Constraining the age of the Côa valley (Portugal) engravings with radiocarbon dating

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Radiocarbon ages for the Côa petroglyphs are very similar to those obtained by Watchman (1995). Fundamental problems in the use of radiocarbon dating at Côa include evidence for the addition of younger carbon in an open system, and evidence of contamination from older sources of carbon. Radiocarbon measurements, therefore, cannot be used to decide whether the engravings are or are not of Palaeolithic age.

The Côa valley petroglyphs (Figure 1), galvanizing archaeologists world-wide (Bahn 1995b; Chippindale 1995; Clottes et al. 1995; Jorge 1995; Loendorf 1995; Zilhão 1995c; Züchner 1995), have been a public controversy within Portugal (Salena 1995). Since their existence was made public in November 1994, the uproar created by the possible destruction of this Upper Palaeolithic-style art played an important role in stopping (at least temporarily) a major dam project that would flood the petroglyph sites (Zilhão 1995b).

There are claims that the petroglyphs are definitely not Palaeolithic. Alan Watchman argues that the engravings are younger than 1700 b.p. — based on interpretations of 14C ages associated with rock coatings (Watchman 1995; 1996). Robert Bednarik (1995a; 1995b; 1995c; 1995d) argues for ages younger than 7000 years based on microerosion dating and style. Archaeologically, a recent age for stylistically Palaeolithic art would undermine stylistic analyses of rock art and their chronological basis (Jorge 1995; Zilhão 1995a; Züchner 1995).

My focus is whether available radiocarbon results can constrain the ages of Côa engravings.

Assumption of rock coatings as a closed system

A key assumption in radiocarbon-dating petroglyphs is that rock coatings form a closed system (Dorn 1994; Watchman 1996). The most common rock coating at Côa is silica glaze, growing on exposed rock surfaces and along sub-surface joint faces. Rock coatings of mostly amorphous silica occur in warm deserts (Fisk 1971), in cold deserts (Weed & Ackert 1986), along tropical rivers (Alexandre & Lequarre 1978), and in mid-latitude humid temperate settings (Robinson & Williams 1987; 1992; (Farr & Adams 1984; Weed & Norton 1991) that has been used to radiocarbon-date rock paintings (Watchman 1992; 1994) and petroglyphs (Nobbs & Dorn 1993).

I observed two different types of silica glazes in Côa samples (Figure 2). One is mostly silica, likely equivalent to Watchman’s (1995; 1996) ‘white amorphous silica’ deposits. The other is silica with abundant aluminium — likely equivalent to Watchman’s (1995; 1996) ‘silty brown’ accretion. A minor component of silica glaze, iron skin, occurs in discontinuous patches (Figure 2). The texture and geochemistry of silica glaze on petroglyphs is similar to coatings on adjacent natural joint faces and coatings exposed in dam and road cuts.

I agree with Watchman (1995) that aluminium-rich silica glaze is more common, contains detrital grains of various minerals, and typically rests on top of aluminium-poor silica glaze. I also concur that a stratigraphy of ‘silica under silty brown’ (Watchman 1996: 28) is common on natural joint faces, but this stratigraphic relationship did change from cross-section to
ages. Sample designations are presented in Table 1. Pieces of schist were chipped from each petroglyph with a tungsten-carbide needle. Petroglyphs were sampled at locales where the bottoms of the grooves were ~2–4 mm beneath the adjacent joint face.

I stress that control samples were collected from the same joint faces as petroglyphs, but in different positions. In the case of FC-95-2b, FC-95-5a, FC-95-8a, control samples were collected close to engravings. Control sample FC-95-2a came from within silica glaze where the panel was formerly covered by soil material that had been excavated by archaeologists. In the case of FC-95-5b and FC-95-8b, it was possible to collect samples from ~1–2 cm within still-unspalled joint faces in places where the overlying block had begun to separate.

For weathering-rind samples, silica glaze was removed with a tungsten-carbide needle under x45 magnification, checked by scanning electron microscopy. For intra-glaze organics and interface organics, silica glaze was mechanically removed with a tungsten-carbide needle under x45 magnification. The material was pretreated with HCl, HF and NaOH in an approach outlined elsewhere (Dorn 1994).

Radiocarbon in an open system
Analytical data indicate that silica glaze at Cova does not form a closed system. AMS 14C ages from panel positions range from 4700 b.p. to 18,000 b.p. (Table 1); these are much younger than corresponding 234Cl exposure ages (Phillips et al. this issue). The sole exception is panel 14 at Canada do Inferno, where the panel 234Cl age is 16±1.5 ka (table 1 in Phillips et al. 1997, p. 101, above). If silica glaze was closed to the addition of younger carbon, 14C ages for all but one of the panels should be infinite. They are not, and the simplest explanation is continued exchange of organic matter in an open system. Reasonable mechanisms exist for periodic insertion of younger carbon when siliceous coatings spill or dissolve, or epilithic or endolithic organisms add organic matter to the coating (Figure 3) or to the weathering rind.

Figure 1. Placement of the Cova river valley, a tributary of the Douro River, and the rock art panels that were sampled for dating, modified from Zilhão (1995a).

Figure 2. Electron microscopy illustrating silica glaze and weathering-rind organics on FC-95-4, a goat engraving at Penascosa. The sample is imaged by backscattered and secondary electrons, and analysed by wavelength dispersive spectrometry. The organic matter, which is black in backscattered electrons and bright in secondary electrons, was verified with wavelength dispersive spectrometry. The upper (aluminium-rich) layer likely corresponds with Watchman’s (1985; 1996) ‘silty brown’ material, and the lower (aluminium-poor) layer likely matches Watchman’s ‘grey white amorphous silica’.
panel samples

Canada do Inferno
FC-95-2a: Within overlying rock coating 4700±70 Beta-82450 -24.9
FC-95-2b: Exposed weathering rind 9400±60 Beta-82451 -25.8
FC-95-2b: Exposed, at the interface between rind and coating 18,510±80 Beta-87058 -25.9

Panel Penascosa
FC-95-5a: Exposed weathering rind 10,990±60 Beta-82456 -26.8
FC-95-5a: Exposed, at the interface between rind and coating 10,300±60 Beta-87059 -25.4
FC-95-5b: Rind within unexposed joint crevice, bulk sample 23,560±190 Beta-82457 -26.9
Sample split of less dense organics 17,460±70 Beta-86632 -26.4
Sample split of dense organics 29,990±240 Beta-86633 -23.4

Ribeira de Picos
FC-95-8a: Exposed weathering rind 9180±60 Beta-82463 -25.3
FC-95-8a: Exposed, at the interface between rind and coating 17,090±70 Beta-87059 -25.5
FC-95-8b: Rind within unexposed joint crevice 10,350±60 Beta-82464 -25.6

petroglyph samples

Canada do Inferno
FC-95-1: Left-Oriented Ox 3700±60 Beta-82449 -22.2
FC-95-3: Upper Horse, 1st sample weathering rind 4350±60 Beta-82452 -23.2
FC-95-3: Upper Horse, 2nd sample weathering rind 4590±50 Beta-82453 -24.0
FC-95-3: Upper Horse, interface between rind and coating 3980±60 Beta-87060 -22.3

Panel Penascosa
FC-95-4: Top Goat, 1st sample weathering rind 5010±50 Beta-82454 -24.5
FC-95-4: Top Goat, 2nd sample weathering rind 4960±60 Beta-82455 -24.8
FC-95-6: Big Ox, 1st sample weathering rind 2690±60 Beta-82458 -24.6
FC-95-6: Big Ox, 2nd sample weathering rind 2690±50 Beta-82459 -22.9
FC-95-6: Big Ox, interface between rind and coating 2120±50 Beta-86014 -22.1

Ribeira de Picos
FC-95-7: Horses, 1st sample weathering rind 5480±60 Beta-82460 -23.5
FC-95-7: Horses, 2nd sample weathering rind 4540±60 Beta-82461 -22.4
FC-95-7: Horses, 3rd sample weathering rind 5130±70 Beta-82462 -23.1

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**Table 1. AMS 14C radiocarbon ages on Cõa petroglyphs and adjacent natural panel surfaces.**

When 14C and 36Cl ages are compared for the same panels, rates of organic carbon exchange appears to be slow. Using open-system radiocarbon theory with bomb carbon (McKay et al. 1986), mixing time constants on Cõa panels range from ~15,000 to 25,000 years. The significance of such slow carbon exchange is exemplified for the Horses engraving at Ribeira de Picos (Table 1). Measured ages of ~5000 b.p. equate to ‘true ages’ of ~18,000 b.p., with mixing constants of ~10,000 years (McKay et al. 1986). In other words, petroglyph grooves could have received a large influx of then-modern carbon in the Palaeolithic when rock faces were exposed to a subaerial environment. Subsequent slow rates of post-engraving carbon exchange would produce observed (Table 1) Holocene ages (McKay et al. 1986). Open-system radiocarbon dating is used in soils (Wang & Amundson 1996), but its potential in petroglyph dating has not heretofore been discussed.

**Figure 4** presents a hypothetical scenario wherein 14C ages for weathering-rind organics are consistent with both 36Cl ages and a Palaeolithic age for engravings. The ‘cartoon’ starts with accumulation of organic matter within a joint face in the subsurface. Then, the joint face is exposed ~140,000 b.p. (e.g. sample FC-95-8b) — starting the 36Cl clock (Phillips et al. 1997). An open-system of slow-carbon exchange yields finite radiocarbon ages because open exchange...
occurs, where the radiocarbon age reflects exchange rates and not the true panel age.

The story of Figure 4 changes with an engraving event. In this hypothetical scenario, engraving occurs ~18,000 b.p. — leading to a large influx of then-modern carbon, as occurs when rock material is exposed to a subaerial environment (Bonani et al. 1988; Chaffee et al. 1994; Farr & Adams 1984; Krumbein & Dyer 1985; Nobbs & Dorn 1993; Weed & Norton 1991). Petroglyph-manufacturing essentially floods weathering-rinds with 'then-modern' carbon. Carbon exchange slows as silica glaze re-forms. A dynamic equilibrium reinserts itself whereby a slow mixing time constant of carbon (cf. McKay 1986) forces $^{14}$C ages towards a long-term equilibrium found in ‘control’ panel weathering rinds. In this hypothetical scenario, weathering-rind organics in panel (control) samples represent a long-term equilibrium condition, and petroglyph ages represent a system disturbed by petroglyph-manufacturing — but one that is moving slowly towards an equilibrium condition. With enough time, petroglyph $^{14}$C ages would reach an equilibrium and yield ages similar to adjacent panel faces.

If the model in Figure 4 is correct, petroglyph manufacturing could have occurred in the
Palaeolithic. Using the theory of radiocarbon dating of open systems with the bomb effect (McKay et al. 1986), 36Cl/14C correlations indicate that mixing times are slow enough for measured petroglyph 14C ages to reflect truly an Upper Palaeolithic genesis. Because exchange rates are uncertain, however, radiocarbon can only provide minimum ages in an open system of carbon exchange (McKay et al. 1986) — that is, if older carbon does not contaminate samples.

Discussion of other problems associated with radiocarbon dating at Côa

Watchman (1995; 1996) used a railroad quarry rock face to show that ancient detrital carbon can become incorporated within silica glazes. I observed the same temporal offset in the sample of intra-glaze organics; sample FC-05-2a yielded an age of 4700±70 b.p. (Table 1). Watchman (1995) also noted that graphite within the host rock could add ancient organics to weathering-rind samples.

Older petroglyph ages in Watchman's (1995: 108) dataset were explained as being from 'hill slope cultivation' when 'silt began to wash across exposed rock surfaces and into petroglyphs after they were carved.' Watchman’s (1995; 1996) hypothesis is that the addition of older organics was the product of human disturbance of the landscape about 1700 years ago.

My data reveals that problems with radiocarbon dating organics on Côa rock faces are more complex and cannot be 'corrected' easily. Consider two stratigraphic inversions in Table 1. At panel 14 of Canada do Inferno, weathering-rind carbon (9400±60 b.p.) is half the age of carbon from an interface position (18,510±80 b.p.). A similar inversion occurs at Ribeira de Piscos, where organics resting on top of the rock (17,090±70 b.p.) are almost twice as old as organics within the underlaying weathering rind (9180±60 b.p.). These inversions either reflect the addition of younger organics into weathering rinds, or more likely reflect ancient organic matter trapped by rock coatings — indicating the insertion of older contaminants long before human cultivation.

There is additional evidence that organic matter can be 'inherited' from a time before subaerial exposure. A 14C age for a still-unexposed joint face at Ribeira de Piscos (10,350±60 b.p.) is older than the exposed face of this joint (9180±60 b.p.). The offset is even greater at Penascosa, where the exposed sample (10,990±60 b.p.) is much younger than a sample from the unexposed rock crevice (24,550±190 b.p.). Organics from this unexposed Penascosa joint yield different ages for different materials, all within the same sample; porous organics yielded younger ages (17,460±70 b.p.) than dense-shiny organics (29,990±240 b.p.). The existence of older organics in a subsurface position offers another explanation for ancient radiocarbon ages in quarry samples.

Perhaps the best way to understand Côa carbon is to present a general framework of three sources: host rock; weathering rinds; and on top of weathering rinds.
Organic matter may be within the host rock. Graphite may occur (Watchman 1995), as may other ancient sources of carbon (Timofeyev et al. 1990). Organic matter can deposit within rocks during weathering episodes all in the subsurface. As discovered in Israel, roots can penetrate in rock joints to depths of over 20 metres — depositing organic matter with radiocarbon ages over 30,000 b.p. (Danin et al. 1987). Micro-organisms are known to weather rocks at great depths (Chapelle & Bradley 1996; Fredrickson & Onstott 1996; Fyfe 1996). Ancient roots and microbial remains then undergo diagenesis and can evolve into vitrinite (Chitale 1986) — all in the subsurface.

Organics can also be deposited in weathering rinds before a rock coating forms. Lichens, algae, and fungi can all live within rocks as endolithic organisms (Fyfe 1996; Krumbelin & Dyer 1985; Urzi et al. 1993; Viles 1995). Their remains can comprise ancient organics (Friedmann & Weed 1987).

Organics can accumulate on top of rocks in three positions. ‘Interface’ organic matter is deposited in depressions on rock surfaces, all before a rock coating encapsulates organics (Dorn et al. 1992; Soleilhavoup 1992). Organic matter is deposited within layers of rock coatings (Watchman 1995; 1996), or in places where rock coatings have eroded (Figure 3). Organics are also found on top of rock coatings.

There is good evidence that the dated organic matter can have a mixed origin. Watchman (1995; 1996) argues that the ‘brown silty’ layer (cf. aluminium-rich layer in Figure 2) incorporates ancient organics, and that weathering-rind ages can be contaminated by graphite. My data reveals that ancient organics also occur within rock crevices in the subsurface, and at the interface between the rock coating and underlying rock. Also, different types of organics can be mixed within the same sample. In summary, organics in and under rock coatings can come from the host rock, from erosion of soils, from contemporaneous organics, or from organics deposited long after petroglyphs are engraved.

Consistency with other dating results
In the debate over the antiquity of Côa engravings, there are stylistic arguments in favour of a Palaeolithic age (Bahn 1995a; Clottes et al. 1995; Zilhão 1995a; 1995c; Züchner 1995) and in favour of a Holocene age (Bednarik 1995b; 1995c). I am not qualified to assess these issues.

There is the hypothesis that petroglyphs could have been manufactured at some earlier time, and then re-engraved in the Holocene (Zilhão 1995c). This hypothesis cannot be disproved or supported by my data, by Watchman’s (1995; 1996) 14C data, or by Bednarik’s (1995b) microerosion data. The re-engraving event would have introduced younger carbon and would have re-abraded rock surfaces — resetting both 14C and microerosion clocks.

There have been three types of ‘direct-dating’ data presented in support of a Holocene age: radiocarbon; microerosion dating; and geomorphic instability of the Côa valley. I address each in turn.

Radiocarbon
14C ages obtained by Watchman (1995) are not in conflict with my 14C data. In fact, there is a similar statistical distribution for the 14C ages (Figure 5). While interpretations of these data differ, this blind (Bednarik 1995c: 878) test demonstrates that petroglyph 14C dating is replicable.

I believe that Watchman’s (1995; 1996) 14C ages are consistent with the hypothesis of an open system. 14C ages for intra-silica glaze organics can only be interpreted as minimum ages for the underlying engraving, as long as they are corrected for possible ‘older carbon’ influences. Organic carbon superimposed on top of an engraving can only have been emplaced after the petroglyph was carved.

In order for petroglyph radiocarbon ages (Table 1; Watchman 1995; 1996) to be valid, rock coatings must be closed to the addition of younger carbon. There is only one line of evidence that a closed system may have occurred during the Holocene: weathering-rind organics are older than interface organics for samples from petroglyph grooves (Table 1). (This is not true for panel samples.) If siliceous rock coatings in the Côa valley indeed formed a closed system in the Holocene, and weathering-rind organics are not contaminated by older carbon, petroglyphs ages would be between 2100 B.P. and 5500 B.P. (Table 1) — in other words between 14C ages for interface organics and 14C ages for weathering-rind organics.

The evidence for a closed system in the Holocene, however, is not overwhelming. Older
weathering-rind ages could simply be from periodic erosion of rock coatings (cf. Figure 3) — allowing the addition of younger carbon on top of rock surfaces. There is no evidence in Watchman’s (1995; 1996) data to indicate that silica glaze forms a closed system in the Holocene. More generally, there have been no published tests comparing silica-glaze entombed organics with independent ages. Just because Cõa represents the first blind test of petroglyph radiocarbon dating, where ages of two independent and simultaneous investigations occur in the same range (Bednarik 1995c: 878) (Figure 5), does not imply that these \(^{14}\text{C}\) ages can be used to date Cõa petroglyphs.

In summary, I do not believe that it is possible to make an accurate interpretation of Cõa radiocarbon ages. Younger carbon is added over time, as demonstrated by comparisons of panel \(^{14}\text{C}\) ages and panel \(^{26}\text{Cl}\) ages. Older carbon may be added in the form of graphite in weathering rinds (Watchman 1995): detrital organics incorporated into rock coatings (Watchman 1995); detrital organics trapped by rock coatings on rock surfaces (this study); and organic matter from a prior period of rock weathering (this study). There is evidence that different ages of organics can be included in the same sample.

There is no independent evidence to believe that petroglyph organics are contemporaneous with petroglyph engraving, either at Cõa or in independent tests elsewhere. In summary, petroglyph radiocarbon ages may be too young, too old or just right; they are not easily interpreted.

**Microerosion**

I cannot compare my data with ages obtained with the microerosion technique (Bednarik 1995b) for two reasons.

First, silica glaze on engravings prevents microerosion dating from being used (Bednarik 1992: 281):

> Since the method uses optical observation, and relies on the assumption that no chemicals have accelerated or retarded the development of erosion phenomena, petroglyphs to be analysed must be free of mineral accretions, or other natural deposits concealing them (including coats of rock varnish, carbonate, oxalate, silica, or lichen).

and (Bednarik 1993: 455–6):

Other preconditions for admissibility are that there must be no mineral deposit covering the petroglyph (which in fact means that the method can only be used where the techniques utilizing accretionary deposits are entirely ineffective).

All engravings samples I observed are covered with silica glaze or epilithic organisms; thus they are inappropriate for dating by the microerosion method. Samples may have been collected where coatings spilled. The lack of silica glaze today, however, would not necessarily mean the rock coating was absent in the past. Furthermore, a lack of silica glaze would indicate that rock faces at Cõa are in an open system of carbon exchange.

Second, the microerosion method is complicated by issues of quartz mineralogy, weathering and erosion. There are two general concerns.
A

A key assumption of microerosion dating is that quartz surfaces exposed by petroglyph manufacturing are the same type of quartz and are unweathered before engraving. This cannot be assumed, must be tested, and is rarely true (cf. Hochella & Banfield 1993). There are many different types of crystalline SiO₂ that weather differently (Gibson & LaFemina 1996). At the nanometre-scale of high resolution electron microscopy, quartz weathers to an amorphous state along crystal defects (Pope 1995a). At the micrometre-scale of scanning electron microscopy, quartz weathers internally along larger-scale weaknesses (Pope 1995b). When a petroglyph is made, therefore, quartz can be ‘pre-weathered’ — unless the petroglyph is engraved in newly crystallized magma. This is certainly not the case at Côa — where panels have experienced subaerial weathering for at least 16,000 to 136,000 years, and where joint fractures have been exposed to vadose and phreatic water for untold millions of years. In summary, rates of post-petroglyph quartz microerosion would be highly dependent upon ‘inherited weathering’ within quartz — all assuming the same type of quartz is compared.

Although quartz may look fresh at x45 magnification in the field, it has weathered internally — all before exposure at the surface. At Côa, for example, I noted internal weathering features of holes, fractures and networks in the classification of Pope (1995b); the ‘microerosion clock’ started long before the petroglyph was made. However, my observations on internal quartz weathering were not quantitative; replicate measurements on inherited quartz weathering should be made on the same grains that are analysed for microerosion (cf. Pope 1995a; 1995b).

Geomorphic instability

Bednarik (1995c; 1995d) and Watchman (1996) used deductive arguments to suggest that the landscapes and rock surfaces of Côa are too unstable to support Palaeolithic art. In contrast, ³⁶Cl ages for petroglyph panels, ⁳⁶Cl ages for associated joint faces and ³⁶Cl ages for hillslope materials (table 1 in Phillips et al. 1997, above) all argue for a landscape that is stable enough to support Palaeolithic art.

Conclusions

Although available data are not definitive, there are several reasons why I favour a Palaeolithic age for Côa art.

First, although Côa provided the context for the first blind test of petroglyph radiocarbon dating (FIGURE 5), and although the ‘primary radiocarbon dates of Watchman and Dorn represented the same range’ (Bednarik 1995c: 880) of Holocene ages, I do not believe that these radiocarbon ages provide definitive results. There is good evidence that Côa rock coatings do not form a closed system. There is evidence that ages can mix different types of organics, and that contamination from older and younger material is likely.

Second, ³⁶Cl ages reveal that all of the sampled panels were exposed and available for engraving during the Upper Palaeolithic. Furthermore, ³⁶Cl ages reveal that rates of rock-surface erosion are slow enough to preserve Palaeolithic art (Phillips et al. 1997). Unlike the radiocarbon tests in railroad cuts (Watchman 1995) and unexposed joint faces (this study), where evidence of contamination was revealed, the dam excavation test revealed virtually no potential for ‘inherited’ ³⁶Cl (Phillips et al. 1997).

Third, if petroglyph radiocarbon ages are indeed accurate and not contaminated by younger or older carbon, measured ages could truly reflect manufacturing during the Upper Palaeolithic. Using ³⁶Cl panel ages (Phillips et al. 1997), ¹⁴C ages for panel weathering-rinds (TABLE 1) and open-system radiocarbon theory (McKay et al. 1986), mixing time constants would be sufficiently slow for measured petroglyph ages to fall within the Upper Palaeolithic.

Fourth, I think it unlikely that all of the sampled petroglyphs were re-engraved. But if they were, it would still mean that the engravings
pre-dated the measured petroglyph 14C ages and could be Palaeolithic.

In summary, the only unambiguous data on the age of Côa art come from 36Cl ages — indicating that panels were available for engraving during the Palaeolithic (Phillips et al. 1997). Because 14C ages may be contaminated by older materials, younger materials, or both, it difficult to make definitive conclusions based on 14C evidence.

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