New Approach to the Radiocarbon Dating of Rock Varnish, with Examples from Drylands

Ronald I. Dorn; Persis B. Clarkson; Margaret F. Nobbs; Lawrence L. Loendorf; D. S. Whitley

Annals of the Association of American Geographers, Vol. 82, No. 1 (Mar., 1992), 136-151.

New Approach to the Radiocarbon Dating of Rock Varnish, with Examples from Drylands

Ronald I. Dorn,* Persis B. Clarkson,** Margaret F. Nobbs,***
Lawrence L. Loendorf,**** and D.S. Whitley****

*Department of Geography, Arizona State University, Tempe, AZ 85287,
FAX 602/965-8313.
**Department of Anthropology, Athabasca University, Athabasca, AB TOG 2RO, Canada,
FAX 403/269-8027.
***8 Hazelwood Avenue, Hazelwood Park, S.A. 5066, Australia,
FAX 8/332-7579.
****Department of Anthropology, University of North Dakota, Grand Forks, ND 58202,
FAX 701/777-3650.

Abstract. New electron microscope observations reveal that organic inclusions are often trapped in pockets under rock varnish. Accelerator radiocarbon dating of subvarnish organic detritus provides a new method of constraining when a rock was exposed by cultural or geomorphic processes. Applications are exemplified for human artifacts and landforms found in drylands. Three radiocarbon dates from 30,000 to 36,000 yr B.P. indicate rock engravings in South Australia are among the oldest art yet found in the world and show that humans migrated into what is now the "arid zone" of Australia at least 10,000 years earlier than previously thought. The first direct age control on Nazca geoglyphs and subterranean irrigation aqueducts in southern Peru indicate manufacture around 1400 to 2100 yr B.P. Geoglyphs along the Colorado River were made before 1100 yr B.P. Artifacts from a quarry site in the Mojave Desert, California, yield minimum ^{14}C ages from 3700 to 26,000 yr B.P.

Key Words: AMS, radiocarbon dating, rock varnish, archeology, geomorphology, desert, geoglyphs, rock engravings, petroglyphs, alluvial fans, pukios, Nazca, Peru, human migration, South Australia, Mojave Desert, Colorado River.

ROCK varnish is a dark coating that is ubiquitous on exposed rocks in drylands. Although this accretion of clay minerals and manganese and iron oxides occurs in wetter climates (e.g., Whalley et al. 1990), aridity and alkalinity in deserts promote its stability (Elvidge and Iverson 1983; Jones 1991). The presence of rock varnish on features such as the Pyramids of Egypt (Blackwelder 1948) and its differential development on cultural artifacts and landforms have prompted speculation on its use as an indicator of antiquity (e.g., Hayden 1976; Derbyshire et al. 1984). Many different methods have been used to estimate the age of rock varnish, thereby providing a minimum age for the exposure of the underlying rock by cultural or natural processes (cf. Dorn 1989). Of these, radiocarbon dating is the focus of this paper.

The widespread use of accelerator mass spectrometry (AMS) to measure radiocarbon within the last six years has caused a revolution in the application of radiocarbon dating to fields such as geomorphology, paleoclimatology, archaeology, and other areas of Quaternary research (see review in Linick et al. 1989). The great advantage of AMS is its ability to measure the radiocarbon content in samples of only a few milligrams. This has made it possible to radiocarbon-date coatings on rocks, including rock paintings (Russ et al. 1990), calcium carbonate (Dragovich 1986), oxalate (Watchman 1991), and silica skins (Watchman 1990), as well as rock varnish. This paper presents a new approach to the age determination of rock varnish by radiocarbon dating. Instead of chemically concentrating "bulk" organic matter spread throughout a lower layer in rock varnish, we extract pieces of detrital organic matter that have been encapsulated by accreting varnish.

This new approach has significance for geo-

Annals of the Association of American Geographers, 82(1), 1992, pp. 136–151

graphical research in diverse areas, exemplified here for the use of drylands by prehistoric cultures. Butzer (1991) has observed that there are substantial spatial and temporal gaps in the record of Pleistocene human migration. Pleistocene occupation sites, with stratigraphic sequences appropriate for conventional dating methods, are buried and difficult to locate. In contrast, rock varnish is present on easily identified cultural features exposed at the surface, such as artifacts and rock engravings. Rock varnish is not a tool used to decipher the history of sediments found in a vertical column. Its widespread distribution is an inherent advantage in answering spatial questions. For example, dating rock varnish found on surficial cultural material has the potential to provide a more efficient means of establishing a minimum age for the initial migration of humans into an arid region, as well as to aid in the study of the long-term use of drylands by humans.

Sampling rock varnish also provides a more efficient means of radiocarbon dating desert landforms than searching for deposits of buried organic matter that are rarely preserved in drylands. Ages for desert surfaces are of significance to geomorphology because they can be used to provide insight into long-term rates of dryland geomorphic processes and to test models of landscape evolution.

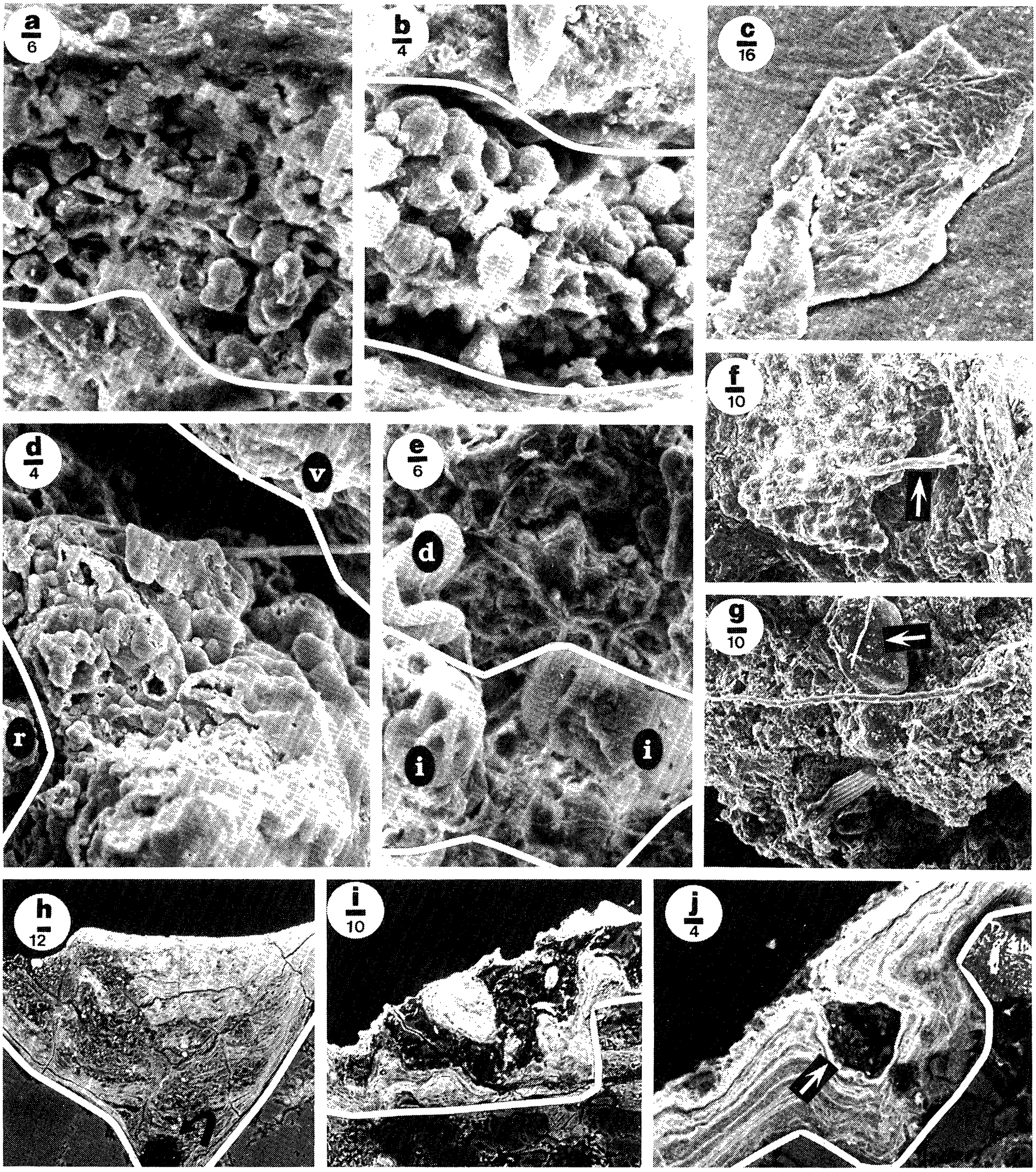
A New Approach to Radiocarbon Dating Rock Varnish

Since Laudermilk (1931) first observed organic carbon as a trace element, only a few studies have been conducted on the nature of organic matter in rock varnish. The stable carbon isotope composition is similar to adjacent plant material (Dorn and DeNiro 1985). The amino acid composition of one Arizona sample reflects a microbial origin (Nagy et al. 1990). Yet with AMS it became possible to radiocarbon-date milligram quantities of organic matter extracted from rock varnish while not knowing exactly what was being dated.

In an evaluation of the potential of radiocarbon dating varnish, Dorn et al. (1989) treated the lowest layer of rock varnish in order to concentrate enough organic matter from a bulk sample for AMS measurement. The samples were collected from sites of known age. The chemical process used to extract organic matter was similar to concentrating of pollen from sediments. Although this research demonstrated the feasibility of radiocarbon dating varnish, there was no clear understanding of where the dated organic matter was actually located in rock varnish. Dorn et al. (1989) assumed that the organic matter was dispersed throughout the varnish, perhaps in oxides of manganese and iron. Subsequently, this assumption has been shown to be false. Transmission electron microscope studies have shown that varnish oxides do not contain organic matter (Krinsley et al. 1990), and preliminary amino acid studies suggest that organic matter is not well preserved within varnish layers (Nagy et al. 1990).

The fundamental methodological advance presented in this paper is based on a determination of where organic matter occurs in rock varnish. Examination of thousands of cross-sections by light and electron microscopy reveals that organic carbon occurs in discrete inclusions as pieces of detritus. These fragments are almost always found either at the very surface of the varnish or trapped under the varnish at the rock interface (Fig. 1a–h). In only a few instances have we observed microinclusions of organic matter in the middle of varnish (e.g., Fig. 1j). Organic

Figure 1. Scanning electron microscope images of subvarnish organic matter seen in rock varnish cross sections. Scale bars in microns. Underneath is the organic matter-rock boundary. In each micrograph, the identification letter is for the microfigure, the line is the scale bar, and the number below the line is the length of the scale bar in microns. In a, b, d, and e, the upper line separates the varnish from the subvarnish organic matter. In others, the line separates varnish and rock. Organic matter (OM) was distinguished by morphology, low counts with energy-dispersive analysis of X-rays (EDAX), very low characteristic varnish peaks (e.g., Mn, Fe, Si, Al) in spot analyses by EDAX, and the similarity of these spectra to organic matter resting on the surface of rock varnishes. Sample numbers correspond with the radiocarbon ages in Table 1. a. Organic matter under varnish on cobble from Nazca geoglyph T7 (Fig. 4b). b. Organic matter under varnish from South Australian



petroglyph K24. c. Mat of subvarnish organic matter removed from South Australian petroglyph WH5 (Fig. 4g). d. Organic matter under rock varnish (upper right) and on top of rock (lower left), from cobble in Colorado River geoglyph CRG-2 (Fig. 4e). e. From Mojave Desert artifact 85-8 (Fig. 4h), where the organic matter and varnish formed in a vesicle-like feature. The letter "i" indicates organic matter (perhaps pollen grains) imbedded in varnish, whereas the letter "d" identifies a grain that may have become detached during sample preparation and may not be in situ. f. Subvarnish organic matter attached to fragment of rock scraped from South Australian petroglyph K23. Arrow indicates organic filament attached to organic mat. g. Subvarnish organic matter scraped from South Australian petroglyph K26. Arrow points to fragment of underlying rock still attached to organic matter. h. Backscatter electron (BSE) micrograph of polished cross-section of varnish, from South Australian petroglyph WH5. In BSE, brighter material has a higher atomic number (Krinsley et al. 1990) and the subvarnish organic matter (arrow) is black. i. BSE of polished cross-section of South Australian petroglyph K15 illustrating abundant silica skin (electron microprobe measurements indicates content of ~91% SiO_2) interbedding with brighter rock varnish. j. BSE of polished cross-section of South Australian petroglyph WH5 (Fig. 4g) illustrating a rare example of organic matter that is not subvarnish (indicated by arrow), but has been incorporated as varnish has accreted in layers.

fragments had not been recognized earlier by the first author because they were misinterpreted as an unimportant varnish structure, far less common than botryoidal or lamellate varnish textures. It was not until late 1989 that these structures were correctly identified as subvarnish organic fragments.

Knowing that microinclusions of organic matter occur underneath rock varnish permits us to assume the following sequence: (1) A cultural or natural process exposes a new rock surface to the atmosphere. This is the event that we want to date. (2) Rock-surface organisms such as lichen, cyanobacteria, or fungi grow in rock depressions. (3) Rock varnish growth in the depression encapsulates the organic matter (Fig. 1). Radiocarbon dating this subvarnish organic matter, therefore, provides a *minimum age* for the exposure of the underlying surface.

While it is theoretically possible that organic matter older than rock exposure settled on the surface of a rock before the varnish started to accrete, perhaps deflated from older soils or ancient exposed lake beds, this is unlikely for three reasons: (1) The $\delta^{13}C$ composition of varnish suggests the organic matter is derived from adjacent plant material (Dorn and DeNiro 1985). (2) AMS ^{14}C dating of varnish collected from sites with independent age control reveal varnish ages that are *always* younger than the controls (Dorn et al. 1989), even though the method used to extract the organic matter was not as precise as the new approach. (3) AMS radiocarbon measurements of carbon on contemporary rock surfaces do not reveal anomalously old ages. Dust and organisms (cyanobacteria and fungi) growing on Fort Paiute, constructed in 1868 in the Mojave Desert of eastern California, were analyzed by AMS. The radiocarbon concentration (compared to "modern") in these samples is 1.21 ± 0.01 (AA-6533) and 1.30 ± 0.01 (AA-6534), respectively.

The following section outlines the methods used to date microinclusions of subvarnish organic matter.

Methodology

The first stage in isolating subvarnish organic matter starts with field sampling. The objective is to collect varnish that has colonized a rock surface reworked by cultural or geomorphic processes. The procedure used is based on fourteen years of error and retrial. As with most dating methods, collecting the wrong type of sample produces an incorrect age. The types of samples that produce incorrect ages are elaborated elsewhere (e.g., Dorn 1989; Dorn et al. 1989, 1992; Krinsley et al. 1990).

We present insights on three of the most common mistakes made in order to illustrate the ease with which errors can crop up in the collection stage. First, any spot of varnish will not do. Micropositions where varnish starts to grow first were determined by studies of historical rock engravings and stones faced during historical construction. Colonization occurs first in vesicles in basalt, impurities in chert, fractures in quartz and silicified dolomite, and grain boundaries in granitic rocks and sandstones.

Second, the darkest and smoothest varnishes should *not* be sampled. These are frequently varnishes that form on the sides of unexposed rock crevices (less than a millimeter wide). This favorable environment for varnish development often produces the best looking varnishes. These "crack varnishes" are then exposed to eyes of field workers by natural rock spalling or when humans break rocks along natural joints. The important point is that determining the age of the crack varnish does not date the cultural or geomorphic process of interest, only when the organic matter fell into the rock fracture. For example, crack varnish collected from a still *unexposed* fracture (less than a millimeter wide) on the west face of Ayers Rock, Australia has an AMS ^{14}C age of 27,100 ± 400 yr B.P. (Beta 19893; ETH 2809) for subvarnish organic matter. (Radiocarbon years before present is abbreviated yr B.P.)

Third, varnish deposition must not be interrupted by mechanical or biogeochemical erosion. Before a sample is processed for varnish radiocarbon dating, multiple cross-sections are examined to ensure that the type of varnish that is dated is evenly layered (Fig. 2a, b). Samples with discontinuous layering (Fig. 2c, d) are not processed. Discontinuities can be produced, for example, by organisms that bore holes into the varnish. These hollows are then filled in with much younger material, leading to inaccurate ages, as shown in prior tests (Dorn 1989; Dorn et al. 1989). Other

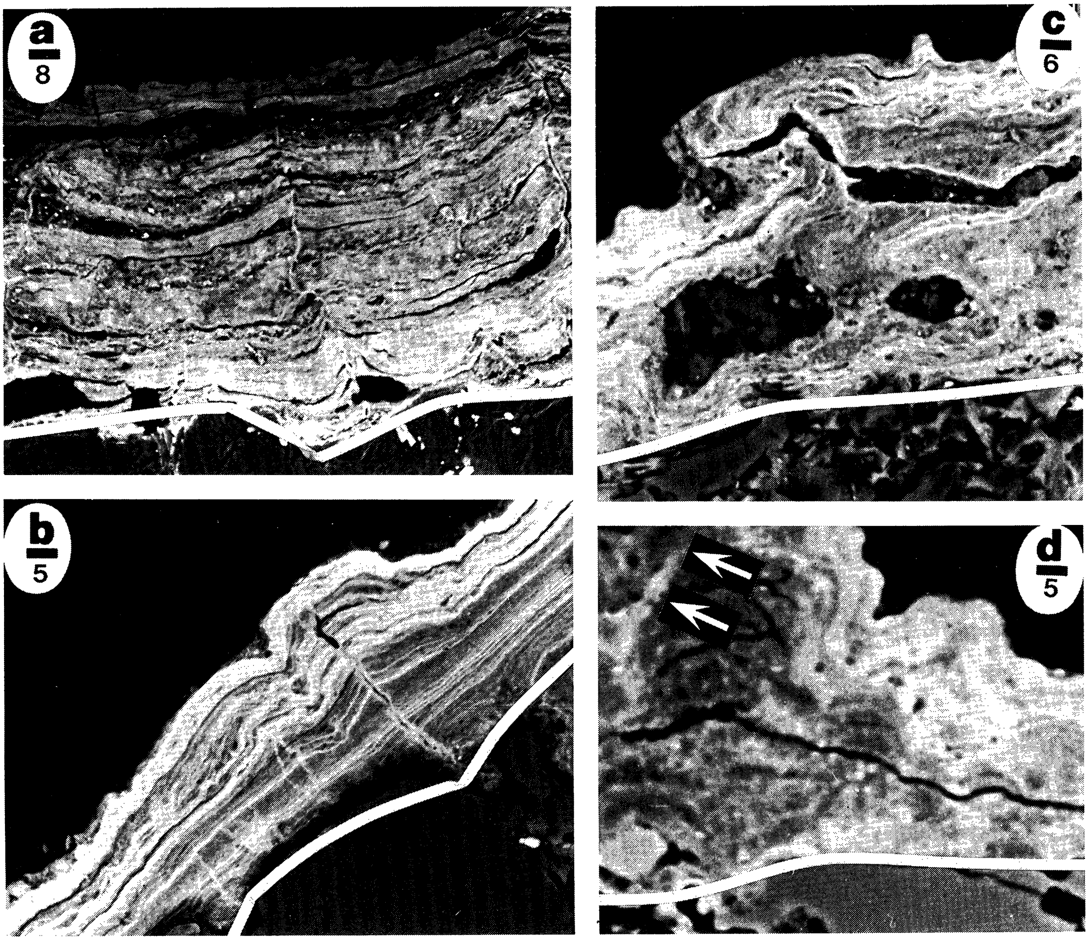


Figure 2. Cross-sections of continous and discontinuous layers in rock varnish, illustrated by backscatter electron microscopy. Figure 2b from petroglyph WH5 (Fig. 4g) and Figure 2a from the desert pavement adjacent to Nazca geoglyph T3 (Fig. 4c) illustrate evenly layered varnishes that are appropriate for dating. Figures 2c from the Panaramatee North petroglyph site (Fig. 3) and 2d from Death Valley illustrate discontinuous layering (arrows) that is inappropriate for dating. Lines indicate the varnish-rock boundary. Scale bars in microns.

cross-sectional characteristics that would disqualify a sample for further processing are explored in detail elsewhere (Dorn 1989; Krinsley et al. 1990; Dorn et al. 1992).

The second stage of sample preparation is selecting the organic microinclusions. The top layer of the varnish is abraded away with a tungsten-carbide needle. This is to remove organics on the surface of the varnish. Then, the needle is used like a micro-bulldozer to turn over the varnish. Sifting through this material under 45× magnification, we find fragments of organic matter *still attached* to the underlying rock (Fig. 1f, g). Attachment to the underlying rock is important, because the objective in sampling is to pick out material that accreted to the rock surface soon after it was exposed. The exact process by which the organic matter attaches to the underlying rock is still under investigation.

Organic matter is distinguished from inorganic varnish by several criteria: a nonplaty morphology, a spongy feel when touched with a fine tweezer or a tendency to disintegrate when pressed, or a whitish edge when broken. After organic-looking fragments are mechanically picked with a fine tweezer (Fig. 1c), there is typically only enough organic matter for an AMS radiocarbon measurement in about one-fourth of the samples thus far collected for dating.

An important concern in sampling is contamination of younger organic matter. Although the top layer of the varnish is first removed, and although organic matter is rarely found in the middle of varnish, it is impossible to rule out the inadvertent inclusion of young carbon. Radiocarbon dates on varnish organic matter must be interpreted as minimum ages. The long-term solution to this problem is the in situ extraction of subvarnish organic fragments with focused lasers.

Third, after microinclusions are isolated, the collection of organic fragments attached to rock is then treated with 20 percent HCl to remove carbonate and concentrated HF to remove loose organics adsorbed to clays. If samples in the terrestrial weathering environment that contain clays are not treated with HF, organic molecules loosely adsorbed onto the clay minerals can contaminate a sample and produce too young an age (Dorn et al. 1989; Gillespie 1991).

Last, the sample is submitted for AMS ^{14}C measurement (see review by Linick et al. 1989).

Cultural and Physical Geography Results

The remainder of this paper illustrates case studies of radiocarbon dating subvarnish organic fragments. Examples from first cultural and then physical geography are selected to highlight different methodological concerns related to working with different types of material. The order of presentation of cultural material is based on difficulty of sample preparation and concomitantly confidence in the results. Petroglyphs are a less complicated system than artifacts and pukios, and geoglyphs are the most difficult type of cultural remains to date with this method.

South Australia Petroglyphs

Petroglyph samples are particularly good to work with for a variety of reasons. Grooves abraded and pecked by artists are adjacent to well-varnished natural surfaces that provide a pool of bacteria to quickly colonize the newly exposed engraving. Petroglyphs are readily distinguished from natural weathering. They are also characterized by minor depressions appropriate for the collection of organic matter that is subsequently encapsulated by rock varnish. Confidence in varnish dating of petroglyphs is also boosted by successful blind tests (Loendorf 1991).

Petroglyphs from South Australia that had been previously cation-ratio dated (Dorn et al. 1988) were resampled in the summer of 1990 to assess the feasibility of collecting subvarnish organic matter. Out of 115 petroglyphs examined, twenty-six petroglyphs had sufficient organic matter for AMS radiocarbon dating. Sufficient funds were available to date seven of these. AMS ^{14}C dates of subvarnish organic matter samples from petroglyphs K21, K23, and K24 from the Karolta site (Fig. 3) overlap with 1 sigma errors of the previously published cation-ratio dates (Table 1). δ^{13}C values for the Australian petroglyph samples, range from −22.4 to −23.4 per mil (R. Sparks, pers. commun., 1990), consistent with a stable car-

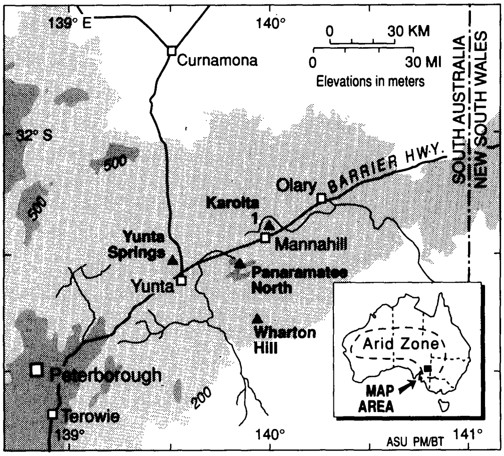


Figure 3. Petroglyph sites in South Australia.

Table 1. Accelerator Radiocarbon Dates for Inclusions of Organic Matter Trapped under Rock Varnish

Sample	^{14}C Measurement ± 1 sigma	Lab no.	(K+Ca/Ti)[a] Ratio in rock varnish[b]
Nazca geoglyphs			
T1 Llama geoglyph on hillside	1400±80 B.P.	TO-1495	17.42±1.62 (51)
T2 Bird geoglyph on Nazca pampa	1520±60 B.P.	TO-1614	17.72±1.12 (82)
T3 Linear geoglyph on Nazca pampa	1460±60 B.P.	TO-1615	17.27±0.69 (64)
T4 Linear geoglyph at Center #1	1670±70 B.P.	TO-1616	17.43±0.84 (73)
T5 Linear geoglyph at Center #2	1720±50 B.P.	TO-1617	17.11±2.08 (70)
T6 Linear geoglyph Center #2	1680±50 B.P.	TO-1618	16.97±1.12 (67)
T7 Trapezoid geoglyph Center #2	2100±50 B.P.	TO-1619	16.70±1.84 (65)
T8 Linear geoglyph on Pampa Gorda	1720±50 B.P.	TO-1620	17.04±1.38 (57)
T9 Orca geoglyph on Nazca pampa	1500±50 B.P.	TO-1621	17.19±1.25 (64)
Nazca pukios			
T10 Orcona Aqueduct	1460±50 B.P.	TO-1622	site not appropriate for cation-ratio dating
T11 Cantalloq Aqueduct	1430±60 B.P.	TO-1623	site not appropriate for cation-ratio dating
Colorado River geoglyphs			
CRG-1 Anthropomorph	1060±65 B.P.	ETH 6572 Beta 37033	8.24±0.43 (63)
CRG-2 Anthropomorph	1195±65 B.P.	ETH 6574 Beta 37035	8.16±0.31 (49)
CRG-3 Quadruped	1145±65 B.P.	ETH 6575 Beta 37036	7.90±0.33 (55)
Mojave Desert artifacts			
Quarry artifact 85-16 corer	3690±65	ETH 6573 Beta 37034	5.09±0.12 (3)
Quarry artifact 85-8 biface, flake scar 1	14,840±115	ETH 6577 Beta 37038	3.77±0.08 (3)
flake scar 2	13,655±105	(AA-6547)	3.77±0.08 (3)
Quarry artifact 85-12 primary flake	26,070±360	ETH 4478 Beta 27774	3.53±0.07 (3)
South Australia petroglyphs			
K15 Curved line[c]	12,650±150	NZA 1369	6.18±0.19 (3) [7400±1400[d]]
K21 Bird track	22,480±340	NZA 1366	4.90±0.14 (3) [25,900±3600[d]]
K23 Curved line	30,230±770	NZA 1378	4.69±0.12 (3) [31,700±3700[d]]
K24 "Abstract" motif	12,970±150	NZA 1414	5.73±0.17 (3) [11,500±1900[d]]
K26 Curved line superimposed by motif K23	31,230±920	NZA 1370	4.61±0.15 (3)
WH1 Possible Drominorthid track[c]	14,910±180	NZA 1367	6.57±0.18 (3)
WH5Oval	36,400±1700	NZA 1356	4.31±0.11 (3)
Ingenio-1 Alluvial Fan, Southern Peru			
Unit 1	21,430±160	TO-1624	11.60±1.00 (10)
Unit 2	15,340±110	TO-1625	12.41±0.64 (10)
Unit 3	8,710±80	TO-1631	13.60±0.88 (10)
Unit 4	1.520±50	TO-1625	17.38±1.43 (10)

[a] Cation ratio measurements by PIXE for all artifacts and petroglyphs except K26, WH1, and WH4 that are by inductively coupled plasma. Geoglyph and alluvial fan cation ratios were determined by wavelength dispersive microprobe. Methods are described in Dorn et al. (1992).

[b] Number in parentheses is how many rocks were analyzed from a geoglyph, or number of cation-ratio measurements for petroglyphs, artifacts, and alluvial-fan deposits. 1 sigma error reported.

[c] Abundant silica glaze inter-bedded with rock varnish.

[d] Numbers in brackets are prior cation-ratio age estimates from Dorn et al. (1988).

bon isotope composition of plants with a C_3 photosynthetic pathway (DeNiro 1987).

Petroglyph WH5 (Fig. 4g), from the Wharton Hill site in arid South Australia (Fig. 3), is among the oldest known rock art in the world. The oval engraving has a ^{14}C *minimum* age of

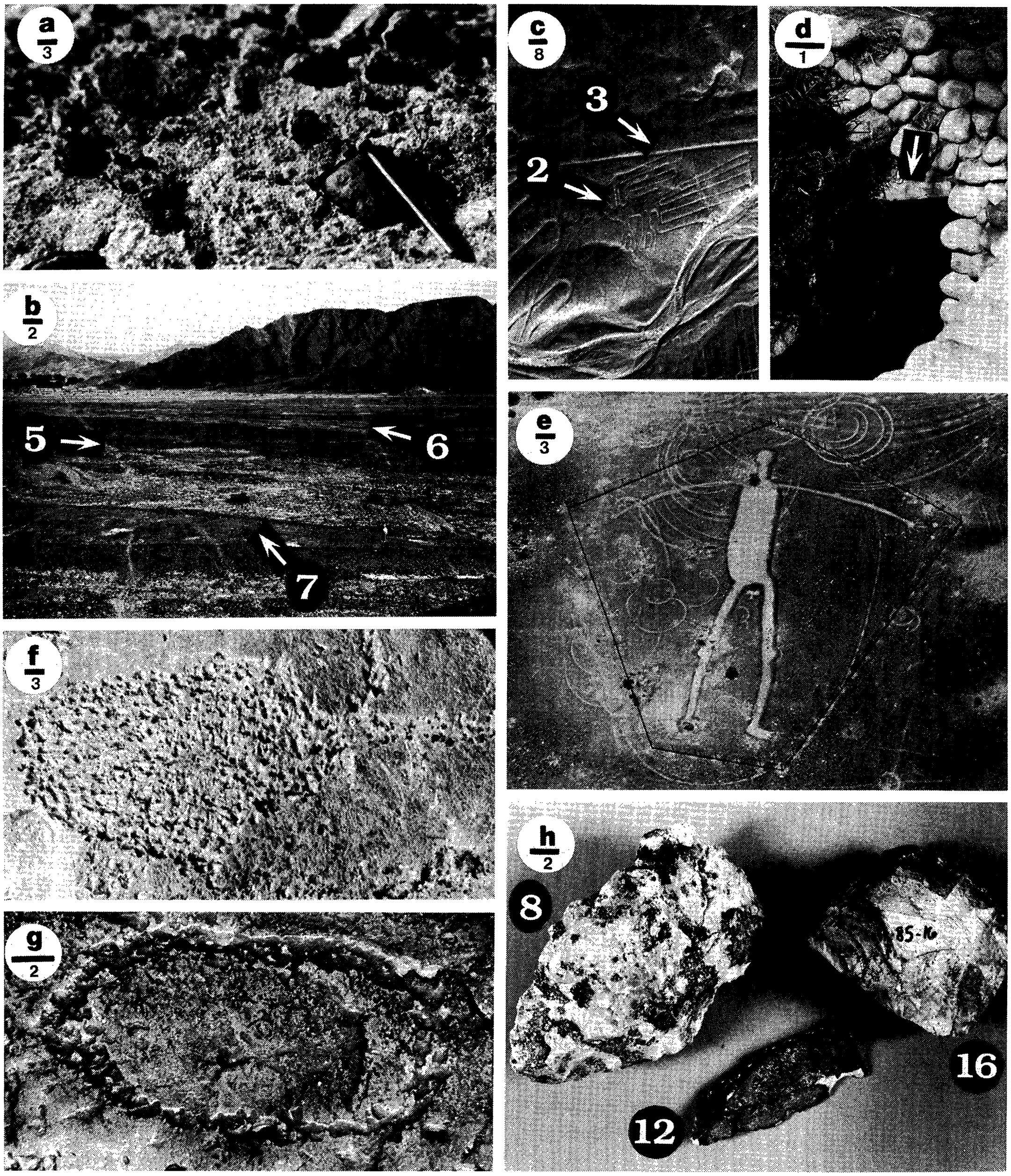


Figure 4. Site photographs that correspond with samples in Table 1. Scale bars in centimeters for a, f, g, h; meters for others. a. Partially reformed pavement in Nazca geoglyph T9. Sampled cobbles were imbedded in light colored silt. b. Oblique photo of Nazca geoglyphs T5 (line), T6 (line), T7 (trapezoid). c. Aerial photo of T2 (bird) and T3 (line). d. Cantolloc pukio of Nazca region, Peru; arrow indicates large roof stone sampled for AMS ^{14}C dating. e. Colorado river geoglyph GCG-2. (Fig. 5) f. South Australian petroglyph K24, from the Karolta site (Fig. 3). g. South Australian petroglyph WH5, from the Wharton Hill site (Fig. 3). h. Mojave artifacts constrained by AMS ^{14}C dating of organic matter trapped under varnish. Numbers correspond with Table 1, and location in Figure 5.

36,400±1700 yr B.P. It is quite possible that WH5 was engraved earlier, since this age is close to the upper limit of the radiocarbon method. Further, this petroglyph was one of the very few places where younger organic matter was found between the varnish surface and the rock interface (Fig. 1j). If only one percent ^{14}C were inadvertently included in the sample, a truly "dead" sample would give a finite ^{14}C age of about 36,000 yr B.P.

Our minimum radiocarbon ages from 30,000 to 36,000 yr B.P. are consistent with the migration of humans into Greater Australia about 50,000 yr B.P. (Roberts et al. 1990). However, WH5 at 36,000 yr B.P., along with K23 at 30,000 yr G.P. and K26 at 31,000 yr B.P., reveal that humans have occupied what is at present the "arid zone" of Australia at least 10,000 years earlier than previously thought (Smith 1987).

Unlike the other petroglyphs, with a close correspondence between the prior cation-ratio age and the new radiocarbon measurement, engraving K15 has a cation-ratio age about half the ^{14}C age (Fig. 4f; Table 1). Unlike the other varnishes radiocarbon dated, a layer of amorphous silica (e.g., Curtiss et al. 1985; Watchman 1990) interfingers with the varnish on petroglyph K15 (Fig. 1i). This may be analogous to the varnish/silica interdigitation described in Butzer et al. (1979).

In order to assess the influence of amorphous silica, leaching experiments were conducted on two groups of scrapings of natural Australian varnishes collected from the same cliff surface at Yunta Springs, South Australia (Fig. 3). One subgroup had abundant silica skins, like K15. The other subgroup had little development silica skins. Three subsamples of 200 mg of scrapings from each group were placed in 200 ml of distilled water at 25° C. They were agitated four times a day for three weeks; water was allowed to evaporate to 20 ml to concentrate cations, and then decanted and analyzed by inductively coupled plasma. The water leached from the varnish subgroup with abundant silica skins had 30–45 percent less Ca and K in solution than the water leached from varnish without silica skins. In cation-ratio dating, the $(K^{+}+Ca^{2+})/Ti^{4+}$ ratio declines with the age of the rock varnish, as more mobile cations like potassium (K) and calcium (Ca) are leached preferentially to titanium (Ti) (Dorn 1989; Dorn et al. 1992).

One interpretation of this experiment and for the anomalously younger cation-ratio age for K15 is that coatings of amorphous silica help reduce rates of cation leaching. This case study highlights a major advantage of radiocarbon over chemical dating methods. Chemical reactions are subject to environmental variables other than time that must be controlled, in this case the presence of silica skins.

Mojave Desert Artifacts

Rock varnish forms on flake scars of artifacts dropped on desert pavements (Hayden 1976). Artifacts were collected from the Manix Basin of the Mojave Desert (Fig. 5), the same area of the Mojave Desert where artifacts were obtained for an earlier study involving cation-ratio dating of lithic artifacts at quarry workshops (Bamforth and Dorn 1988). Artifacts were collected from desert pavements on the surface of an eroded alluvial fan, above the shoreline of Pleistocene Lake Manix (Meek 1989). Of 53 artifacts collected, only three had sufficient subvarnish organic matter for AMS ^{14}C dating, and one artifact had enough for two dates (Table 1; Fig. 4h).

Three of the four measurements predate the

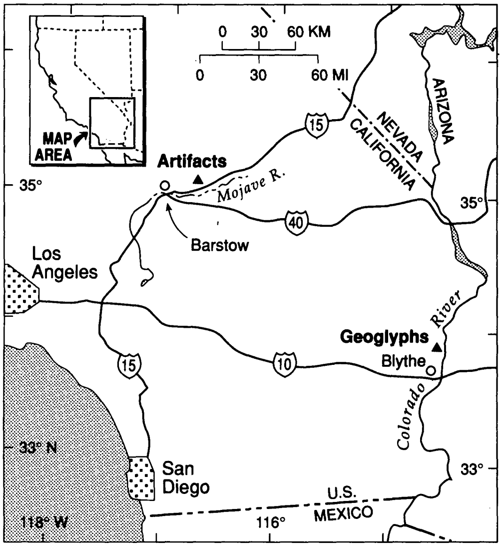


Figure 5. Location of geoglyphs sampled along the Colorado River and artifacts collected in Central Mojave Desert.

"Clovis" invasion of the New World felt to occur about 12,000 yr B.P. (Meltzer 1989). The organic matter on artifact #12, a primarily flake that is completely coated with varnish in Figure 4h, is over 26,000 yr B.P. Organic matter was analyzed from two different flake scars by two different laboratories on artifact #8 (Fig. 4h). The difference in age amounts to a little under 10 percent, and it probably relates to the way rock varnish grows. Some organic matter was encapsulated about 14,900 yr B.P. and then other material was varnished about 13,700 yr B.P. Since we treated the samples with HCl, older carbonate dust can be ruled out as a contamination. Crack varnish is not a complication, since the varnish was sampled from flake scars that were exposed when the artifact was worked. The simplest hypothesis is to view these pre-Clovis radiocarbon dates as minimum ages for the exposure of flake scars by humans.

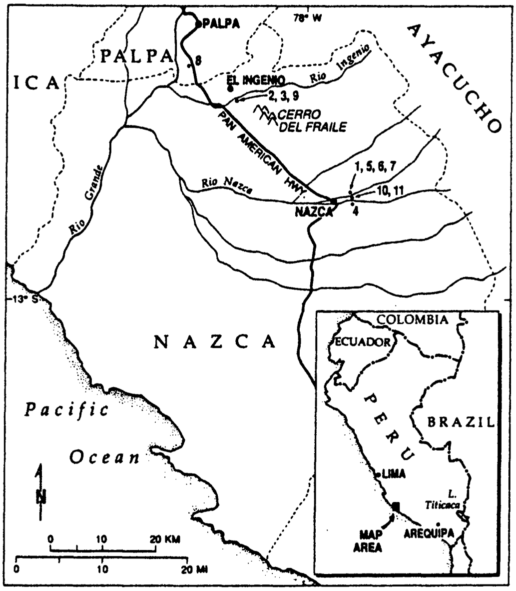


Figure 6. Geoglyph, alluvial fan, and pukio sites in southern Peru. Numbers correspond with Table 1 and Figure 4. The Ingenio-1 fan displayed in Figure 8 debouches from the west side of Cerro del Fraile, near the Pan American Highway.

Pukios of Southern Peru

Subterranean aqueducts, called pukios, are abundant in the Nazca region of southern Peru (Fig. 6; Schreiber and Lancho 1988), yet they have no age control. They are roughly similar to Old World qanats, bringing Andean ground water for irrigation in dryland floodplains. Schreiber and Lancho (1988) used archaeological inference to argue for manufacture during the Nasca cultural period, while Barnes and Fleming (1991) interpret historical information to argue for manufacture during the Spanish colonial period. (By convention "Nasca" refers to the prehistoric culture, whereas "Nazca" refers to the area.) There are wood posts in the pukios, but they are replaced periodically during maintenance and are hence not appropriate to assess when the pukios were first built.

Rock varnish was collected from meter-plus-long stone lintels making the roof of pukios at Cantalloc (e.g., Fig. 4d) and Orcona (Numbers 10 and 11 in Fig. 6). The texture of the rock varnish, as examined by backscatter scanning electron microscopy, is unlike any rock varnish in the adjacent dryland environment. It is most similar to rock varnish found on cobbles in streams in tropical Queensland. This is consistent with varnish formation in an environment of flowing water; water-formed texture indicates that the varnish was not "inherited" from a period of varnish formation prior to emplacement. Furthermore, the varnish could not have started to form until after the roof stones were faced. According to J. Lancho-Rojas (1989), their size, shape, and the location of the lithologies they were quarried make the stone lintels reasonable candidates for prehistoric emplacement. Like all varnish ^{14}C ages, these must be considered minimum ages for the emplacement of the roof stones (Table 1).

We conclude that at least some of the construction of the pukios of Nazca was completed during or before early Nasca culture. These data are consistent with the interpretation of Schreiber and Lancho (1988) for the Nazca pukios. Of course, it is possible that the construction of other subterranean aqueducts for the delivery of irrigation water could have occurred during the Spanish colonial period (Barnes and Fleming 1991).

Geoglyphs

The Nazca geoglyphs of southern Peru (Fig. 4a–c, Fig. 6) were made by clearing darkly varnished cobbles in desert pavements. This exposed to the atmosphere what was underneath: lighter-colored silt and unvarnished cobbles. The exposure of the unvarnished cobbles started the varnish clock. This section describes our assumptions and experiments to assess the feasibility of using rock varnish to establish minimum ages for geoglyphs.

Studies of desert pavements in North America and Israel, after historical disturbance, have shown that partial regeneration of the pavement takes place in an initial pulse within a few years to a few decades (Lowdermilk and Sundling 1950; Sharon 1962; Cooke 1970; Bales and Pewe 1979; Eckert et al. 1979; Elvidge and Iverson 1983). Complete pavement regeneration has not taken place in any of the studied geoglyphs. This may be due to: the extreme aridity of the region slowing the pavement regeneration process; a shortage of subsurface cobbles close enough to the surface to be thrust up by wetting and drying of clays in the soil (cf. Springer 1958; Cooke 1970); pedogenic calcrete or gypcrete cementing subsurface cobbles together; or perhaps because cobble upthrust is not responsible for pavement regeneration in the very arid Nazca region.

Clasts now observed within a geoglyph may have four possible origins: (1) Subcentimeter-sized particles can blow into geoglyphs on the Nazca pavements. (2) Some cobbles are "inherited" from the previous natural desert pavement, either because they were left during manufacturing or washed in afterwards by overland flow. (3) Many pavement clasts were exposed at or near the time of geoglyph manufacturing. (4) Still other cobbles may have been exposed after geoglyph manufacturing by upthrusting, erosion of silt through deflation, overland flow, or human disturbance. (Geoglyph T2 seen in Fig. 4c was probably "swept" by M. Reiche; cobbles exposed by sweeping would not have developed enough varnish to sample.)

A strategy was devised to sample subvarnish organic matter from only cobbles that belong to type (3), since the goal is to obtain the closest minimum age for geoglyph manufacturing. Type (1) clasts are easily eliminated by sampling particles with the smallest axis > 2cm and by sampling cobbles imbedded in the pavement (Fig. 4a). Type (2) clasts are readily eliminated if the cobble is of a rock type that varnishes well, because the inherited cobbles have a well-developed varnish. However, if the cobble is quartzite or another lithology that is slow to varnish, it can appear light in color with thick varnishes found only in grain boundaries and cracks.

The remainder of the clasts have only patches of varnish and the task is to distinguish which ones were exposed by geoglyph manufacturing or soon after. Rock varnish cation ratios were used to help preselect type (3) cobbles to be used in radiocarbon dating. Cation ratios are only used to establish a relative age sequence. This is a conservative use of varnish cation-ratio dating, since six different varnish research groups have concluded that the cation ratio of $(K^+ + Ca^{2+})/Ti^{4+}$ decreases over time (see review in Dorn 1989).

Over fifty cobbles (smallest axis >2cm) with a spotted varnish appearance were sampled from nine Nazca geoglyphs of Peru (Fig. 4a–c; Fig. 6; Table 1). Some of the Nazca cobbles had partial crusts of pedogenic gypsum that are common in soils in the region (Noller 1990), indicating former burial. Flakes of rock varnish were scraped off each cobble, mounted in epoxy, polished, and analyzed for their cation ratio by wavelength dispersive electron microprobe.

Fig. 7 presents ordered cation ratios from cobbles of five Nazca geoglyphs. Cobbles with lower cation ratios are felt to be "inherited" from the natural pavement, since lower cation ratios indicate greater antiquity. Cation ratios in the flat part of the curves in Fig. 7 are interpreted to be those cobbles exposed during geoglyph manufacturing or soon after. Higher cation ratios are interpreted as cobbles exposed by gradual pavement reformation or perhaps human disturbance after geoglyph manufacturing. Cobbles with low cation ratios were not sampled for radiocarbon dating nor were cobbles with cation ratios higher than the plateau. Table 1 presents AMS ^{14}C ages of subvarnish organic matter removed from underneath the varnish on cobbles in the flat part of the curves in Fig. 7; these are felt to best reflect cobbles exposed by geoglyph manufacturing.

The first minimum ages for the Nazca lines

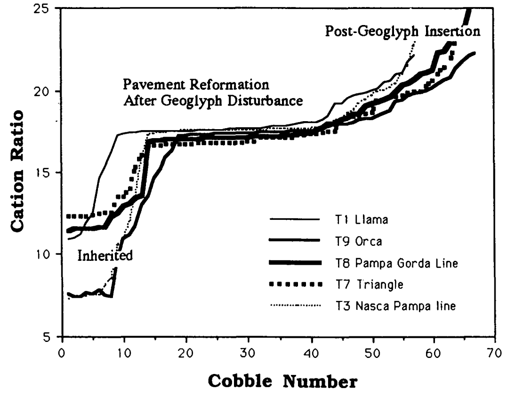


Figure 7. Cobbles sampled from five Nazca geoglyphs are ordered by their mean cation ratios [$(K^+ + Ca^{2+})/Ti^{4+}$], as determined by wavelength dispersive microprobe analyses on varnish scrapings. Cobbles are broken into three groups by the different cation ratios. Lower ratios indicate greater age, and these cobbles probably washed in and "inherited" their ratios from the adjacent natural pavement. Cobbles with cation ratios on the flat plateau probably were exposed by geoglyph manufacturing; these are the cobbles sampled for AMS ^{14}C dating. The last group of cobbles are those with ratios higher than this plateau and probably represent ongoing pavement regeneration or perhaps human disturbance after the geoglyphs were made. Error bars (~5–30 percent) for each cation ratio (based on standard errors of at least 8 electron microprobe measurements per cobble) are not presented because it would make the graph unreadable. They are given in Table 1 for each geoglyph.

and figures are presented in Table 1. They overlap with a conventional ^{14}C date of 445–605 A.D. on a wood post found where two linear geoglyphs intersected (Strong 1957, 46). Using ceramics left on top of and near the geoglyphs, Silverman (1990) also argued for manufacturing by Nasca culture during the Early Nasca phase of the Early Intermediate Period felt to be from 200 B.C. to A.D. 600. Our minimum ages are consistent with this interpretation, but we cannot rule out later (Clarkson 1990) or earlier episodes of geoglyph manufacturing.

Geoglyphs etched into desert pavements are also common in southwestern North America (e.g., Hayden 1976; Johnson 1986; von Werlhof 1987), but the lack of age control has inhibited placement in a cultural context established by stratigraphic studies. Cobbles from geoglyphs along Colorado River north of Blythe, California (Fig. 5), were sampled and preselected with cation ratios, as with the Nazca geoglyphs. Enough organic matter for a ^{14}C age was obtained from three geoglyphs (e.g., Fig. 4e). These minimum ages indicate that at least one period of geoglyph manufacture took place along the Colorado River before about 1100 yr B.P. (Table 1). It took place in widely separated parts of the New World during a roughly similar time period.

Alluvial Fan in Peru

An alluvial fan near the Nazca geoglyphs of southern Peru, Ingenio-1, exemplifies how the new method of varnish radiocarbon dating can be used to constrain ages of desert landforms. The Ingenio-1 fan exits a small drainage basin (~0.9 km^2) in the Cerro del Fraile range south of the town of Ingenio (Fig. 6). The top of the basin crests at about 900 m and the apex of the fan is about 450 m. The vegetation cover is at present negligible, confined to a few isolated herbs and desert shrubs in active quebradas.

Ingenio-1 fan is built onto the surface of Pampa San Jose, the desert pavement that composes the blackboard of the Nasca geoglyphs. Ingenio-1 fan faces west. The drainage basin is at a low elevation in the rainshadow of the Andes Mountains. Most of the current rainfall comes from the east during the summer. Extreme rainfall events are required to generate debris-flow deposits (Hooke 1987) that are found in abundance on the fan (Fig. 8). The radiocarbon dating of organic matter encapsulated by rock varnish on the Ingenio-1 fan indicates alluvial-units range in age from before ~21–22,000 yr B.P. to surfaces that lack Nasca-age pottery (Fig. 8).

El Niño-Southern Oscillation (ENSO) events are known to produce a great increase in annual precipitation totals along the north coast of Peru (Caviedes 1984), leading to flooding (Wells 1987). ENSO events that move in from the west would be effective in mobilizing sediments from the west-facing Ingenio-1 watershed, but statistical analyses of ENSO events indicate increased precipitation in northern Peru is associated with concomitant aridity in southern Peru (Tapley and Waylen 1989).

The existence of the debris-flow and

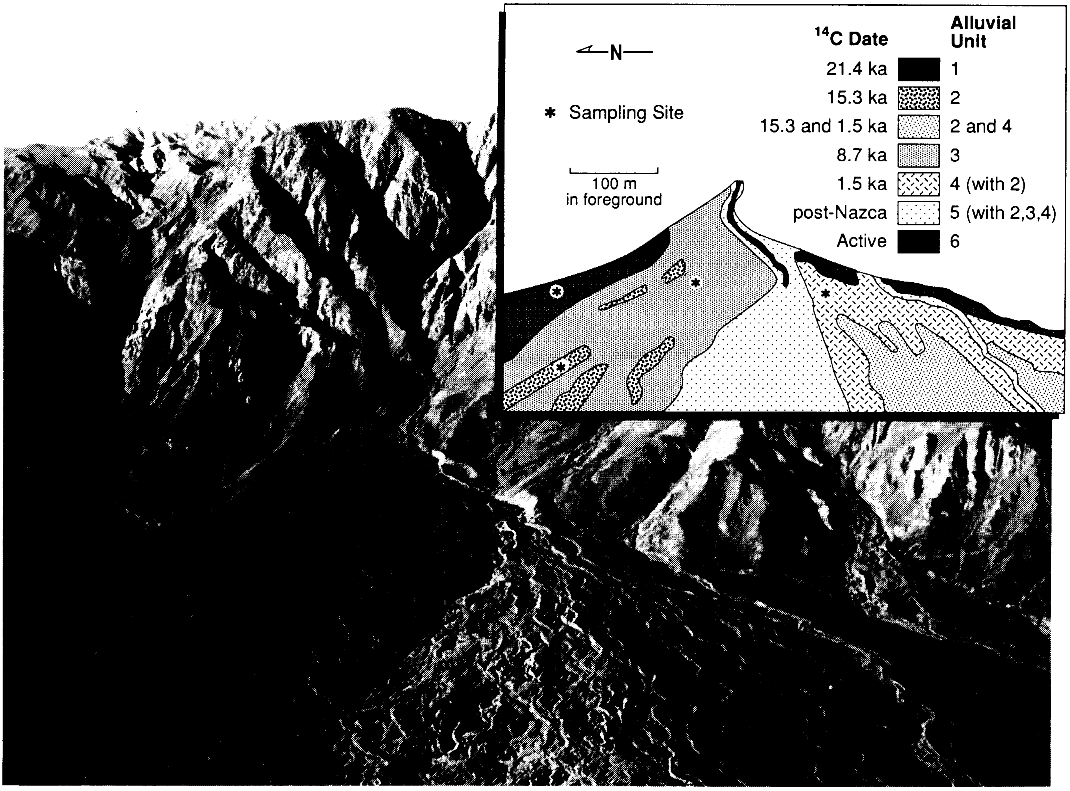


Figure 8. Oblique aerial photo and corresponding generalized map of Ingenio-1 alluvial fan. Ages are based on single varnish radiocarbon dates from the indicated sampling sites (Table 1). While older units have Nasca pottery, the post-Nasca age for unit 5 is indicated by the lack of Nasca-style pottery observed on the surface. There was also no Nasca pottery found in the "active" channel that was mapped by the presence of withered vegetation.

braided-stream deposits on Ingenio-1 demand a mechanism to produce intense precipitation. Others have speculated that comparatively harsh and long-lasting "super El Niño" events could have influenced the south coast of Peru (cf. Morner 1987; McCaffrey et al. 1990). This would fit with the pattern of El Niño currents starting in the north and moving southward (Zuta et al. 1976). Another possible explanation for the Ingenio-1 deposit could potentially involve a more northerly penetration of cold-season precipitation associated with ENSO events (Cerveny et al. 1987).

Regardless of which climatic mechanism produced the Ingenio-1 fan deposits, the sediment was mobilized by high magnitude-low frequency, extreme climatic events in a region that is characterized as hyperarid by all water balance and climate classifications. This region would also be characterized as hyperarid in a regional paleoclimate record. It follows that attempts to correlate alluvial-fan deposits with regional paleoclimatic records can be problematic, since high-magnitude, low-frequency events can produce extensive alluvial-fan morphostratigraphic units.

Conclusions

With the observation that microinclusions of organic matter are present over or under, but rarely within rock varnish, it is now possible to date organic fragments under rock varnish, instead of organic matter that has been chemically concentrated from a bulk sample in a bottom layer. These AMS ^{14}C measurements provide *minimum* ages for surface archaeological material and desert landforms that had no previous age control. This advance is analogous to recent changes in dating lake sediments; instead of obtaining ages on bulk organics, the pollen grains that are used by palynologists for paleoclimatic interpretation of lake cores can also be used for radiocarbon dating (Brown et al. 1989).

This new approach, requiring a tenth the time of the previous technique of scraping to the lowest layer of varnish, is a necessary step towards in situ extraction of organic matter in rock varnish. The next advance will be to use lasers to extract organic inclusions from cross-sections, much like lasers are now used in micron-scale stable carbon isotope analyses of carbonate (Dickson et al. 1990).

Pilot results of this new technique illustrate its potential. Three rock engravings from South Australia are older than 30,000 yr B.P.; one is older than 36,000 yr B.P. These are among the oldest known rock art in the world, and they indicate that what is now the arid zone of Australia was inhabited at least 10,000 years earlier than previously thought. These radiocarbon dates are consistent with all but one previously published cation-ratio age; this deviation may be explained by interbedded silica skins that lower rates of cation leaching. Rock varnish radiocarbon dates provide the first direct minimum ages for the Nazca geoglyphs. The ages suggest construction during the early Nasca culture (~200 B.C. to 600 A.D.) during the rise of the archaeological site of Cahuachi and during the construction of subterranean irrigation aqueducts called pukios. Out of dozens of Mojave Desert artifacts examined, we obtained enough subvarnish organics for four radiocarbon ages on three different artifacts. Three of these ages are before the 12,000 yr B.P. "Clovis" migration into the New World. Alluvial-fan deposits and other desert landforms, even in hyperarid regions, are amenable to radiocarbon age control by the dating of subvarnish organic matter. A speculative interpretation of the first age control on alluvial fans in southern Peru is that paleo-ENSO events may be recorded by sediment mobilization from low-lying desert mountain ranges.

Acknowledgments

Funded by National Science Foundation Presidential Young Investigator Award and Arizona State University Faculty Grant-in-Aid (Dorn), Social Sciences and Humanities Research Council of Canada Grant #410-89-0642 (Clarkson), Australian Institute for Torres Straight Islander and Aboriginal Studies (Nobbs), and the University of North Dakota (Loendorf). National Science Foundation Grant EAR 84-08163 paid for the Arizona State University microprobe. This work would not have been possible without accelerator radiocarbon measurements by Isotrace, New Zealand Department of Scientific and Industrial Research Nuclear Science Group, Beta Analytic and Eidgenossiche Technische Hochschule University in Zurich, and the University of Arizona. We thank B. Trapido for graphical assistance; M. Anders, F. Budinger, J. Clark, D. Donahue, D. Dorn, W. Graf, D. Hanna, C. Vance Haynes, D. Krinsley, B. Johnson, A.J.T. Jull, J. Lancho, R. Morrison, C. Lewis, J. Nobbs, M. Owen, P. Pitluga, H. Silverman, K. Schreiber, L. Toolin, P. Trusty, and A. Watchman for discussions, laboratory, and field assistance; anonymous reviewers for an improved way to present this material; and H. Casey for permission to use Figure 4e. Peruvian samples were collected under permit issued to Clarkson by the Instituto Nacional de Cultura of Peru. California samples were collected at the request of G. Hillier, BLM desert district manager.

References

Bales, J. T., and Pewe, T. L. 1979. Origin and rate of desert pavement formation—a progress report. *Journal of the Arizona-Nevada Academy of Science* 14:84.

Bamforth, D. B., and Dorn, R. I. 1988. On the nature and antiquity of the Manix Lake Lithic Industry. *Journal of California and Great Basin Anthropology* 10:109–26.

Barnes, M., and Fleming, D. 1991. Filtration gallery irrigation in the Spanish New World. *Latin American Antiquity* 2:48–68.

Blackwelder, E. 1948. Historical significance of desert lacquer. *Geological Society of America Bulletin* 59:1367.

Brown, T. A., et al. 1989. Radiocarbon dating of pollen by accelerator mass spectrometry. *Quaternary Research* 32:205–12.

Butzer, K. W. 1991. An old world perspective on potential mid-Wisconsinan Settlement of the Americas. In *The First Americans: Search and Research*, ed. T. D. Dillehay and D. J. Meltzer, p. 137–56. Boca Raton, FL: CRC Press.

———**; Fock, G. J., et al.** 1979. Dating and context of rock engravings in South Africa. *Science* 203:1201–14.

Caviedes, C. N. 1984. El Niño. *Geographical Review* 74:268–90.

Cerveny, R. S.; Skeeter, B. R.; and Dewey, K. F. 1987. A preliminary investigation of a relationship between South American snow cover and the Southern Oscillation. *Monthly Weather Review* 115:620–23.

Clarkson, P. B. 1990. The archaeology of the Nazca pampa: Environmental and cultural parameters. In *The lines of Nazca. Memoirs 183 of the American Philosophical Society,* ed. A.F. Aveni, p. 117–72. Philadelphia: American Philosophical Society.

Cooke, R. U. 1970. Stone pavements in deserts. *Annals of the Association of American Geographers* 60:560–77.

Curtiss, B.; Adams, J. B.; and Ghiorso, M. S. 1985. Origin, development and chemistry of silica-alumina rock coatings from the semiarid regions of the island of Hawaii. *Geochimica et Cosmochimica Acta* 49:49–56.

DeNiro, M. J. 1987. Stable isotopy and archaeology. *American Scientist* 75:182–91.

Derbyshire, E., et al. 1984. Quaternary glacial history of the Hunza Valley, Karakoram Mountains, Pakistan. In *The International Karakoram Project* vol. 2, ed. K.J. Miller, p. 456–95. Cambridge: Cambridge University Press.

Dickson, J. A. D., et al. 1990. Intracrystalline carbon and oxygen isotope variations in calcite revealed by laser microsampling. *Geology* 18:809–11.

Dorn, R. I. 1989. Cation-ratio dating of rock varnish: A geographical perspective. *Progress in Physical Geography* 13:559–96.

———, et al. 1989. Accelerator mass spectrometry radiocarbon dating of rock varnish. *Geological Society of America Bulletin* 101:1363–72.

———, et al. 1992. Rock varnish on Hualalai and Mauna Kea Volcanoes, Hawaii. *Pacific Science* 46:11–34.

——— and DeNiro, M. J. 1985. Stable carbon isotope ratios of rock varnish organic matter: A new paleoenvironmental indicator. *Science* 227:1472–74.

———; Nobbs, M.; and Cahill, T. A. 1988. Cation-ratio dating of rock engravings from the Olary Province of arid South Australia. *Antiquity* 62:681–89.

Dragovich, D. 1986. Minimum age of some desert varnish near Broken Hill, New South Wales. *Search* 17:149–51.

Eckert, R. E., et al. 1979. Impacts of off-road vehicles on infiltration and sediment production of two desert soils. *Journal of Range Management* 32:394–97.

Elvidge, C. D., and Iverson, R. M. 1983. Regeneration of desert pavement and varnish. In *Environmental effects of off-road vehicles,* ed. R.H. Webb and H.G. Wilshire, pp. 225–43. New York: Springer Verlag.

Gillespie, R. 1991. Charcoal dating—oxidation is necessary for complete humic removal. *Radiocarbon* 33 (2):199.

Hayden, J. 1976. Pre-altithermal archaeology in the Sierra Pinacate, Sonora, Mexico. *American Antiquity* 41:274–89.

Hooke, R. L. 1987. Mass movement in semi-arid environments and the morphology of alluvial fans. In *Slope stability,* ed. M.G. Anderson, and K.S. Richards, pp. 505–29. New York: Wiley.

Johnson, B. 1986. Earth figures of the lower Colorado and Gila River deserts: A functional analysis. *The Arizona Archaeologist* 20.

Jones, C. E. 1991. Characteristics and origin of rock varnish from the hyperarid coastal deserts of northern Peru. *Quaternary Research* 35:116–29.

Krinsley, D.; Dorn, R. I.; and Anderson, S. 1990. Factors that may interfere with the dating of rock varnish. *Physical Geography* 11:97–119.

Lancho-Rojas, J. 1989. Personal communication, May 17.

Laudermilk, J. D. 1931. On the origin of desert varnish. *American Journal of Science* 21:51–66.

Linick, T. W., et al. 1989. Accelerator mass spectrometry: The new revolution in radiocarbon dating. *Quaternary International* 1:1–6.

Loendorf, L. L. 1991. Cation-ratio varnish dating and petroglyph chronology in southeastern Colorado. *Antiquity* 65:246–55.

Lowdermilk, W. C.; and Sundling, H. L. 1950. Erosion pavement, its formation and significance. *Transactions of the American Geophysical Union* 31:96–100.

McCaffrey, M. A.; Farrington, J. W.; and Repeta, D. J. 1990. The organic geochemistry of Peru margin surface sediments: I. A comparison of the C37 alkenone and historical El Niño records. *Geochimica et Cosmochimica Acta* 54:1671–82.

Meek, N. 1989. Geomorphic and hydrologic implications of the rapid incision of Afton Canyon, Mojave Desert, California. *Geology* 17:7–10.

Meltzer, D. J. 1989. Why don't we know when the first people came to North America? *American Antiquity* 54:471–90.

Morner, N. 1987. Past CO_2-excursions and possible "Super El-Niño" events. *INQUA Abstracts* 228.

Nagy, B., et al. 1990. Sedimentological processes affecting the development of rock varnish. *Geological Society of America Abstracts with Program* 22:91.

Noller, J. S. 1990. Marine origin for salts in soils of the hyperarid Peruvian Desert. *EOS* 71:1235.

Roberts, R. G.; Jones, R.; and Smith, M. A. 1990. Thermoluminescence dating of a 50,000-year-old human occupation site in northern Australia. *Nature* 345:153–56.

Russ, J., et al. 1990. Radiocarbon dating of prehistoric rock paintings by selective oxidation of organic carbon. *Nature* 348:710–11.

Schreiber, K., and Lancho-Rojas, J. 1988. Los puqios de Nasca: un sistema de galerías filtrantes. *Boletín de Lima* 59:51–62.

Sharon, D. 1962. On the nature of hamadas in Israel. *Zeitschrift für Geomorphologie N.F.* 6:129–47.

Silverman, H. 1990. Beyond the pampa: The geoglyphs in the valleys of Nazca. *National Geographic Research* 6:435–56.

Smith, M. A. 1987. Pleistocene occupation in arid central Australia. *Nature* 328:710–11.

Springer, M. E. 1958. Desert pavement and vesicular layer of some soils of the desert of the Lahontan Basin, Nevada. *Proceedings of the Soil Science Society of America* 22:63–66.

Strong, W. D. 1957. Paracas, Nazca, and Tiahuanacoid cultural relationships in south coastal Peru. *Society of American Archaeology Memoir* 13.

Tapley, T. D. J., and Waylen, P. R. 1989. A mixture model of annual precipitation in Peru. *The Professional Geographer* 41:62–71.

von Werlhof, J. 1987. *Spirits of the Earth. A study of Earthen art in the North American deserts.* El Centro, CA: Imperial Valley College Museum.

Watchman, A. 1990. What are silica skins and how are they important in rock art conservation. *Australian Aboriginal Studies* 1:21–29.

———. 1991. Age and composition of oxalate-rich crusts in the Northern Territory, Australia. *Studies in Conservation* 36:24–32.

Wells, L. E. 1987. An alluvial record of El Niño events from northern Coastal Peru. *Journal of Geophysical Research* 92:14,463–70.

Whalley, W. B., et al. 1990. Ferromanganese rock varnish in North Norway: A subglacial origin. *Earth Surface Processes and Landforms* 15:265–75.

Zuta, S., et al. 1976. Aspectos fisicos del fenomeno "El Niño" 1972–1973. *United Nations Food and Agricultural Organization, Fisheries Reports* 185:3–61.

Submitted 1/91, revised 9/91, accepted 9/91.