that the date is rendered unreliable.

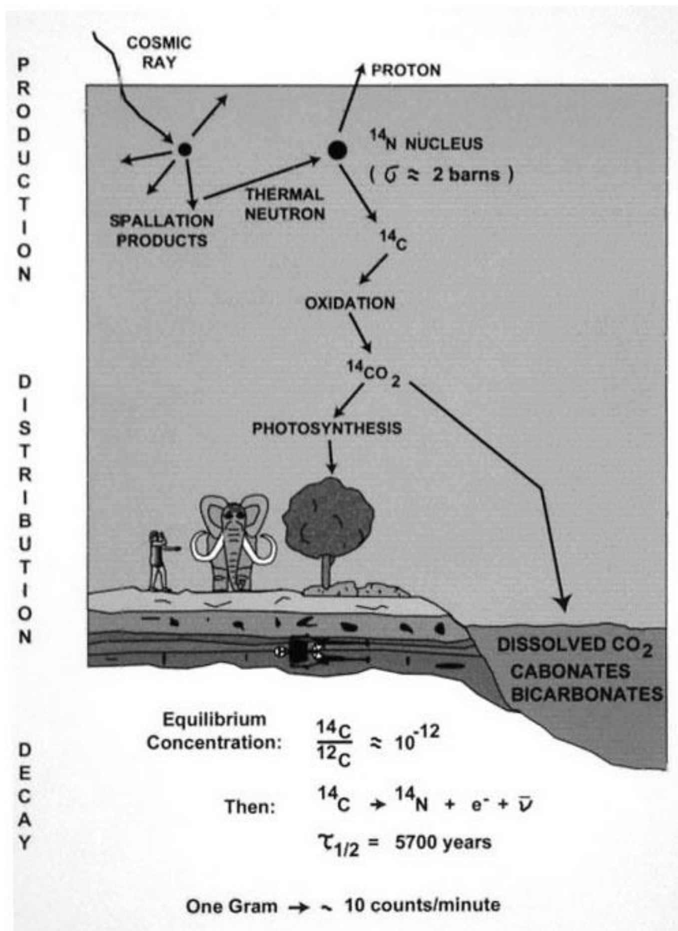

Figure 3: Schematic of the production of carbon-14 in the upper atmosphere, distribution to plants via photosynthesis, distribution to animals via ingesting plant material, and decay after death of plants and animals. Schematic taken from the University of Arizona's AMS Laboratory website (http://www.physics.arizona.edu/ams/education/theory.htm).

Limitations. Finding datable organic debris and charcoal in arid alluvial fan settings is rare. In addition to its rarity, the detrital effect described above could yield ages that are much older than the sediments from which the sample was collected, and younger organic material can be introduced into sediment by burrowing and root growth. Bulk samples can be collected and floated by laboratories to determine if any organic material is present, but this step is an additional cost to the actual AMS radiocarbon dating of the sample and bulk age estimates may have larger detrital error effects. Given the uncertainties with bulk sampling, they may still provide the basis of dating young soils and sediments in alluvial fan systems when other dating methods are not available. For example, radiocarbon ages obtained from bulk samples taken from an alluvial fan near the base of the Ajo Mountains in southern Arizona (Liu et al., 1996) yielded reasonable ages that were in stratigraphic order. The radiocarbon ages were compared to cosmogenic ^{36}Cl accumulation ages, and although the radiocarbon ages were younger than the cosmogenic ages by several thousand years, they provided a meaningful age estimate of the sediments from which they were collected (Liu et al., 1996).

Cosmogenic Nuclide Dating of Surface Exposure

Description. Cosmogenic dating is based on measuring the amount of nuclides generated by cosmic radiation that has accumulated on the upper few feet below the earth's surface. The production of nuclides in the subsurface exponentially decreases with increasing depth beneath the surface. The Earth's surface is bombarded with high energy neutrons that form when cosmic rays entering the atmosphere collide with nuclei. The collision of neutrons (and muons) and nuclei within certain atoms in minerals leads to the creation of new nuclides. The new nuclides progressively accumulate in exposed and near-surface rocks over time and can therefore provide an age of the surface exposures once their concentrations have been determined. The accumulation of cosmogenic nuclides is a function of the time of rock exposure to cosmic radiation, rock chemical composition and the intensity of cosmic radiation, which is dependent on the geomagnetic latitude, altitude, and mass shielding depth. Surface ages can be estimated with ^{3}He, ^{14}C, ^{10}Be, ^{26}Al and ^{36}Cl (see Table 1 for age ranges per nuclide). ^{14}C, ^{10}Be, and ^{26}Al nuclides are measured from pure quartz samples, ^{3}He typically is measured from olivine crystals, and ^{36}Cl is measured from whole rock samples.

Because clasts undergo cycles of erosion, transport and deposition, the amount of cosmogenic nuclides builds up prior to the final event of deposition. This residual concentration of cosmogenic nuclides is referred to as inheritance and must be accounted for in the age determination of an alluvial surface. Repka et al. (1997) collected 30 clasts and amalgamated their ^{10}Be and ^{26}Al concentrations so that they could calculate the average inheritance of these nuclides. The average inheritance from these clasts corresponded to an error of 30 to 40 Ka, which would have resulted in erroneously older terrace ages. Depth profiles can also be used to indicate how much movement clasts may have experienced since deposition. Disturbed clasts may have more exposure to cosmogenic nuclides, even after burial and some surface clasts may have been buried and exhumed as erosion of the surface took place. Dating a surface clast that has been buried and then exhumed would result in an erroneously young age. Judicious selection of samples and depth profiles is paramount to estimating the age of any surface.

Nuclide	Target Nuclides	Half-life (yrs)	Approx. Useful dating range (yrs before present)	Materials commonly dated
Helium-3	Uranium-235 Uranium-238 thorium-232	12	1,000 to several million	olivine
Beryllium-10	Oxygen-16, Silicon-28, Beryllium-7, Beryllium-9, Boron-10, Carbon-13	1.6 million	< 5 million	quartz, olivine, magnetite, plagioclase
Carbon-14 (not the same as C-14 formed from N-14)	Oxygen-16, Oxygen-17, Silicon-28, Nitrogen-14, Boron-11	5,730	< 20,000	quartz
Aluminum-26	Silicon-28, Sodium-23	705,000	< 5 million	quartz
Chlorine-36	Calcium-40, Potassium-39, Chlorine-35	301,000	< 1 million	potassium-feldspar, plagioclase, calcite, chlorite, fluid inclusions in quartz

Table 1: Cosmogenic nuclides commonly used in surface exposure dating and their age ranges.

Robinson et al., (2000) applied the cosmogenic dating method to three Quaternary deposits on the western piedmont of the White Tank Mountains, in Maricopa County. Using relative dating techniques they estimated the ages of the surface to be O > 1,000,000 yrs, M = 10 – 1,000,000 and Y < 10,000 years old. They sampled for ^{10}Be, ^{26}Al, and ^{36}Cl cosmogenic nuclides on all three surfaces and completed two depth profiles up to 8.8 meters deep. The results of their study were inconclusive and warranted more sampling for inheritance estimations. To date, this has been the only cosmogenic nuclide dating study performed in Maricopa County and surrounding vicinities. Although only one study has been completed in Maricopa County, cosmogenic nuclide dating could be developed into a viable dating tool once inheritance estimates and sampling protocols are developed.

Sampling Techniques. Not all alluvial surfaces can be dated with cosmogenic dating methods. A datable surface should not exhibit erosional features, such as dissection and the clasts on the surface must not have been disturbed or exhumed. Once a surface has been selected for dating, boulders exposed on top of the surface are collected. The upper few centimeters of the boulder's surface will be targeted for age estimation in the laboratory. Samples should be taken from horizontal or near horizontal surfaces. To estimate the amount of inherit cosmogenic nuclides present on a surface, measurements must be made on several clasts per depth of the surface. As mentioned above, a depth profile must be excavated and several clast samples (up to 50) should be collected from the profile so that the amount of inheritance can be calculated from the amalgamated sample concentrations. The depth of the profile would depend on the thickness of a clast-rich deposit, but generally would be a few feet.

Limitations. Several factors can inhibit the use of cosmogenic dating of alluvial fans. In particular, young deposits have been known to have problematic and complex inheritance histories. Reworking of gravel from older landforms in the vicinity of young alluvial fan is likely, and this would contribute clasts from landforms with different exposure histories. The influence of inheritance on the estimated age diminishes with the age of a fan (Gosse et al., 2005). If enough samples were collected and yielded stratigraphically good dates, and those dates were corroborated with other techniques, such as OSL and relative dating of pedogenic components of the landform, then a chronology of fan development and associated features could determined.

Th230/U Disequilibrium Dating of Pedogenic Carbonates

Description. Uranium radioactively decays to several isotopes over time. In a closed system, if a mineral is left undisturbed for several million years, the activity of each daughter isotope will come to be equal to that of the parent uranium isotope. In most cases, the mineral is disturbed and daughter isotopes escape and a break in the decay chain will result in disequilibrium. When a break in the decay chain occurs, the nuclides above and below the isotope in the chain are in disequilibrium and they strive to reach equilibrium by forming more daughter products. The formation of pedogenic carbonate represents an example of a system in disequilibrium. Uranium is quite soluble and its daughter product thorium is not, so it is reasonable to assume that all the thorium in a sample is the product of uranium decay disequilibrium. The age of the carbonate can be determined by measuring the extent to which the decay product 230^{Th} has grown back in the carbonate matrix.

Ku et al. (1979) used the disequilibrium relationships among Th230, U234, and U238 to date pedogenic carbonates that formed in the arid and semi-arid climate of Vidal Valley, in southeastern California. They leached carbonate rinds from several clasts found on Pleistocene geomorphic surfaces and corrected for contamination by separating the carbonate matrix from the silicate component with chemical separation techniques. Their results indicated that dating pedogenic carbonates was a viable dating method for Pleistocene surfaces and was in stratigraphic agreement with relative dating techniques. Sharp et al. (2003) dated pedogenic carbonate rinds in the Wind River Basin of northwestern Wyoming with Th230/U thermal-ionization mass spectrometry (TIMS). They targeted microscopic rind laminations from carbonate rinds found in Pleistocene glacio-fluvial terraces. In addition to the dates they obtained for the terraces they determined that the lag time between alluvial deposition and the formation of carbonate rinds was about 2000 to 5000 years. The Th230/Udating of Holocene carbonate rinds using TIMS may prove useful for surfaces that are greater than 5000 years old.

Sampling Techniques. Several pebbles must be collected from the same soil horizon with a deposit, and all of the samples should exhibit similar rind thickness and general appearance.

When sampling pebbles for carbonate rind dating, it is recommended to avoid pebbles with truncated laminations since they were likely the result of erosion of carbonate during transport of the pebble with accretion resuming upon repeated deposition (Ku, et al., 1979). Another type of pebble coating or rind to avoid is one in which salt splitting has allowed young carbonate to be precipitated between the pebble and the oldest carbonate layer (Ku et al., 1979). Sharp (2003) collected 35 to 70 pebble-sized clasts at each sampling locality. The pebbles were cut, polished, examined and photographed at 5 to 20X magnifications to select the microscopic sample point on the carbonate rind. Under the microscope, pristine rind material was selected by finding sample areas in each rind that were dense, translucent, reddish brown, and characterized by sub-millimeter-scale laminae lying sub-parallel to the clast-rind boundary (Sharp, 2003).

Limitations. Th230/U disequilibrium dating of pedogenic carbonates has been used to successfully date Pleistocene alluvial deposits, but dating younger Holocene deposits has not been done largely because of the lag time in deposition of the sediments and the formation of carbonate rinds on clasts. This method may prove useful in the future to date early Holocene deposits if work to refine the method progresses. Some researchers are wary of using pedogenic carbonates to date any deposit since the formation of pedogenic carbonate on clasts is not a truly closed system. The formation of the carbonate is posited to occur from the clast surface, outward, away from the clast. Some research suggests that there is microscopic pore space between the clast and the forming rind and that water and other microscopic particles can infiltrate the rind, thus resulting in erroneously young age determinations. The two studies cited in the section above were successful in dating alluvial deposits and surfaces with this method and their results were consistent with other dating methods.

Varnish Microlamination Dating of Surface Rock Varnish

Description. Rock varnish is a slowly accreting dark coating on subaerially exposed rock surfaces in arid to semiarid deserts (Liu and Broecker, 2007) and forms as microlaminations. Varnish microlamination dating (VML) is a correlative age dating method first used by Dorn (1988) to study the chronostratigraphy of alluvial fan deposits in Death Valley. Liu (2003), Liu and Broecker (2000 and 2007), and Liu and Dorn (1996) have improved VML dating methods by correlating varnish microlaminations from deserts found all over the world. The VML method assumes that the formation of varnish microlaminations is largely influenced by regional climatic variations, and that climatic signals have been recorded in varnish as microlaminations of varying color and composition (Liu and Dorn, 1996; Liu et al., 2000). Varnish microlaminations are composed of about 30% manganese and iron oxides and up to 70% clay minerals and several trace and rare earth elements (Liu, www.vmldatinglab.com).

Liu and Broecker (2007) studied hundreds of rock varnish samples from late Pleistocene and Holocene alluvial fan surfaces and other geomorphic features in the western United States. Their analysis resulted in a replicable microlamination sequence that consisted of 12 evenly spaced dark layers intercalated with 13 orange/yellow layers (Figure 4) (Liu and Broecker, 2007). They interpret the dark layers as having formed during relatively wet climatic periods. Several of the Holocene geomorphic features had been previously dated with other methods, such as AMS radiocarbon, so that they could calibrate the ages of their assigned layering units (Figure 4).

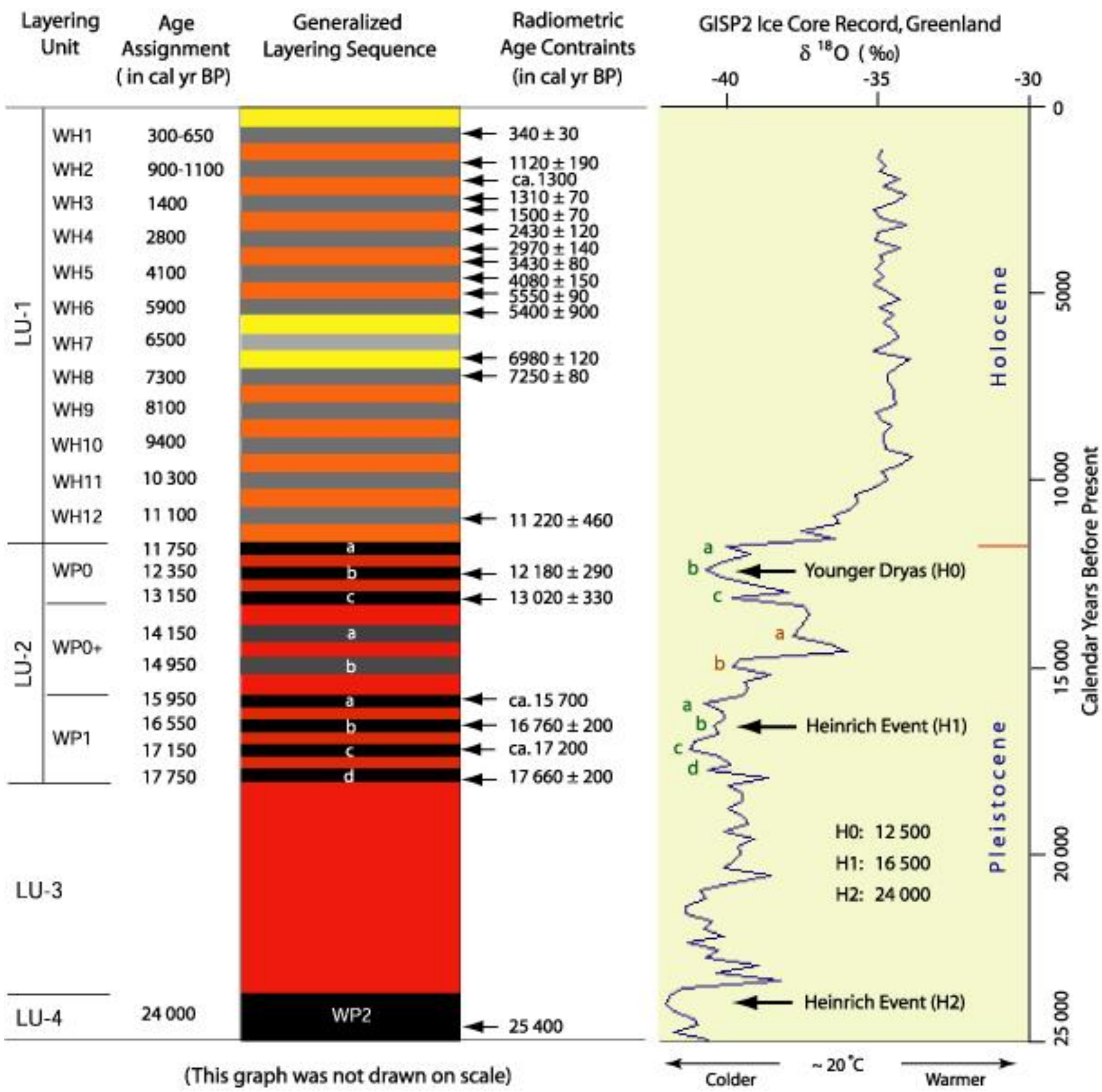

Figure 4: Late Pleistocene and Holocene varnish microstratigraphy and associated layer units, age assignments and comparison with Pleistocene varnish and the GISP2 Ice Core Record (Liu, www.vmldatinglab.com); WH = wet event in Holocene, WP = wet event in Pleistocene, LU = layering unit.

Sampling Techniques. Samples collected from alluvial surfaces for VML dating should be taken from exposed rock surfaces. Two types of varnish may form, one on rocks exposed at the surface of a landform and the other beneath the rocks (Liu and Dorn, 1996). Exposed varnishes are the only varnishes that display consistent microlamination sequences (Liu and Dorn, 1996). Liu and Dorn suggest that scientists be trained in sample collection methods by the VML

Laboratory employees and then samples can be shipped to their lab so that they can make ultra thin sections of the samples for correlation.

Limitations. The major drawbacks of using VML dating on Maricopa County fans are that: (1) it is a relatively new method and has only been applied to 2 sites in Arizona, and one them is an otherwise undated alluvial fan near the McDowell Mountains; (2) Holocene varnish microstratigraphy would need to be further calibrated in southern Arizona; and (3) sampling protocols need to be performed by someone specializing in VML dating. The first and second issues could be addressed with more investigations in Arizona and the use of other dating techniques to assess and calibrate VML dating. For example, if the global climate has changed from a wet to dry to wet as recorded by deep sea sediments in the North Atlantic Ocean, would that cycle of wet to dry to wet be recorded in rock varnish in Arizona's deserts? Would the local climate actually have a different signal in response to global climate changes? In addition to problems with direct global correlation, the development of varnish microlaminations may occur at different rates and would be time transgressive, therefore rendering calibrated ages from different sites invalid. We suggest, after researching its apparent usefulness in dating other arid landforms, that VML dating be applied to dating fans in Maricopa County. The method could be applied as experimental, and if deemed useful, it could develop into a viable technique for dating Holocene alluvial fan surfaces throughout Maricopa County.

Pedogenesis and Surface Morphology

Description. The degree of soil development can be used as a relative measure of the amount of pedogenic change that has occurred in the parent material. Soils chronosequences can be developed for soils that have developed in a particular region in which all of the factors of soil formation, except time are reasonably constant. Contrasts between different soil profiles in terms of carbonate content and form, particle size variations, depth of soil development, strength of material, clay content and films, and color can change as a function of time. These properties can vary for soils of the same age, however, because of local variations in aspect, erosion, lithology of clasts, movement of ground and surface water and biological activity. Some researchers have developed soil development indices (Birkeland, 1999; Harden and Taylor, 1983; Berry, 1994) to quantify soil ages based on pedogenic features, but because pedogenic features can vary so greatly on the same aged surface, the use of these indices as rough numerical soil age estimates can be problematic.

In a semi-arid environment like that of the White Tank Piedmont, the degree of soil development is proportional to surface age. As the surface ages, a soil profile develops, and its structure, color and content changes. Clay and calcium carbonate accumulate in the soil from eolian sources and chemical weathering of the parent material, forming distinct soil horizons. The degree of soil profile development, particularly in the clay and carbonate horizons, can be used as a proxy for surface age. The soil surface also tends to become reddish in color with time due to oxidation of iron (rubification) as well as accumulation and weathering of clay. Young, active surfaces lack soil profile development, and on active alluvial fans consist of stream bed alluvium.

Geomorphic surfaces may also develop an accumulation of pebbles and cobbles at the surface as they age. These gravel coverings are known as desert pavement, which form as a byproduct of windblown silt and clay accumulation in the soil column. Repeated wetting by precipitation causes the fine-grained materials to swell, lifting the larger gravels to the surface. Repeated surface drying creates cracks into which more fine windblown material may accumulate. Over thousands of years these processes form a mantle of closely packed gravels that resembles asphalt pavement (Dohrenwend, 1987; Vanden Dolder, 1992). The pebbles and cobbles that form the pavement surface, if they contain sufficient ferromagnesian minerals, will develop a dark black patina on their tops and an orange coating underneath that is known as desert varnish.

Landform surfaces free from new deposition will also begin to erode due to direct rainfall and the ensuing runoff on the surface. As the surface erodes, new tributary channel networks develop which become more incised and integrated with time. The channels gradually deepen and widen, creating a greater degree of relief between the channel bottoms and the ridges which separate them. The degree of relief can be directly observed in the field or on aerial photographs, but can also be detected by the examining the crenulation (curviness) of topographic map contours.

The degree of relief of an apparently inactive landform relative to adjacent active, young surfaces is also an important characteristic. Because active alluvial fans are aggrading landforms, it follows that some older surfaces may gradually become buried by sediment deposition derived from the adjacent younger active alluvial fan. Therefore, where there is little topographic difference between younger and older surfaces, the investigator must take care to evaluate the rate of, and potential for, long-term aggradation of the fan. Typically, the rate of fan aggradation is greatest near the hydrographic apex, with lower accumulation rates as the distance from the apex increases and/or the active fan widens.

AZGS surficial geology mapping differentiate surfaces based on the types of geomorphic characteristics discussed above. Therefore, the map data also provide information about surface age, stability, and flood potential. Young surfaces with little soil development are likely to continue to experience flood inundation, sediment deposition, and channel movement. Older surfaces are unlikely to experience such processes. Older surfaces with cemented soils and entrenched channels also tend to be more stable because their soils are more resistant due to the cohesion provided by clay, carbonate, and pavement, as well as due to containment of flow within defined, vegetation-lined channels. That is, the likelihood of the channel changing its location over time is greatly diminished. Conversely, areas with non-cohesive, coarse soil materials and little lateral relief are more susceptible to lateral changes in channel position.

Even with local variations in pedogenic features, their use as relative age indicators is practical and often the only way to constrain the age of a soil and its surface, which can provide the basis for evaluating dates generated by chronometric or numerical techniques. Geomorphic mapping of alluvial fan surfaces is based on several factors, such as degree of preservation of bar and swale topography, desert pavement development, general rind thicknesses, reddening of underlying soils and bottoms of surface clasts, vegetation types and density, degree of carbonate development, plasticity of soil, and presence of B-horizons. The use of pedogenic features to estimate the age of soils and their surfaces is helpful in determining what deposits are youngest to oldest in a given area, and a numerical *range* can be assigned to those deposits. For example, if an alluvial fan surface in Maricopa County has been mapped as a "Qo" surface, its associated soil probably contains laminar carbonate layers and chunks of thick carbonate rinds, and the surface is likely > 1,000,000 years old. Fan deposits that have very weakly to weakly developed soils with minimal carbonate and clay accumulation can be estimated to be middle to late Holocene aged.

Young alluvial fan deposits have rough surfaces that are composed of bar and swale topography and as the fan surface ages, it becomes smoother and eventually armored with desert pavement. With further aging of the alluvial fan surface, it can become dissected, with rounding of its edges and dissecting channels. Hsu and Pelletier (2004) applied linear hillslope diffusion to cross-sectional gully profiles taken from Quaternary alluvial fan surfaces at the base of the Ajo Mountains in southern Arizona. They focused on pre-dated fan surfaces with ages of approximately 10 ka to 1.2 Ma and found that their method produced ages with 30 to 50% accuracy. They cautioned that their method should not be used to correlate and relatively date alluvial fan surfaces (Hsu and Pelletier, 2004) until the method has become more refined.

Limitations. Relative dating methods such as the use of pedogenic features to characterize soils do not provide specific numerical age values, but rather broad age ranges. The variation in pedogenic features as mentioned above vary from region to region, although there usually are consistent cross-correlating features. For example, if a soil is thought to be late Pleistocene in age and it contains reddened soils in one locality, but not another, then other features can be used to constrain the age estimate, such as the degree of carbonate buildup. Topography and vegetation have been shown to be as important as time in explaining soil genesis, and can control the distribution and types of soil features in a given region (Walker, 2005). Even with the largely unconstrained nature of relative dating methods such as pedogenesis and surface morphology, these methods should be used as a first order approximation of age because they are useful in distinguishing between Holocene and Pleistocene surfaces. These methods are cost effective and should be used to isolate areas that may need more labor and cost intensive methods to determine their ages.

Rock Surface Weathering

Description. Physical and chemical weathering processes begin to alter geomorphic surfaces and their sediments right after they are deposited. Boulders exposed on geomorphic surfaces develop weathering rinds, rock varnish (discussed previously), and can disintegrate over time. Weathering rind thickness is usually indicative of the time the boulder has been exposed and subjected to physical and chemical weathering processes. Relative ages between surfaces can be estimated by measuring weathering rind variations on similar lithologic samples. Knuepfer (1994) suggests that surface weathering rind variation dating in the western United States is best suited for application to shorter time intervals, such as the Holocene, whereas subsurface rinds may be utilized for longer time intervals. This is due in part to the decrease in chemical weathering rates over time. Early stages of weathering rind growth follow a power-law increase and growth slows down as the buildup of weathering residues impedes the movement of water into the rock. Weathering rinds should be measured on homogeneous, fine-grained lithologies, such as basalts and limestones, to ensure that the rates of rind formation are consistent from sample to sample (Knuepfer, 1994). In addition, sample selection should be limited to clasts that do not have rinds that were developed prior to transport to their current locations. Comparison of rinds on tens of samples of the same lithology on the same surface may elucidate which rocks have inherited rinds. Transport of rocks as bedload in floods tends to rejuvenate rock surfaces due to rind removal by abrasion and other processes (Knuepfer, 1994).

The rock surface weathering features described above is relatively inexpensive and could provide correlative age constraints, especially if they are calibrated by using one or more of the numerical methods described above. In other words, surfaces with the same climate and rock types that have been dated with OSL or even cosmogenic nuclides could be analyzed for rind thicknesses, and degree of weathering. A chronology and associated rind thicknesses per general rock type and degree of weathering could be applied to other surfaces that have not been dated with numerical dating techniques.

Limitations. To date, a comprehensive study to calibrate surface ages in the Southwest based on rind thicknesses and degree of weathering has not be completed. Calibration of these methods would require hundreds of measurements of rinds and degree of weathering on multiple surfaces and their associated geomorphic surfaces would need to be dated with independent numerical methods. The variability in rind thickness or weathering would likely be high as both of those surface weathering processes are controlled by lithology, local climate, altitude, aspect, biological activity and the movement of water in the soil column. Few lithologies lend themselves to consistent rind production. Weathering rind measurements would need to be focused on fine-grained, homogeneous lithologies, such as basalts.

Palynology

Description. The introduction of exotic plants and animals after the arrival of European settlers to the Americas resulted in the deposition of exotic plant debris, fungus, and exotic pollen grains that can provide age estimates of the sediments and soils in which they were deposited. For example, *Salsola*, commonly referred to as tumbleweed was introduced to the United States in 1871 with a shipment of flax seed to South Dakota. After approximately 10 years, tumbleweed had been distributed across the western U.S. and its pollen deposited in sediments and soils. Cattle grazing in the western United States began with the arrival of European settlers. This led to the introduction of *Sporomiella,* a dung fungus associated with livestock that has been observed in sediments and soils in the southwest. The presence of this spore in soils and sediments can also be used to infer their young ages (Burney et al., 2003; Young et al., 2002; Davis, 1990). An alluvial fan displaced by the San Andreas fault in central California was dated by the identification of historic pollen types from tumbleweed and eucalyptus (Young et al., 2002). Pollen grains from tumbleweed and eucalyptus, and the *Sporomiella* fungus were identified in silts collected in the upper ¾ of a meter of the excavation and these types were not found in samples taken at much deeper depths, thus suggesting the silts were deposited during historic time (Young et al., 2002). In addition to the identification of historic grains, pollen horizons were constructed based on the concentration of pollen and the type of sediment the sample was taken from. Fine-grained, laminated silts contained several pollen species, while coarse grained sands did not contain any pollen (Young et al., 2002). This is due in part, to the movement of pollen out of the sands after deposition. Construction of pollen horizons in a sedimentological context is important to constrain the possibility of movement of pollen.

Sampling Techniques. Collecting samples for concentration and identification of pollen types can be done by extracting soil or sediments from an exposure or by coring. Exposures need to be scraped and cleaned prior to sampling and approximately 300 grams should be collected per sample. Samples should be floated for identification of plant debris. Concentration of pollen is done with a series of acid washes (HCl and HF) and centrifuging. Concentration and identification of pollen, spores and plant debris can be done with specialty laboratories such as Paleo Research Laboratory in Colorado.

Limitations. The identification of historic pollen grains, spores or other plant debris must be performed by trained palynologists. This endeavor, including acid washing is time consuming and costly. In addition, historic index taxa may not be present in samples, and if they are, movement in the soil column must be considered. As mentioned in the above example, some sediment may be completely void of pollen grains, even after careful collection, preparation and identification procedures have been followed. Ages obtained from identifying historic spores or pollen grains are only bound by the introduction of historic plants and livestock and cannot be used to resolve ages younger than 1900 A.D.

Archaeology

Description and Limitations. Although the use of archaeology to help constrain the ages of alluvial fan deposits is limited, it can provide valuable age constraints for some fan sediments. The identification of potsherds, stone tools, farming remnants, fire pits and other artifacts has been used in the past to infer the sediment and surface ages. If artifacts are found within the soil or sediment column of an alluvial fan, they could provide age estimates of the sediments and surfaces overlying them.

Recommendations

Relative, numerical and correlative dating methods can be used to date Holocene alluvial fans in the southwest, including Maricopa County. However, accurately estimating the ages and establishing a chronology of alluvial fan development in Maricopa County will require a multi-method approach. Relative dating methods are an important first step, and are used to generate a contextual geomorphic interpretation as well as detailed maps that define the physical framework of the alluvial fan system. The relative dating results provides a basis for evaluating what type of material and surface to sample and what dating methods would be most useful. Generally, numerical dating methods should always be coupled with relative age indicators. If numerical ages are obtained from alluvial fan sediments and surfaces like those found in Rainbow Valley or Tiger Wash, then indirect dating techniques like VML, weathering rind thickness measurements, surface roughness and degree of soil formation can be calibrated from those same sediments and surfaces. When relative dating methods have been calibrated at several sites within Maricopa County, a regional chronology of fan and surface development can be constructed that would apply throughout Maricopa County. The process of constructing a regional chronology could take several years to complete, and would require the involvement of several types of dating and surficial geology experts. Once completed, it would provide useful guidelines in the PFHAM for dating and delineating young alluvial fan surfaces.

There are several relative dating methods that can be used to generate landform base maps, and provide estimates of surfaces ages. There are two to three numerical and correlative methods that can be used refine surface and sediment ages. Below is a list of those methods and their general limitations:

- Geomorphic mapping and application of relative dating methods (surface morphology, degree of soil and desert pavement development, vegetation type and density, carbonate content and structure) should be performed prior to applying any numerical dating techniques. Relative dating techniques do not provide direct ages and may not be useful in resolving ages of Holocene surfaces. In addition, most of these relative age indicators have not been calibrated for fans and sediments/soils in Maricopa County and surrounding regions.

- OSL and AMS radiocarbon dating methods are the most applicable numerical dating methods in dating alluvial fan sediments. OSL dating has not previously been applied to alluvial fans in Maricopa County, and the method would need to be refined for this region. AMS radiocarbon dating is problematic because of the nature of detrital organic input and the low production of organic debris.

- Cosmogenic nuclide dating and varnish microlamination correlation are the most favorable methods for estimating surface ages. Cosmogenic nuclide dating of relatively young alluvial surfaces is limited by problems associated with inheritance, but may prove useful once inheritance values are estimated with repeated use. Varnish microlamination (VML) is a correlative method and should be evaluated further in Maricopa County. This technique is not widely in use and must be performed by one or two specialists.

References Cited

Aitken, M.J., 1998. *An Introduction to Optical Dating*, Oxford University Press, pg. 1-280.

Berry, M.E., 1994. Soil-geomorphic analysis of late-Pleistocene glacial sequences in the McGee, Pine and Bishop Creek drainages, east-central Sierra Nevada, California, *Quaternary Research*, 42, pg. 160-175.

Birkeland, P.W., 1999. *Soils and Geomorphology*, Third edition, Oxford University Press, New York and Oxford, pg. 1-430.

Burney, D.A., Robinson, G.S., and Burney, L.P., 2003. *Sporomiella* and the late Holocene extinctions in Madagascar, *in Proceedings of the National Academy of Sciences of the United States.*

Davis, O.K., 1990. Pollen analysis of Soda Lake, Carrizo Plain, California, Report to The Nature Conservancy, 785 Market Street, San Francisco, CA 94103.

DeLong, S.B., and Arnold, L.J., 2007. Dating alluvial deposits with optically stimulated luminescence, AMS 14C and cosmogenic techniques, western Transverse Ranges, California, USA, *Quaternary Geochronology*, 2, pg. 129-136.

Gosse, J., McDonald, E., and Finkel, R., 2003. Cosmogenic nuclide dating of arid region alluvial fans, Geological Society of America, *Abstracts with Programs*, pg. 228.

Harden, J.W., and Taylor, E.M, 1983. A quantitative comparison of soil development in four climatic regimes, *Quaternary Research*, 20, pg. 342-359.

Huntley, D.J., Godfrey-Smith, D.I. and Thewalt, M.L.W., 1985. Optical dating of sediments, *Nature*, 313, pg. 105-107.

Huntley, D.J., Hutton, J.T. and Prescott, J.R., 1993b. Optical dating using inclusions with quartz grains, *Geology*, 21, pg. 1087-1910.

Hsu, L., and Pelletier, J.D., 2004. Correlation and dating of Quaternary alluvial-fan surfaces using scarp diffusion, *Geomorphology*, 60, pg. 319-335.

Knuepfer, P.L.K., 1994. Use of rock weathering rinds in dating geomorphic surfaces, *in Dating in Exposed and Surface Contexts*, ed. By C. Beck, Albuguerque: University of New Mexico Press, pg. 15-25.

Ku, T.L., Bull, W.B., Freeman, S.T., and Knauss, K.G., 1979. 230^{Th}-234U dating of pedogenic carbonates in gravelly desert soils of Vidal Valley, southeastern California, *Geological Society of American Bulletin,* Part I, 90, pg. 1063-1073.

Libby, W.F., 1952. *Radiocarbon Dating*, 2^{nd} edition, Chicago University Press, pg. 1-175.

Liu, T., 2003. Blind testing of rock varnish microstratigraphy as a chronometric indicator: results on late Quaternary lava flows in the Mojave Desert, California, *Geomorphology*, 53, pg. 209-234.

Liu, T. and Broecker, W.S., 2007. Holocene rock varnish microstratigraphy and its chronometric application in drylands of western USA, *Geomorphology*, 84, pg. 1-21.

Liu, T. and Broecker, W.S., 2000. How fast does rock varnish grow? *Geology*, 28, pg. 183-186.

Liu, T. and Dorn, R., 1996., Understanding the spatial variability of environmental change in drylands with rock varnish microlaminations, *Annals of the Association of American Geographers,* 86, 2, pg. 187-212.

Liu, B., Phillips, F.M., Pohl, M.M., and Sharma, P., 1996. An alluvial surface chronology based on cosmogenic 36Cl dating, Ajo Mountains (Organ Pipe Cactus National Monument), Southern Arizona, *Quaternary Research*, 45, pg. 30-37.

Mahan, S., Miller, D.M., Menges, C.M., and Yount, J.C., 2007. Late Quaternary stratigraphy and luminescence geochronology of the northeastern Mojave Desert, *Quaternary International*, 166, pg. 61-78.

Pearthree, P.A., House, P.K., and Vincent, K.R., 2000, Geomorphologic assessment of alluvial fan flood hazards in southern and central Arizona, in Floodplain Management in the Desert?! Arid Regions Floodplain Management 8th Biennial Conference, Las Vegas: American Association of State Floodplain Managers, p. 82-91.

Repka, J.L., Anderson, R.S. and Finkel, R.C., 1997. Cosmogenic dating of fluvial terraces, Fremont River, Utah, *Earth and Planetary Science Letters*, 152(1-4), pg. 59-73.

Robinson, S. E., Arrowsmith, J R., and Granger, D.E., 2000. Using AMS Measurements to date and decipher arid piedmont depositional processes, *EOS Transactions AGU, 81*, 48, F26.

Sharp, W.D., Ludwig, K.R., Chadwick, O.A., Amundson, R., and Glaser, L.L., 2003. Dating fluvial terraces by 230^{Th}/U on pedogenic carbonate, Wind River Basin, Wyoming, *Quaternary Research*, 59, pg. 139-150.

Walker, M., 2005. *Quaternary Dating Methods*, Wiley& Sons, Ltd., pg. 1-268.

Young, J.J., Arrowsmith, J R., Colini, L., Grant, L.B., Gootee, B., 2002. Three-Dimensional excavation and rupture history along the Cholame Segment of the San Andreas fault, California, Bulletin of the Seismological Society of America Special Volume, 92, 2670-2688.