KEYWORDS: *Fossil - Human footprint - Beachrock - OSL dating - Western Australia*

Fossilised human footprints on the coast of north Western Australia

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Abstract. A line of eleven human footprints in rock survives as trace fossils on the northern coast of Western Australia. Their unique occurrence on a ledge of 'beachrock' found in the intertidal zone indicates they may be of relatively recent origin. OSL dating of quartz grains from the rock layer containing them reveals an age of approximately 2000 years.

FOR a number of years people living at a remote location in Western Australia have been aware of a line of human footprints embedded in rocks nearby (Figure 1). These footprints are not artificially made or chipped out of the rock, but have been made by humans walking across the land when the ground was soft. Each footprint shows an impression at the heel as the weight of the person is transferred through the foot to the ground, and in most examples there is a marked ridge of rock around one side or at the front of the foot, consistent with a soft or mud-like ground being displaced forward and side-ways by each foot (Figure 2).

At other parts of north Western Australia, particularly around the Broome area, it is well known, locally, that dinosaur footprints occur in rocks exposed at low tide along the coast. While dinosaurs became extinct about sixty five million years ago, how could human footprints also be fossilised in rocks of the region and could they be very ancient?

The footprints

The footprints described here occur along a rock shelf lying between a bay on the east and sand dunes to the west (Figure 3). The rock shelf faces the bay and is thus protected from the direct wave action of the open sea. Figure 4 shows a rough plan of the location, but the exact location cannot be given because local people fear vandalism, as has occurred with visitors attempting to cut dinosaur footprints out from other rock in nearby regions.

Figure 5 is correct to scale and shows ten footprints forming a line 6.5 metres long and facing approximately south. An eleventh footprint, facing north-west, is located 5.5 metres north of these and there are possibly another two or three footprints, not as well defined, nearby. The two footprints at the top of Figure 5 are both from left feet indicating possibly there is a missing right footprint between them if the person paused here and placed their right foot down. It is difficult to be certain of what happened because at this section the rock surface is now irregular and crumbling.

Figure 1. *Sand fills a line of human footprints fossilised in beachrock.*

The footprints vary in length from 19 cm to 25.5 cm and it is apparent that part of this range is due to variations in impact of the feet upon the then-soft sand. These sizes suggest adults, at least one probably a man. Taking the footprint at the top of Figure 5 as the first, the

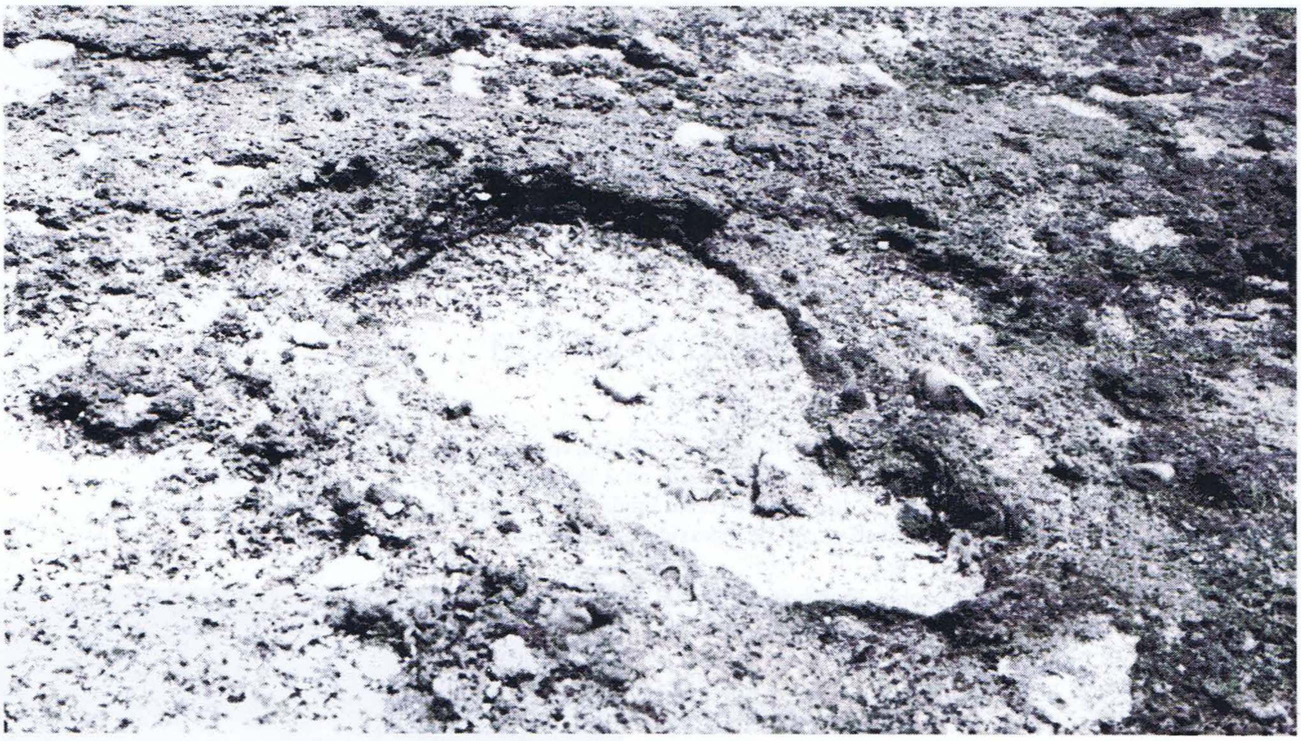

Figure 2. *Fossilised footprint showing lateral displacement of sand resulting in raised rock edge.*

Figure 3. *Beachrock has formed at the intertidal zone beside a protected bay. Footprints (arrowed) in foreground.*

lengths of the footprints are, to the nearest 0.5 centimetre, 24, 25.5, 24, 23, 23, 23, 22.5, 20, 24.5, 21.5 and 19 cm. At least two people walked this line because the sixth footprint from the top is a right foot out of place with the rest. Again, lower down the eighth and ninth footprints, 20 cm and 24.5 cm, are both from a right foot implying two different people. The isolated footprint further away is remarkable in that it curves over the rock as if it was originally placed over a small ridge of sand and each toe is clearly defined. The big toe dips 3 cm and the other toes 1 cm deep into the rock. The preservation of individual toe prints is due to the fact that the toes were splayed on impact and the small sand ridge, about 5 cm high, left the sand slightly drier and less runny when the footprint was made.

The rock shelf consists of a basal layer of hard, blackish limestone over which lie layers of softer rock consisting of fragments of broken coral and shell cemented to sand grains. The footprints have formed in one of these overlying layers (Figure 6). These rock lay-

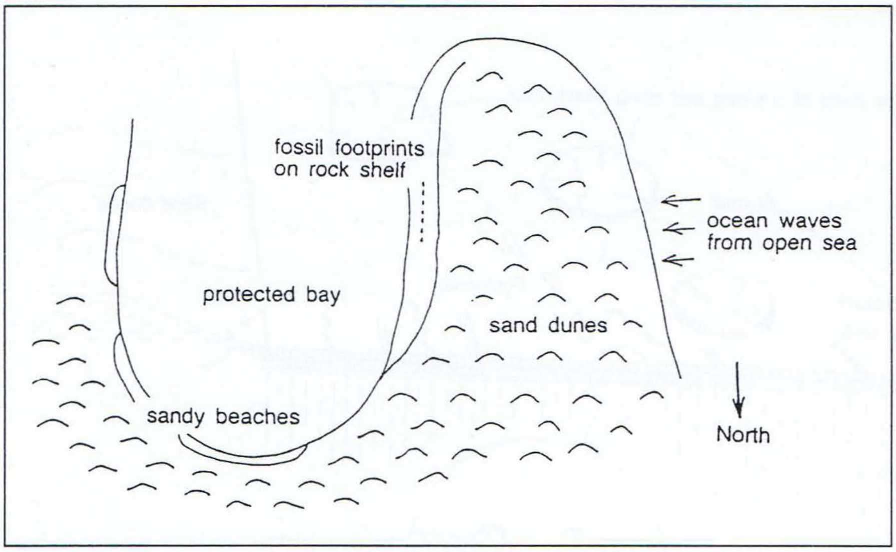

Figure 4. *Site plan of fossil footprints site (rough sketch).*

ers of sand, coral and shell matrix vary in thickness from about 1 cm to 15 cm and form overlapping sheets covering the rock shelf. The rock surface varies from sand and small fragments of coral and shell grit in some places, to larger pieces of coral and complete shells cemented to the sandstone in others (Figure 7). The rock shelf is almost horizontal with the top layers sloping slightly towards the water, the slope being more pronounced nearer the water's edge. Figure 6 is a schematised cross-section, not to scale, and the width of the rock ledge is approximately 85 m, with the footprints being approximately 55 m from the cliff edge and 30 m from the edge of the sand dunes. The limestone rock shelf ends in a 5-m drop to sand below, exposed at the lowest tides. The footprints are at an elevation of approximately 8.5 m and since most high tides in the region reach only 6 to 8 m they are covered by seawater only with the highest tides. This region has amongst the largest tide variations in the world, ranging from a (negative) low tide of -0.6 m to a high of 9.6 m.

Weathering has created gaps between the soft, crumbly layers with sheets of rock lifting off and lying loosely on the surface in many places. The rock is stable where the footprints have survived, but has crumbled on either side making the record of footprints incomplete.

At the site of the footprints, layer 1 (Figure 6) is a soft pinkish rock made up of coarse sand grains and shell and coral debris. It ranges in thickness 0.5-2 cm, and in places is pushed up forming a ridge around the footprints as the weight of the people pushed the sand out around the feet. In adjacent areas, up to several metres away, this layer is weathered and broken and can be seen to range mostly 1-4 cm in thickness. There, larger pieces of coral and shell similar to those found in the nearby sand make up part of the rock.

Layer 2 at the footprint site is soft greyish rock consisting of sand, shell grit, and fragments of coral and shell with many pieces up to 6 cm in size. A few metres away this layer includes a 9 cm coral piece. A black mineral in the sand forming this layer gives it the greyish appearance and may be one of the beach sand minerals such as rutile. Figure 8 shows a concentration of this mineral which has pooled in the base of one of the footprints prior to the ground cementing as rock. Although I have defined layers 1 and 2 at the footprint site, I should point out that for much of the rock shelf this sandstone layering is irregular, poorly defined, overlapping and fragmented, as can be seen in the accompanying photographs. There may have been several or many layering episodes and further layers may exist below the surface in places.

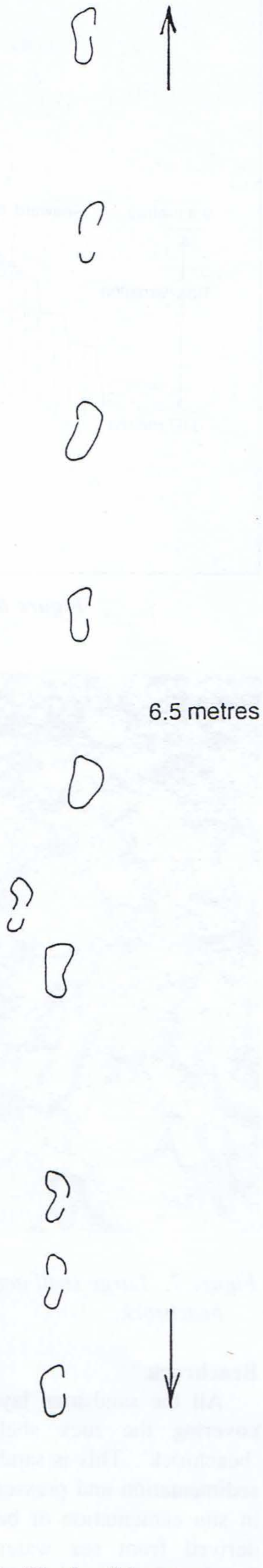

Figure 5. *The fossil human footprints, plan drawn to scale.*

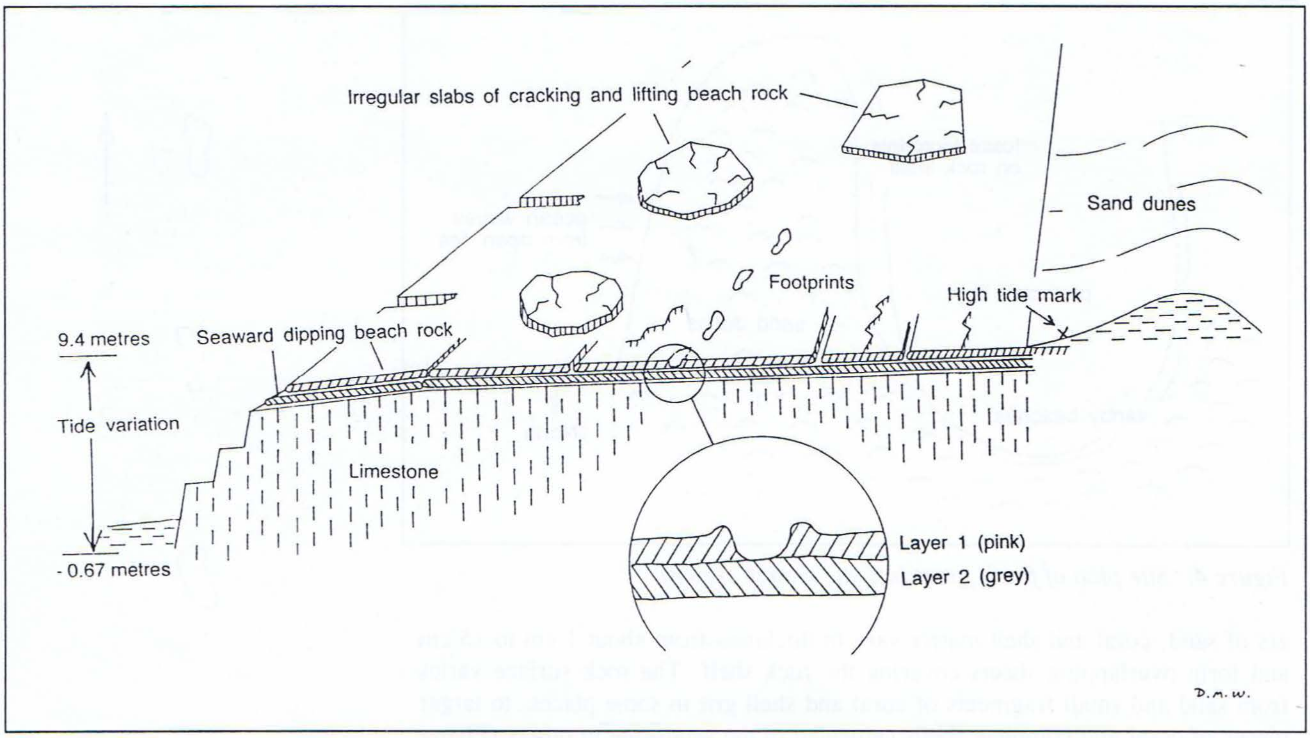

***Figure 6.** Fossil human footprints site, schematic stratigraphy, not drawn to scale.*

***Figure 7.** Large shell and coral fragments cemented in beachrock.*

Beachrock

All the sandstone layers, including layers 1 and 2, covering the rock shelf consist of what is called 'beachrock'. This is sandstone which has not formed by sedimentation and pressure from layers above, but from in situ cementation of beach sand mostly by chemicals derived from sea water covering it with the tides. Beachrock forms at the intertidal zone along beaches and shorelines when the balance of nature allows cementing minerals to bind sand or other particles at a greater rate than the wave action of the sea causes particle movement and erosion. It has been suggested that beachrock might form below the surface where there is less particle movement, but the existence of these footprints suggests that beachrock can form under subaerial conditions on the exposed surfaces of coastal sand and debris.

Typical beachrock may be a calcarenite, a conglomerate or a breccia. The lamination and disposition of the rock are the same as those of the local unconsolidated beach sediment, to which the grains of rock correspond also in composition and texture (Bathurst 1975: 368). Just as a sandy beach slopes down to the water's edge, so too will beachrock form with a seaward dip, corresponding to the original beach slope.

Several factors are involved with the formation of beachrock:

(i) *Supply of calcium carbonate*

Beachrock occurs most frequently in tropical and subtropical waters where the presence of coral reefs and marine life result in high sea levels of calcium carbonate ($CaCO_3$). The beachrock holding these human footprints has formed over limestone, a rich source of calcium and other minerals, and is located in the tropical region of Western Australia.

(ii) *Precipitation of calcium carbonate*

In shallow tropical seas the water becomes supersaturated with calcium carbonate which may precipitate on the shore following evaporation. Other factors such as changes in water temperature and higher oxygenation of surface water due to wave action may also contribute to

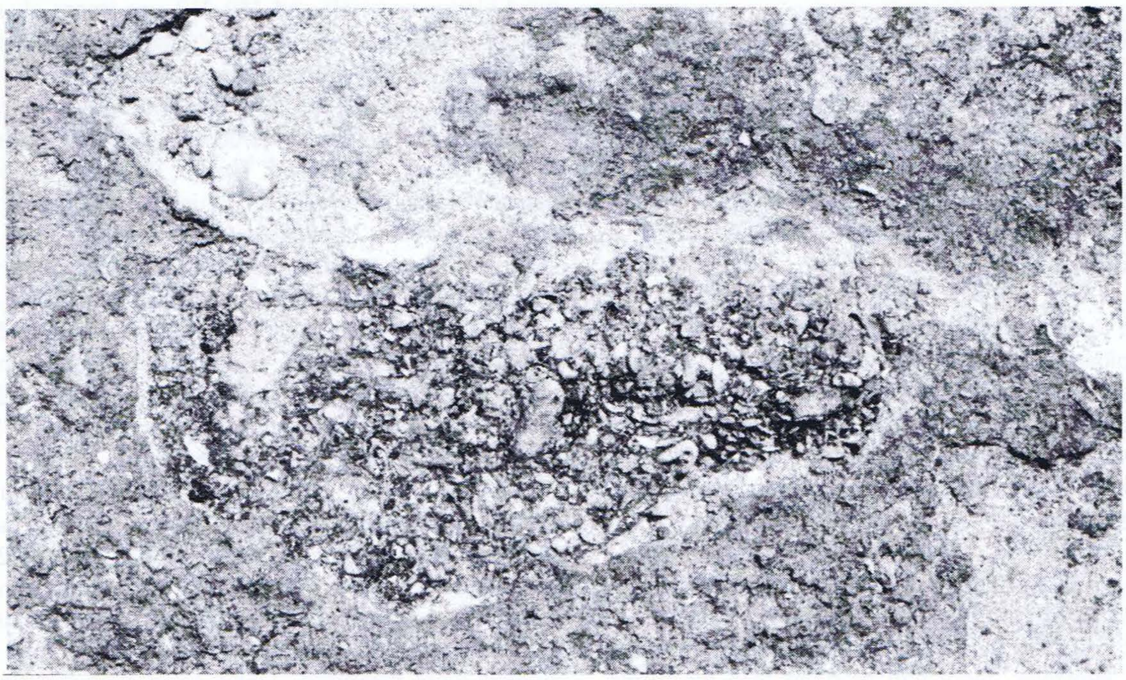

Figure 8. Base of footprint showing dark mineral sand, shell and coral fragments.

the supersaturation and precipitation of calcium carbonate. Algal photosynthesis may also remove carbon dioxide from water saturated for calcium carbonate, leaving carbonate precipitate as a cementing substance on the sand (Bathurst 1975: 225).

(iii) *Cementation*

Two forms of calcium carbonate, aragonite and high-magnesium calcite are found in marine organism such as foraminifera, coralline algae, corals, bivalves and molluscs. From there they occur in seawater and are the most common cementing substances forming beachrock from beach sand and debris. Calcite (rhombohedral calcium carbonate) crystallises from relatively cool solutions whereas aragonite (orthorhombic calcium carbonate) crystallises at higher temperatures.

The process by which aragonite is precipitated in some conditions and calcite in others is also dependent on the presence of different ions in the sea water which affect the mineral equilibria. Supersaturation with respect to both calcite and aragonite is a necessary condition for aragonite precipitation. However, the ion having the greatest ability to inhibit the growth of calcite is Mg^{2+} and in the presence of $MgCl_2$ only aragonite is formed, in its absence only calcite (Bathurst 1975: 242-4).

As the beachrock forms, the pore space between grains is reduced by further solution and cementation. Aragonite is commonly the cementing substance found in recent beachrock, but this may invert to calcite in older sandstones (Pettijohn and Potter 1972: 420). Sometimes aragonite cement is dissolved and replaced by calcite. Any reduction in pore space results in a harder rock. However, without compaction and pressure from layers of rock above, beachrock remains relatively soft when found in situ at the intertidal zone.

The beach sand in this region of Australia is of two types coming from two sources. Firstly, carbonate sand is of biogenic origin, related to the prevalence of molluscs, algae, corals, foraminifera and bryozoan carbonate sand on the continental shelf off southern and western Australia, where living bryozoa are abundant (Davies and Williams 1978: 150-1). Secondly, desert dunes of red, silty quartzose sand have been submerged and dissected by massive erosion. Beach sand directly eroded from these 'pindan' sand ridges retains a pink colouration and this may account for the pink seen in layer 1 of the fossil footprint site.

Dating the footprints

(i) *Based on the geological formation of the rock*

The footprints occur in beachrock surviving as it formed in situ at the intertidal zone. This beachrock lies within the intertidal zone of today's tides and slopes down to the water's edge the same as if it were now a sandy beach. This indicates that it formed when the seas were at the same level as they are today. The sea reached its approximate present level at about 6000 years ago (Chappell 1976: 14; Hickey 1981) and this is the maximum possible age for the footprints.

It is unlikely that the rock was formed in some earlier interglacial when the sea was at a similar level because erosion and sedimentation over the landscape would mean it would be extremely unlikely for the water's edge to return to the same position and level with the footprints still surviving in this soft rock. This is different to some of the coastal dinosaur footprints in the region which may have become preserved under different conditions, in harder rock, and which are now mostly submerged under the water, able to be seen only at the lowest tides.

As for the minimum possible age, I have seen beachrock in the Darwin area which has formed incorporating Second World War debris and other modern-day rubbish such as metal and broken glass. This phenomenon has also been reported from other parts of the world and so, based on the location of the rock alone, one can see how the footprints could have formed as recently as just decades ago.

(ii) *Based on human records*

The oldest Aborigines, in their seventies, living in the locality of these fossil human footprints remember the footprints from when they were children. These footprints have also been incorporated into local Aboriginal legend, suggesting an age of at least two or three human generations.

(iii) *Problems with dating the shell or cement components of beachrock*

One could date the coral and shell fragments within the rock. However, these will be older than the formation of the rock itself, though possibly by only a short time. Another component to consider is dating the cement itself, since this should reflect the exact time when the rock was formed. However, the cements, because of their mineralogical instability, may be dissolved or recrystallised with the deposition of new cement since the time of the original formation of the rock [consider also the issues concerning reprecipitated calcium carbonate dating discussed in Bednarik, this issue of *The Artefact*]. Thus, dating the cement may be unreliable.

(iv) *OSL dating of quartz sand grains*

Optically stimulated luminescence (OSL) dating is a method whereby the luminescence emitted by individual mineral grains is measured to determine when those grains were last exposed to sunlight. It only takes a few minutes of sunlight to reset this luminescence 'clock' and any archaeological specimen for analysis must be collected in such a way that no sunlight falls on it.

As quartz sand grains form into rock, there is a point at which the inner grains are sealed and protected from external light. A sample of the rock layer in which the footprints were made was taken for analysis and OSL dating of quartz sand grains in this layer revealed they were last exposed to sunlight just under 2000 years ago. This is taken as being the approximate time at which the rock formed and preserved the human footprints.

A report giving the technical details of the method and the results, provided by Dr Richard 'Bert' Roberts from La Trobe University, Melbourne, follows.

Optical dating procedures

The sunlight-exposed material on the outside surface of the beachrock sample was removed to a depth of a few millimetres under subdued red laboratory illumination. Two sand-size fractions from the beachrock were then extracted for optical dating: 90-125 μm (typical of wind-blown material) and 180-212 μm (more characteristic of water-lain deposits). The quartz grains were isolated using standard laboratory procedures (Aitken 1998) and finally etched in 40% hydrofluoric acid for 45 minutes to remove the alpha-dosed outer rinds from each of the grains. The pure quartz fractions were then mounted on stainless steel discs using a silicon oil spray, and the optically stimulated luminescence (OSL) emissions were detected using a Risø TL reader fitted with a Thorn-EMI 9235QA photomultiplier tube and two U-340 filters. Optical stimulation by green-plus-blue (420-550 nm) light was provided by a tungsten-halogen lamp fitted with a GG-420 filter and an interference filter, and laboratory irradiations were made using a calibrated ^{90}Sr/^{90}Y beta source mounted on the reader.

The 90-125 μm grains were mounted as 3 mm-diameter sub-samples (aliquots), which corresponds to approximately 800 grains per aliquot; a total of 24 aliquots was measured. The 180-212 μm grains were prepared both as 1 mm-diameter aliquots (~10 grains) and as 3 mm-diameter aliquots (~100 grains); a total of 48 aliquots were measured. Single-grain analyses were not made because the material was presumed to have been exposed to sufficient sunlight before burial to have reset the OSL signal, and this assumption is supported by the OSL data. Each aliquot was illuminated for 100 s, the OSL decay over the first 5 s being used as the dating signal, and the final 20 s being used to define the background signal. This follows the procedures described elsewhere (Murray and Roberts 1998; Roberts et al. 1998).

The single-aliquot regenerative-dose protocol (Murray and Roberts 1998; Roberts et al. 1998) was used to determine the palaeodose for both grain-size fractions. A preheat plateau test was made (using preheats of 160-300°C for 10 s) and no dependence on preheat temperature was observed; similar findings have been reported previously (Murray and Roberts 1998; Roberts et al. 1998). Palaeodose estimates obtained for all preheats within this temperature range have therefore been used in the final age determination.

The beta and gamma dose rates were estimated from measurements of the uranium, thorium and potassium concentrations in a portion of the beachrock, using high-resolution gamma-ray spectrometry. This method also permits an assessment of the state of radioactive equilibrium of the uranium and thorium decay chains. The gamma contribution to the total dose rate was halved because of the very shallow depth (2π geometry) of the beachrock sample. The cosmic-ray dose rate (0.265 milligrays per year, mGy/year) was estimated from published data (Prescott and Hutton 1988) under the assumption that there has been no overburden removal at the sample site because the sample was collected from near the modern high tide mark. A value of 0.03 mGy/year was assumed for the internal alpha and absorbed beta dose rate (on the basis of measurements made on other north Australian quartz sediments) and beta dose attenuation factors were taken from Mejdahl

(1979).

The sample was received in a totally dry state, but this is unlikely to be representative of the average water content for the entire period of burial because the sample is, even now, covered by seawater at the highest tides and must have been saturated by seawater during the early stages of beachrock formation. A water content of 5 ± 2.5% has therefore been assumed. If instead a water content of 10% is assumed, then the ages given below increase by only 70-85 years; the ages are thus insensitive to variations in water content.

Optical dating results

An optical age is calculated from the palaeodose divided by the dose rate. The ages and supporting data for the two grain-size fractions are listed below:

90-125 µm grains:	palaeodose	1.28 ± 0.05 grays (Gy)
	dose rate	0.70 ± 0.05 mGy/year
	optical age	1850 ± 150 years
180-212 µm grains:	palaeodose	1.43 ± 0.09 Gy
	dose rate	0.68 ± 0.05 mGy/year
	optical age	2120 ± 200 years
Weighted average age:		1920 ± 140 years.

In terms of the dose rate, the cosmic-ray contribution is unusually significant (~40% of the total) owing to the low activity concentrations of uranium (see below), thorium (^{232}Th, 5.7 ± 0.3 becquerels per kilogram, Bq/kg) and potassium (^{40}K, 21 ± 3 Bq/kg) in the beachrock. The uranium decay chain is in severe disequilibrium, with ^{238}U, ^{226}Ra and ^{210}Pb activity concentrations of 51 ± 2, 4.2 ± 0.3, and 23 ± 3 Bq/kg, respectively. The excess of ^{238}U over its daughter product ^{226}Ra is attributed to the relatively enriched uranium content of calcium carbonate in the beachrock, while atmospheric fallout of ^{210}Pb is deemed to be the cause of its excess over its parent ^{226}Ra. Lead fallout is commonly observed in surface sediments such as the beachrock sample submitted for dating. Radium leaching by seawater appears not to be prevalent, based on the demonstration of radioactive equilibrium between ^{228}Ra and its daughter ^{228}Th in the ^{232}Th decay chain; such equilibrium shows that significant leaching of ^{228}Ra has not occurred during the last 10 years.

The mean palaeodose and associated error are calculated using a central age model (Roberts et al. 1998), and histogram plots of the palaeodoses for each grain-size fraction are shown (Figure 9). Histograms are not the best means of showing such data because of the differing precisions of the individual palaeodose estimates, but they illustrate sufficiently that the palaeodoses are normally distributed for both size fractions. This result supports the proposition that the quartz grains were well bleached before burial, because insufficient bleaching typically results in an asymmetric palaeodose distribution. Each grain-size fraction had one aliquot that gave a significantly smaller palaeodose. These were included in the calculation of the above ages, but the ages are insensitive to the inclusion or omission of these two aliquots; if they are omitted, each of the above ages increase by just 50 years and the standard errors decrease slightly.

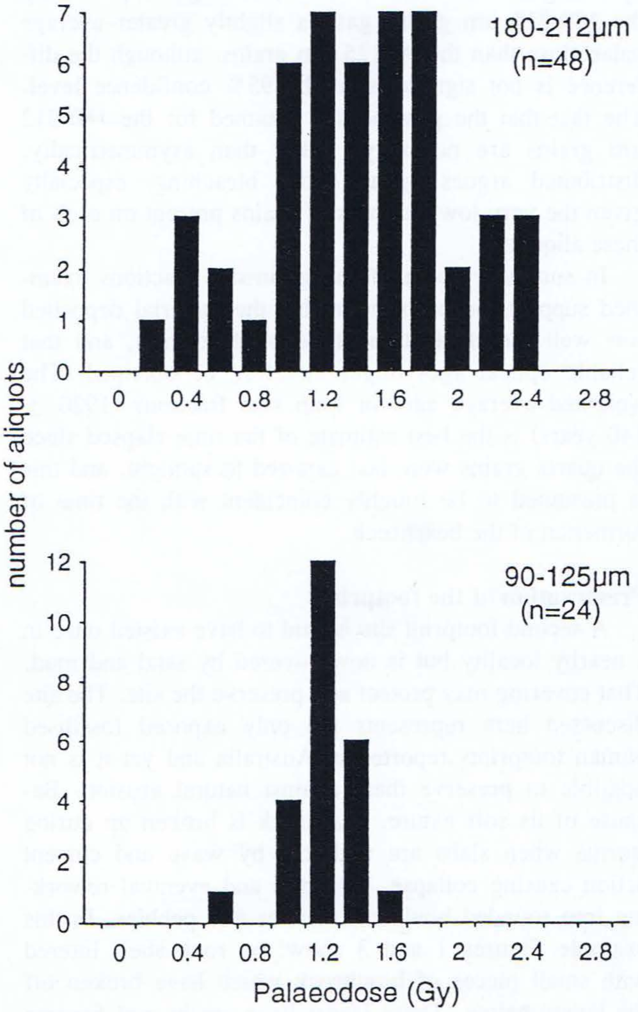

Figure 9. *Histograms of the measured palaeodoses for the two grain-size fractions analysed from the fossil human footprints site.*

The 90-125 µm grains yielded a much narrower range of palaeodoses than did the 180-212 µm grains. This probably reflects the larger number of grains present on each 90-125 µm aliquot as well as the likelihood that these (probably) wind-blown grains received prolonged exposure to sunlight prior to their incorporation in the beachrock. These grains are presumed to have been blown from the nearby coastal sand dunes. The aliquot with the significantly smaller palaeodose can be seen to the left of the main distribution. It is presumed that this aliquot contained some younger grains which had fallen into a deep crack in the beachrock sample; such grains would not have been removed during sample preparation.

Fewer 180-212 µm grains were loaded on each aliquot, and this may be responsible for the wider spread in palaeodoses shown by this grain size. Also, because these larger grains are probably derived from intertidal beach sand (i.e. water rather than wind transported), there is also the possibility that some of the 180-212 µm grains on each aliquot had not been sufficiently bleached by sunlight before final burial. This might explain why the 180-212 µm grains gave a slightly greater average palaeodose than the 90-125 µm grains, although the difference is not significant at the 95% confidence level. The fact that the palaeodoses obtained for the 180-212 µm grains are normally, rather than asymmetrically, distributed argues against poor bleaching, especially given the very low numbers of grains present on each of these aliquots.

In summary, both of the grain-size fractions examined support the proposition that the material deposited was well bleached at the time of deposition, and that reliable optical ages might therefore be obtained. The weighted average age for both size fractions (1920 ± 140 years) is the best estimate of the time elapsed since the quartz grains were last exposed to sunlight, and this is presumed to be roughly coincident with the time of formation of the beachrock.

Preservation of the footprints

A second footprint site is said to have existed once in a nearby locality but is now covered by sand and mud. That covering may protect and preserve the site. The site discussed here represents the only exposed fossilised human footprints reported in Australia and yet it is not possible to preserve them against natural erosion. Because of its soft nature, beachrock is broken up during storms when slabs are undercut by wave and current action causing collapse, breakage and eventual reworking into rounded boulders, cobbles and pebbles. In this example Figures 1 and 3 show the rock shelf littered with small pieces of beachrock which have broken off the layers below. These layers have cracks and fissures and the footprints survive in one area where the beachrock is more stable and resistant. Wave action from the highest tides or storms and rain will be the main factors eventually eroding this rock formation.

There are reports of people cutting dinosaur footprints from other rocks in the region and such collecting certainly poses a threat to this site. Because the rock is soft and the footprints are easily missed, another potential threat is from the action of motor vehicles inadvertently driving over the footprints, but due to the remoteness and current restrictions to the area these events are less likely at present.

Acknowledgments

My thanks go to people living near these footprints who showed them to me and gave permission for sampling, dating and publication of photos. Also to Philippe Puig, geologist, and to the Darwin staff of the Northern Territory Department of Mines and Energy. J. Olley (CSIRO Land and Water, Canberra) carried out the high-resolution gamma spectrometry analyses, and Bert Roberts and H. Yoshida (Department of Earth Sciences, La Trobe University, Melbourne) did the OSL measurements. Bert Roberts wrote the optical dating procedures and results for inclusion in this paper. Funding was provided by the author. Thanks are also due to the two anonymous referees of this paper.

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REFERENCES

AITKEN, M. J. 1998. *An introduction to optical dating*. Oxford University Press, Oxford.

BATHURST, R. G. C. 1975. *Carbonate sediments and their diagenesis*. Elsevier Scientific Publishing Company, Oxford.

CHAPPELL, J. 1976. Aspects of late Quaternary palaeogeography of the Australian-East Indonesian region. In R. L. Kirk and A. G. Thorne (eds), *The origin of the Australians*. Australian Institute of Aboriginal Studies, Canberra.

DAVIES, J. L. and M. A. J. WILLIAMS. 1978. *Landform evolution in Australasia*. Australian National University Press, Canberra.

HICKEY, S. H. 1981. *Preliminary investigation of stranded beach ridges, shoal bay, Northern Territory: a small chenier plain*. Department of Mines and Energy, Darwin.

MEJDAHL, V. 1979. Thermoluminescence dating: beta-dose attenuation in quartz grains. *Archaeometry* 21: 61-72.

MURRAY, A. S. and R. G. ROBERTS. 1998. Measurement of the equivalent dose in quartz using a regenerative-dose single-aliquot protocol. *Radiation Measurements* 29: 503-15.

PETTIJOHN, F. J., P. E. POTTER and R. SIEVER. 1972. *Sand and sandstone*. Springer-Verlag, New York.

PRESCOTT, J. R. and J. T. HUTTON. 1988. Cosmic ray and gamma ray dosimetry for TL and ESR. *Nuclear Tracks and Radiation Measurements* 14: 223-7.

ROBERTS, R., M. BIRD, J. OLLEY, R. GALBRAITH, E. LAWSON, G. LASLETT, H. YOSHIDA, R. JONES, R. FULLAGAR, G. JACOBSEN and Q. HUA. 1998. Optical and radiocarbon dating at Jinmium rock shelter in northern Australia. *Nature* 393: 358-62.

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