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Luminescence dating of anthropogenically reset canal sediments from Angkor Borei, Mekong Delta, Cambodia

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Abstract

This paper presents a case study in the analysis of anthropogenically reset sedimentary materials, through work undertaken to identify and date sediments in an ancient canal in the Mekong Delta, Cambodia. The emergence of rice cultivating communities, utilising canals for both hydraulic management and transport, represents an important stage in the social evolution of southeast Asia. The emergence of complex polities in the region, which may have depended on both international trade and intensified agriculture, led ultimately to the formation of the famous Khmer empires which dominated the region on several occasions through the 1st and 2nd millennia AD. French colonial scholars identified possibly ancient canals in the region that may have played roles in trade, agriculture, or both. This series of ancient canal features near Angkor Borei has been the subject of recent investigations in a collaboration between the Universities of Glasgow and Hawaii. Luminescence profiling measurements were used to identify the canal bed, by exploiting the contrast between a regional substrate of some 50 ka depositional age and more recent archaeological sediments. In this manner it has been possible to identify the sedimentary substrate, undisturbed canal sediments, and redeposited material. Ages have been estimated for substrate and canal infill sediments. The work represents the first convincing demonstration of luminescence dating of one of these important regional features, and indeed the first confirmation of the presumed antiquity of the canal system around Angkor Borei.

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1. Introduction

Luminescence methods have been applied to dating Quaternary sediments for more than 20 years, determining enclosure ages for sediments whose prior luminescence history has been to a greater or lesser extent reset by exposure to daylight during transport and deposition (e.g., Aitken, 1998). Thermoluminescence (TL) techniques are limited in their applicabilty to Holocene materials, but photo-stimulation techniques (e.g. OSL, IRSL, etc.) have provided a range of tools capable of dating recent sediments and depositional events under favourable conditions. The recent availability of high-power blue light emitting diodes (Bøtter-Jensen et al., 2000), and the development of adaptive techniques for stored dose determination, such as the quartz single-aliquot regenerative (SAR) procedure (Murray and Wintle, 2000), have significantly improved prospects for luminescence dating for young sediments. This in turn offers new opportunities within archaeological settings to study features which would otherwise be difficult to date directly, such as constructional surfaces and drainage features in sedimentary substrates. Selection and characterisation of dating samples is critical in such work. Here we present results using luminescence techniques to characterise the chronostratigraphy of an ancient infilled canal near Angkor Borei in southern Cambodia. The work has identified bleached sedimentary components which indicate canal construction, utilisation and infilling in the 1st millennium AD.

1.1. Background

The study area, near the ancient settlement of Angkor Borei in the lower Mekong Delta in southern Cambodia (Fig. 1), is associated with the emergence of one of southeast Asia's earliest polities, called Funan by Chinese writers. This complex society emerged in the 1st millennium AD, and has been linked to the development of international maritime trade linking

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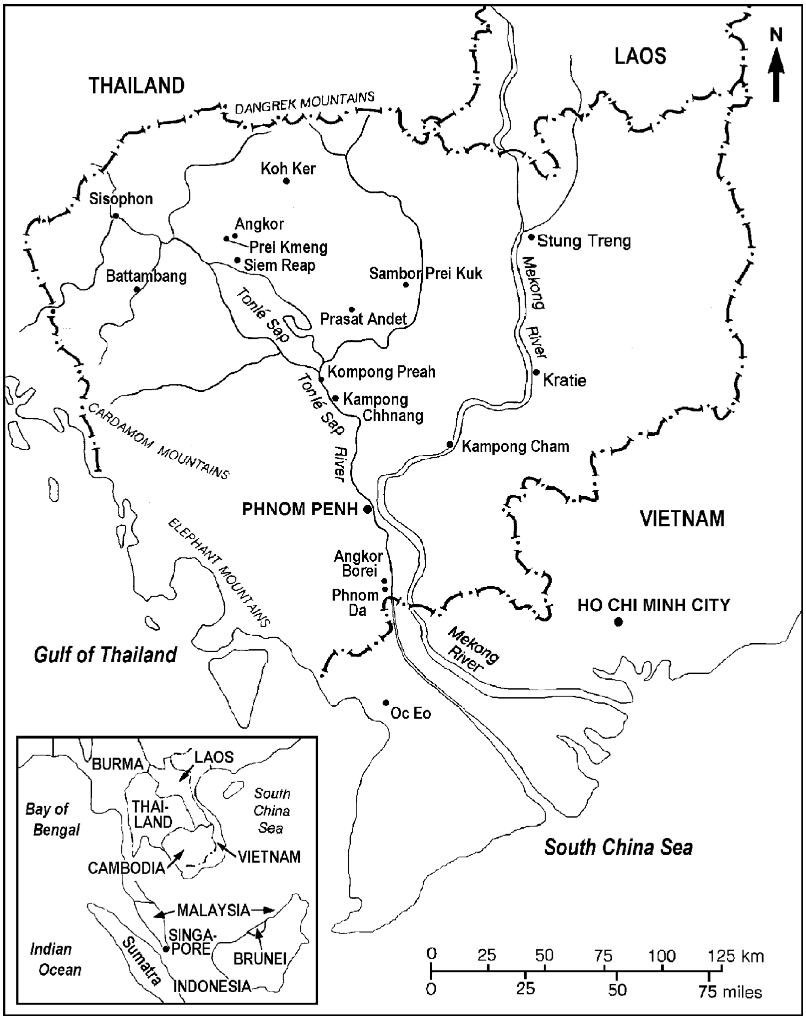

Fig. 1. Location map showing the position of Angkor Borei.

southeast Asia to China and India (Higham, 1989; Ray, 1989). Ongoing work by the Lower Mekong Archaeological Project is exploring the extent to which international contacts are reflected in the archaeological record (Stark, 1998, 2001; Stark et al., 1999; Stark and Bong, 2001; Stark and Bishop, 2001).

More than 200 km of canals, many of which predate French colonial development, were recorded in the area in the 1930s, including two prominent canals in the vicinity of Angkor Borei (Canals 1 and 2) (Paris, 1931, 1941). These canals may have provided links between the ancient city of Angkor Borei and a complex of other early sites including coastal settlements like Oc Eo, to the south in Vietnam (Malleret, 1959-63; Trinh Thi Hòa, 1996). Our aerial photograph interpretation shows that the canals have locally exploited palaeochannel systems, as in north central Thailand (Godley et al., 1993; Bishop and Godley, 1994) but otherwise they exhibit straight traces connecting ancient sites. Canals are functionally important to transport, trade, and perhaps even retreat agriculture (Fox and Ledgerwood, 1999), in addition to representing significant organisation of labour. Establishing their ages is not straightforward, however. For example, Godley et al. (1996) failed to recover charcoal or pottery when augering in ancient canals in north central Thailand, and, in any event, the age relationships between sedimentary charcoal and canal excavation and/or infilling are often unclear. Moreover, the sedimentary sequences in infilled canals are often not easy to interpret due to physical similarities between substrate and canal infill sediments.

Fieldwork was undertaken near Angkor Borei in May 2001 to explore the potential for utilising optically stimulated luminescence (OSL) as a tool for dating and interpreting the sedimentary stratigraphy of canal 2. Luminescence discontinuities were postulated at the interface between basal substrates (expected age 50–100 ka) and canal (expected age <2 ka) as a result of differing optical bleaching histories. Such discontinuities might be identifiable in luminescence profiles obtained from relatively small samples and clarify interpretation of canal stratigraphy. A further aim was to recover

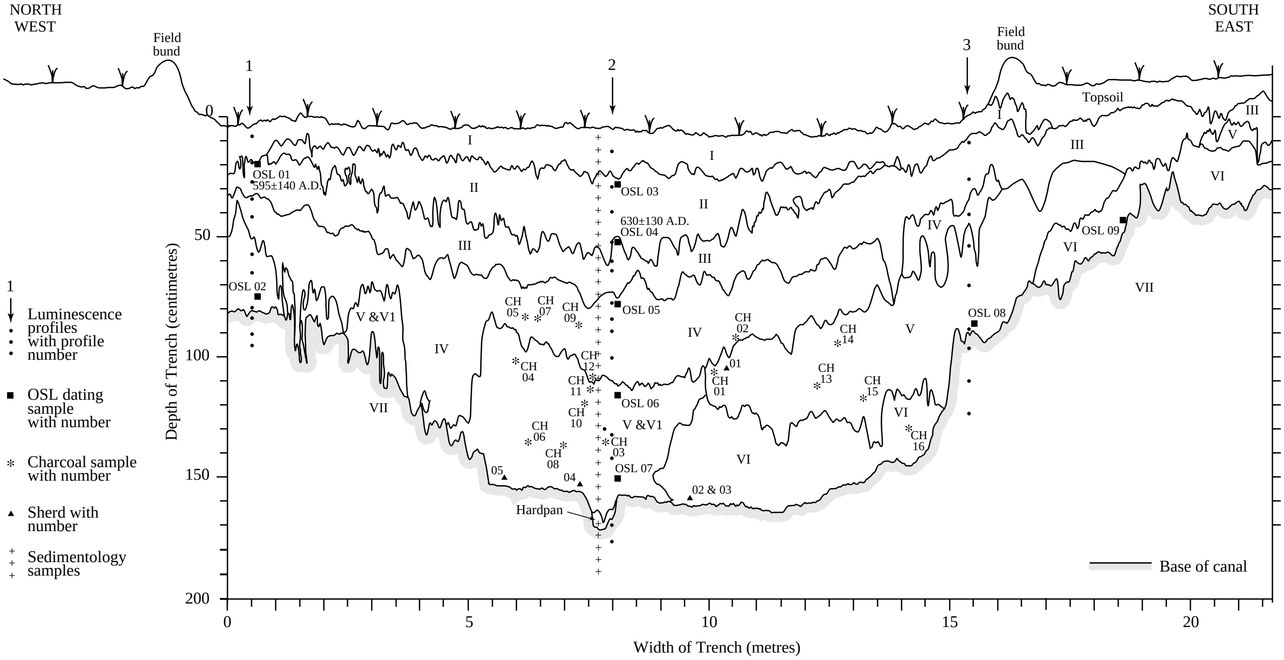

Fig. 2. Summary diagram of the stratigraphic section in the north wall of the trench excavation across Paris canal 2, showing the stratigraphic contexts of luminescence profile samples, luminescence dating samples, charcoal samples, sedimentology samples, and sherds (vertical exaggeration × 5). Units V and VI are locally combined to aid clarity.

material to date the construction and infilling of the canals.

2. Fieldwork and sampling

A dry section of Paris's canal 2 was located on the ground using aerial photographs and augering. A 24 m long and 2 m deep trench was excavated, revealing a succession of seven sedimentary units forming two principal U-shaped depositional units, presumably corresponding to the excavation, infilling and possible re-use of the canal (Fig. 2). Thirty-three small luminescence samples were collected on three vertical sections through the canal infill (profiles 1–3; Fig. 2) to assess whether well-bleached layers corresponding to the major stratigraphic units could be detected using simple luminescence screening measurements. Larger tube dating samples (OSL1–OSL9; Fig. 2) were also collected at major stratigraphic breaks, and around the presumed canal base. Luminescence samples were collected by driving opaque tubes into the trench face under the shade of a canopy, with profiling samples being extruded under cover into opaque sample containers, and the tube samples being retained intact and sealed to retain moisture. Gamma dose rates were recorded in tube sampling holes using a 25 mm × 25 mm cylindrical NaI detector calibrated at the pad facility in East Kilbride. Sediments were also collected from a modern canal and from a sandy river bank, to assess the extent of bleaching of contemporary sediments. Reduced pottery sherds were recovered from close to the presumed canal base, as were charcoal and wood fragments from within the canal infill.

3. Luminescence measurements

Luminescence measurements from the sediment samples have been undertaken for a number of purposes. The profiling samples were initially investigated using a combination of polymineral samples and etched quartz to examine bleaching and approximate equivalent doses and apparent ages for the various units identified in the canals. Thereafter the nine dating tube samples were subjected to quartz single-aliquot-regenerative OSL measurements to assess ages where possible. Two of these samples (OSL1 and OSL7) were subjected to additional small aliquot dose distributional analysis (Spencer et al., 2003) to investigate bleaching and mixing properties in further detail. Finally, some experiments have been conducted to assess the possibility that separated feldspar samples may potentially experience more complete bleaching than quartz under turbid aquatic conditions. Brief experimental details for these measurements follow.

3.1. Luminescence profiles

The small profiling samples were split, and disaggregated in deionised water prior to wet sieving to recover 90–150 μm coarse grains. If the organic-rich fine fractions formed viscous gels during disaggregation, oven drying followed by re-suspension in deionised water greatly facilitated dispersion of the coarse fraction. Sieved grains were treated with 1 M HCl and then split into two portions, the first of which was washed in deionised water and then in pure acetone prior to drying and deposition on stainless steel discs for polymineral silicate measurements. The second portion was etched in 40% HF for 40 min, then treated with 1 M HCl again prior to washing and dispensing as a quartz extract. The rationale for investigating both quartz and polymineral responses, and for comparing different stimulation approaches, was to exploit differences in sensitivity to environmental history and optical bleaching in characterising the depositional environment for potential dating samples.

The polyminerals were subjected to a simple multiple stimulation regime, comprising preheating at 220°C for 30 s prior to readout of IRSL, post-IR blue OSL and then TL using a Risø DA-15 luminescence reader. Natural signals were followed by measurements of the response to a 5 Gy laboratory dose. For each of the 33 profiling samples paired discs were measured and the mean equivalent dose for each pair was estimated using simple linear scaling. Approximate apparent ages were also calculated using provisional dosimetry data based on the field gamma spectrometry measurements. Quartz samples were subjected to a similar procedure, in this case preheating the samples for 30 s at 240°C followed by 120 s readout using 470 nm diodes in the DA-15 reader at 60% power.

3.2. Tube samples

The nine tube samples were subjected to more conventional treatment. Following water content measurements the dried material was split and 20 g portions used both for thick source beta counting (Sanderson, 1988) and high-resolution gamma spectrometry using a 50% relative efficiency Ortec Gamma-X detector. The remaining material was dry sieved and the 90–150 μm material recovered. Following HCl treatment, 15 min cleaning with 15% HF, and repeat HCl washing, sodium polytungstate was used to separate <2.52, 2.52–2.58, 2.58–2.62, 2.62–2.74 and >2.74 g cm^{-3} fractions. The 2.62–2.74 fraction was subjected to additional treatment with 40% HF for 40 min followed by further HCl, deionised water and acetone washes. This yielded quartz extracts for SAR measurements. The lighter feldspar fractions were also retained for subsequent use, as were finer fractions.

3.3. Single aliquot quartz OSL measurements

Single aliquot regenerative procedures similar to those previously utilised in this laboratory (e.g., Murray and Wintle, 2000; Sanderson et al., 2001) were followed for quartz samples from all nine tubes. Sets of 16 discs were used, grouped into subsets of four, which were preheated at temperatures of 240°C, 250°C, 260°C and 270°C for 30 s prior to readout. The readout cycle comprised stimulation under the same conditions as the profiling samples, with readout of natural and a series of regenerative doses interleaved with the response to test doses of 1 Gy. The regenerative cycle comprised doses of 2, 4, 6, 8 and 10 Gy for all samples; for two samples additional dose points of 20, 40, 60, 80 and 100 Gy were added to define the high dose behaviour. The 2 Gy point was repeated to verify that sensitivity corrections based on test-dose normalisation were functioning correctly. At the end of each SAR cycle a zero-dose point was measured to evaluate potential residual signals due to thermally induced charge transfer during the measurement cycle. Finally the response to IR radiation was also recorded for each disc, as a means of checking for IR sensitive impurities such as residual feldspars, micas and zircons.

OSL data were reduced by extracting net signals from the first 5–10 s of stimulation after subtraction of integrated signals from the last 50–90 s of measurement. Natural and regenerated signals were normalised to the subsequent test-dose response, and equivalent doses evaluated both for each disc, and for groups of discs by interpolation of saturating exponential fits to the dose response curves. Recycling ratios and their uncertainties were also evaluated, as were the test-dose trends and sensitivity to preheating. Finally, equivalent dose estimates for each disc were pooled for each sample. Luminescence ages were calculated using standard microdosimetric models, with uncertainties that combined measurement and fitting errors from the SAR analysis, all dose rate evaluation uncertainties, and allowance for the calibration uncertainties of the sources and reference materials used for dose rate standardisation.

3.4. Small aliquot OSL work

Samples OSL1 and OSL7 were additionally subjected to small-aliquot dose determination, using 96 aliquots per sample, and a simplified SAR regime (Spencer et al., 2003). Linear equivalent doses were estimated following test-dose normalisation and calibration at a single regeneration point, and used to evaluate the extent of homogeneity of the dose distribution for basal and upper canal samples.

3.5. Feldspar analyses

Some additional work was also undertaken to investigate the dating properties of feldspars extracted from one upper sample (OSL3) and two lower samples

(OSL6 and OSL7) to follow up the indication from profiling results that feldspars may have been more fully reset in the turbid aquatic environment of the canal base than was quartz. Equivalent doses were evaluated using a SAR-like procedure utilising the same regenerated dose regime and interleaved test doses as the quartz measurements. All samples were however pre-heated at a single temperature of 200°C for 30 s prior to readout; both IRSL and post-IR blue OSL signals were also recorded at each stage. For each set of 16 discs measured starting with the natural dose, an additional set of four discs was also investigated which had an added laboratory dose of 5 Gy prior to readout, for the purpose of evaluating sensitivity changes that might undermine SAR analysis. Finally, a grain size experiment using the same readout procedure (but without added doses) was conducted for samples OSL3 and OSL6, comparing equivalent dose estimates for <10, 10–30 and 90–150 μm material.

4. Results

4.1. Profiling

The results for all profiles are shown in Fig. 3. Despite the simple approaches this information is extremely useful in helping to interpret the canal stratigraphy. The basal samples from unit VII corresponds to the deepest three samples in profile 1, the deepest two in profile 2 and the deepest three in profile 3. All have equivalent doses and apparent ages which are significantly in excess of those corresponding to the $\leqslant 2$ ka expected archaeological age of the canal. This result confirms the identification of unit VII as substrate, in keeping with the field interpretation, and points to the interface between unit VII and units V and VI as the primary canal base. Units V and VI are represented by samples 7 and 8, 9–11 and 4–6 in profiles 1, 2 and 3, respectively. For these units it can be readily observed that the polymineral post-IR blue OSL signal in particular shows values which register the primary anthropogenic discontinuity, and which appear to be quantitatively consistent with a 1.5–2.5 ka primary age. By contrast TL equivalent doses are systematically elevated, which is consistent with expectations based on relative bleaching rates of TL and OSL. IRSL signals show many of the same trends, but also appear to show slightly less well-defined basal contrast. The quartz data also appear to show that the interface between unit VII and units V and VI corresponds to the original canal base, but indicate a less abrupt transition than post-IR blue signals from the polymineral phase. Further up the sections, the interface between the top of unit V and the base of unit IV corresponds to a disturbed horizon which apparently contains poorly bleached sediments. Above this, in all three sections, well-bleached material can be obtained from units I and II, with apparently consistent EDs in quartz and polymineral data sets.

Thus, the profiling data confirm the independent identification of the anthropogenic canal sediments based on stratigraphic evidence. The data may be taken to suggest an initial construction age of approximately 2 ka, followed by a period of utilisation resulting in accumulation of some 50–100 cm of sediment. Whether the disturbance recorded in units V and IV is the consequence of an environmental instability or changes in the anthropogenic management cannot be determined at this stage. In any event the final stages of infill appear to be accompanied by more stable conditions giving a progressive diminution of equivalent dose with decreasing depth.

Modern control samples are also encouraging, the coarse sand sample in particular being reset to residual doses equivalent to <20 years age. We now turn to quantitative OSL age determinations from the most significant and promising sedimentary units.

4.2. Quartz SAR results

The separated quartz from all nine OSL tube samples had excellent luminescence properties, similar in many respects to those observed earlier from regional cover sands in Thailand (Sanderson et al., 2001). Decay shapes were well reproduced within each run, signal intensities reaching residual levels within the first 5–10 s of stimulation. Typical sensitivities of discs with 1–5 mg of material ranged from 2×10^4 to approximately 10^5 counts per Gy. Test dose responses tended to increase during the SAR runs, but only by some 20% over the 0–10 Gy part of the dose response curve. Recycling ratios fell within error of unity.

Normalised OSL signals were evaluated for natural and all regenerated dose points both on an individual basis, and in groups of four discs, to evaluate dependence of preheating. It was noted that coefficients of variation for these subsets under laboratory irradiation were significantly smaller (typically <3–4%) than those observed from the natural cycle. Normalised laboratory responses also showed little variation from sample to sample, and therefore it was decided to combine data sets to form an overall dose response curve which was used to estimate individual ED values for each disc, and weighted mean values across a series of discs.

The underlying rationale for this approach was that the most significant variations observed were in the natural cycle—presumably due to variable initial bleaching and mixing behaviour. These variations were much larger than either the Poisson errors associated with normalised OSL signals from individual discs, and the variations in laboratory response from disc to disc.

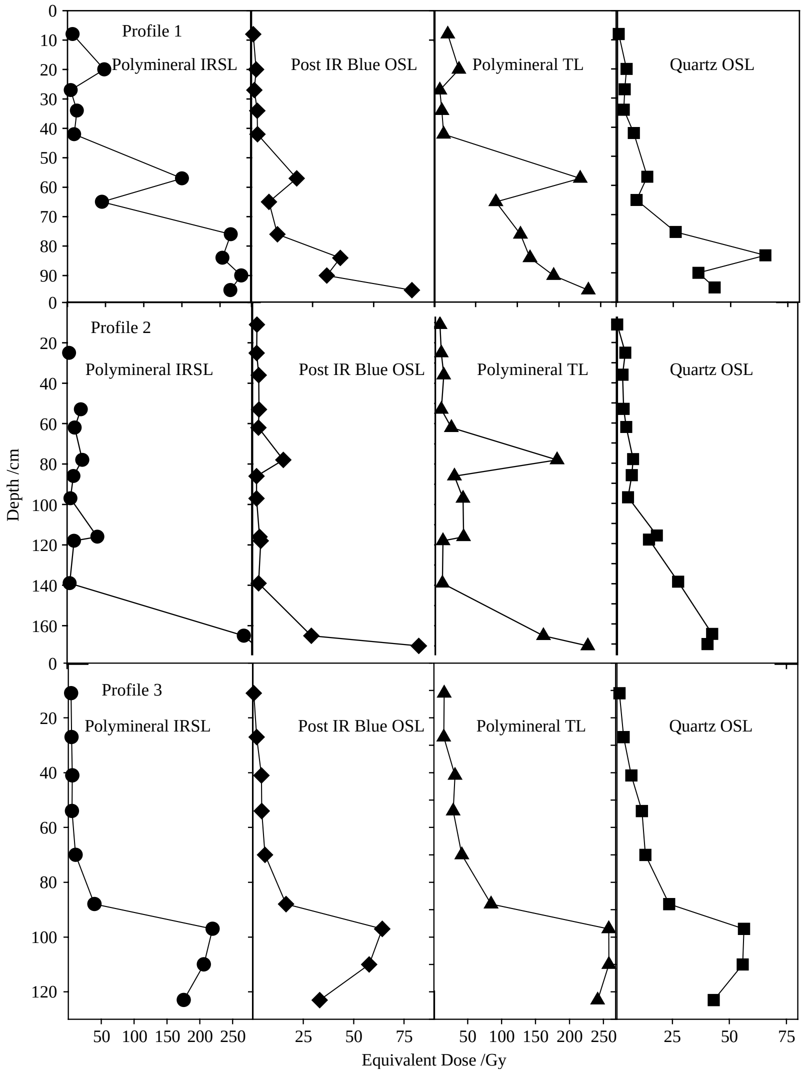

Fig. 3. Luminescence profiling results from profiles 1 (western section), 2 (middle section) and 3 (eastern Section) of the canal trench.

By folding fitting errors from the composite curve into final dose estimates we are taking some account of non-Poisson measurement errors, as well as small variations in the individual dose response of each disc. Neither IR response (below detection limits and typically equivalent to <0.05% of OSL test dose response) nor OSL decay shape data suggested any significant feldspar contamination. While a build of slow OSL (cf., Bailey et al., 1997) towards the end of the SAR runs could be observed, zero dose points recorded at the end of the runs represented an extremely small fraction (typically <2–3%) of measured intensities from the SAR data.

The outcomes of SAR analysis and age estimation are summarised in Table 1, and dose distributions from the individual disc are illustrated in Fig. 4. The dose distributions suggest that for some samples sedimentary mixing between the anthropogenic component and older substrate material is a significant problem. There is a qualitative difference between the upper unit samples (OSL1, OSL3, OSL4 and OSL5) and samples closer to the basal interface (OSL2, OSL6, OSL7 and OSL8) which is reflected in the latter's broader dose distributions which vary in gross excess of the individual measurement uncertainties of each disc. This in turn is reflected in age estimates, which were based on weighted mean and standard errors from the data sets. These estimates can cope with a limited high dose tail, but not with significant bias to the whole distribution. The upper unit III age determinations of 595±140 AD (OSL1) and 630±130 AD (OSL4) imply a slow infilling of the canal after its abandonment in the second half of the first millennium AD. Sample OSL 3 from unit II, measured with only four discs and showing the highest water content of the whole series, yielded an older age estimate (120 BC±410), as does sample OSL5 from the top of the perturbed unit IV (15 BC±240). Whether these late 1st millennium BC/early 1st millennium AD

Table 1
Quartz SAR results from OSL1 to OSL9

Sample	Profile	Depth (cm)	Stratigraphic unit	Equivalent dose (Gy)	Recycling ratio	Beta dose rate (mGy/a)	Gamma dose rate (mGy/a)	Water content (%)	Age (a)	Comment
OSL1	1	19	III	3.75±0.30	1.014±0.010	2.399±0.025	0.85±0.02	26.9	1405±140	Layer III profile 1 595±140 AD
OSL2	1	73	V/VI	13.2±1.04	0.999±0.007	1.78±0.05	0.83±0.015	15.1	5545±480	Mixed age material
OSL3	2	23	II	4.71±0.88	1.054±0.031	2.26±0.03	0.728±0.01	46	2120±410	Four discs only 120 BC±410
OSL4	2	50	III top	3.63±0.30	1.008±0.014	2.66±0.03	0.813±0.01	33	1270±130	Layer III (top) profile 2 630±130 AD
OSL5	2	74	IV top	6.71±0.83	1.012±0.010	2.68±0.03	0.839±0.01	26	2015±240	Layer IV top 15±240 BC
OSL6	2	110	V/VI	12.63±1.11	1.036±0.010	1.23±0.04	0.723±0.01	40.9	7800±780	Mixed age material
OSL7	2	144	VI base	34.0±2.8	0.996±0.007	2.58±0.03	0.749±0.01	29.1	7830±620	Mixed age material
OSL8	3	87	V base	176.7±114	1.009±0.012	2.14±0.05	0.785±0.004	19.5	69650±45000	Mixed age material
OSL9	East of 3	60	VI	24.97±0.96	1.013±0.008	1.46±0.05	0.784±0.004	13.2	8125±500	Evidence of mixing

determinations are biased by mixing processes is not entirely clear. In any event these SAR results are generally consistent with the interpretation of the canal as deriving from the Funan period.

The basal samples are more problematical, sample OSL8, for example, giving indeterminate results which imply severe mixing between that basal substrate of >50 ka age and any canal infill sediment. The other basal samples OSL2, OSL6, OSL7 and OSL9 produce age estimates between 5.5 and 8.1 ka—which clearly would predate the expected archaeological age by several millennia. OSL 2, 6 and 7 appear to show signs of mixed age material but it is unclear at this stage whether this argument can be readily extended to sample OSL9, at the interface of units VI and VII.

4.3. *Small aliquot OSL work*

Small aliquot measurements were undertaken on one upper sample (OSL1) and one basal sample (OSL7) to examine in more detail the evidence from the conventional SAR analysis of sedimentary mixing. Fig. 5 shows the small aliquot dose distributions, and associated *F*-plots from these two samples (Spencer et al., 2003). The qualitative differences between the two samples are immediately apparent. The upper sample shows a very tight distribution, with ED peak at approximately 3–4 Gy, which is highly consistent with the conventional SAR determination of 3.75±0.3 Gy used for age determination. There is evidence of a limited high dose tail but it is notable that reducing the size of the aliquots does not result in an increased spread in the distribution. This result confirms the status of sample OSL1 as being composed essentially of well-bleached material, with perhaps an extremely small proportion of partially bleached grains which do not significantly bias the stored dose values.

By contrast the breadth of the dose distribution associated with sample OSL7 has increased—in both the low dose and high dose tails—in comparison with the conventional samples. The leading edge of this distribution at 5–10 Gy represents lower dose values than observed in the conventional samples, exactly as would be expected from the original work by Olley et al. (1998, 1999). The variation in the upper part of the distribution is also enhanced. Clearly the small aliquot approach has provided diagnostic confirmation of the suspected mixing process affecting these samples. This confirms that the 7.8 ka apparent age associated with sample OSL7 does not represent an external environmental event, but is an artefact caused by mixing of unbleached grains from the substrate and younger material from the canal infill. Spencer et al. (2002) have discussed whether leading edge dose determination can be used for robust age determination, and suggested that the development of statistical approaches such as the *F*-plot or potentially

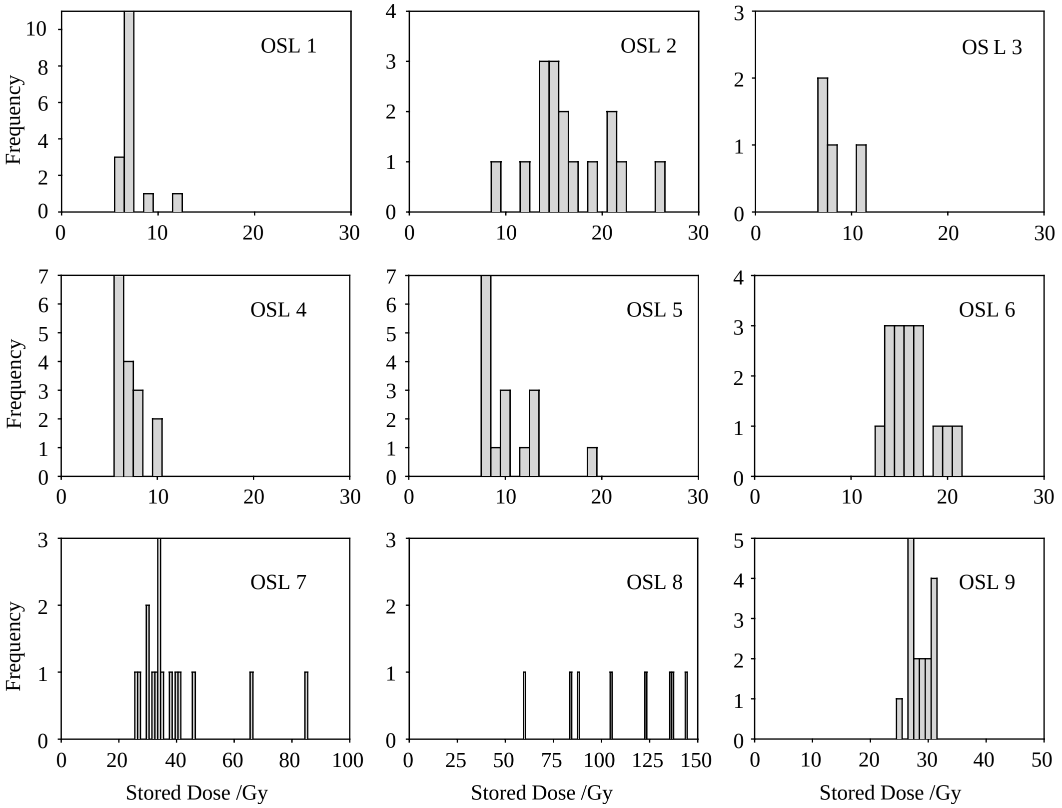

Fig. 4. Quartz SAR dose distributions from samples OSL1-9.

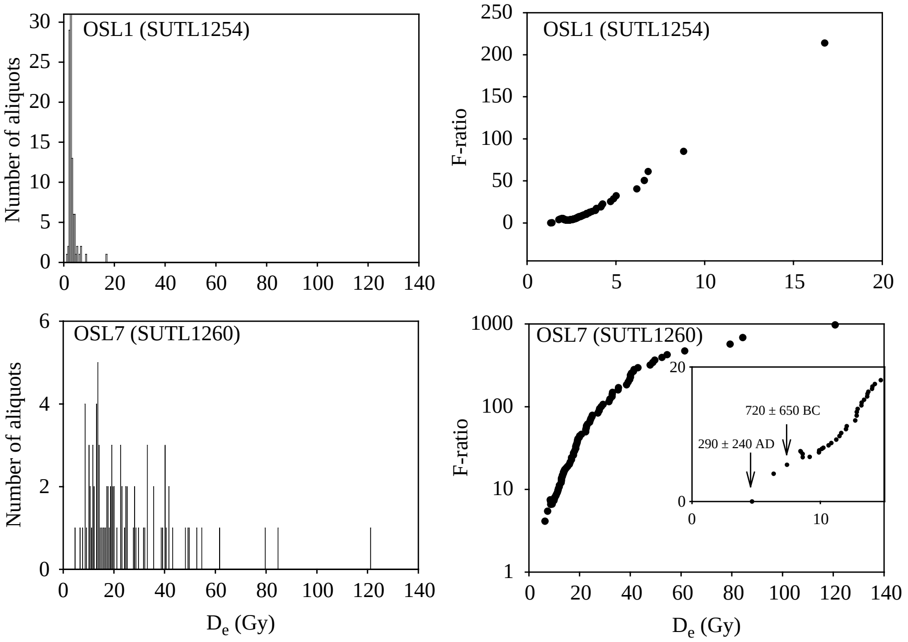

Fig. 5. Small aliquot dose distributions from an upper sample (OSL 3) and a lower sample (OSL 7).

χ^2 plots from these distributions would add objectivity to such attempts. In the case of sample OSL7, it appears that even the leading edge of the small aliquot distribution—which corresponds to ages between 290±240 AD and 720±650 BC—is poorly separated from the rising edge of the dose distribution. This implies that the proportion of poorly bleached grains in the sample is too high for the 50–100 grain aliquots analysed to have formed a distinct uncontaminated peak in the dose distribution. Whether smaller aliquots or

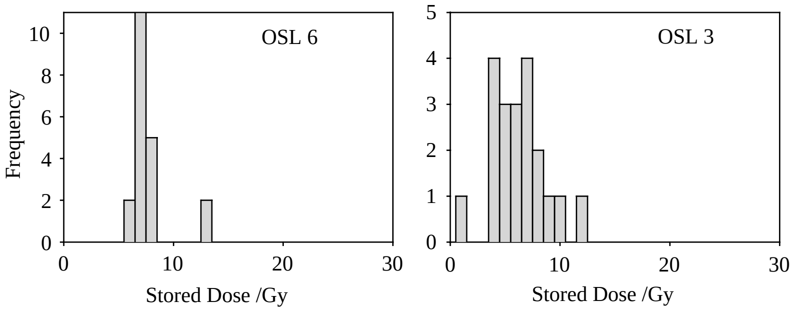

Fig. 6. Dose distributions from feldspar SAR runs for samples OSL3 (unit II) and OSL 6 (unit V/VI).

indeed single grain measurements would be able to resolve such a peak remains to be seen.

In the meantime the small aliquot data suggest that primary canal excavation should be no earlier than mid first millennium BC to early first millennium AD, and could potentially be slightly later. The small aliquot data also add confidence to the dating of the upper units.

4.4. Feldspar analyses

Luminescence profiling data showed several instances, including in basal units where polymineral samples (expected to be dominated by feldspars), gave lower ED values than those obtained from quartz. Given the clear evidence that substrate mixing limits the dating of basal units with quartz-based techniques, further attention was given to assessing the dating potential of separated feldspars. Fig. 6 shows dose distributions obtained from samples OSL3 (unit II, profile 2) and OSL 6 (unit V/VI, profile 2) using potassium feldspar separates in the 90–125 μm grain size and 2.51–2.58 $g\,cm^{-3}$ density fraction. The mean stored doses and ages obtained for these data sets are 4.66±0.56 Gy, 1850±240 BP (OSL3), and 6.3±0.41 Gy, 3300±270 BP (OSL6). The result from OSL3 is very similar to the quartz SAR result, although there may be minor evidence of mixed age material in the sample. For OSL6 the dose distribution is very significantly less spread than the corresponding quartz determination, and the apparent age is lower, confirming that the feldspar may well be better bleached, or subject to less substrate mixing than the quartz. These age estimates have taken account of a nominal internal K content, which raised the overall dose rates by approximately 10–12% relative to the quartz system.

A further experiment was conducted with two basal samples, OSL6 and OSL7, to assess briefly whether the grain size dependence of feldspar-related signals was consistent with single age material. The results of simple feldspar SAR experiments are shown in Table 2 both for IRSL and for OSL. IRSL signal intensities were much lower than post-IR blue OSL signals, giving rise to larger errors and greater scatter in data. However IRSL equivalent doses are also systematically higher than the post-IR blue data, both for the fine grain samples and for the separated feldspar coarse grains. It is also notable that ED estimates using OSL are lower for the fine grains than for the coarse grains, despite the additional alpha dose. These results thus suggest that (i) feldspars are better bleached than quartz, and (ii) the finer fractions are better bleached than coarse fractions in these basal units. The underlying reasons for this behaviour may relate to the differences in bleaching spectra for quartz and feldspars (e.g., Bøtter-Jensen et al., 1994; Clark and Sanderson, 1994) coupled to loss of UV/near UV daylight components in water with a high suspended sediment load (cf., Fig. 8; Berger, 1988). Sedimentological factors may also play a part. Future work is needed to understand these observations better. Meanwhile the age implications are interesting. Taking an assumed alpha efficiency of $k = 0.15 \pm 0.02$, and utilising the dosimetric information available yields fine grain OSL ages of 2050±260 BP; 50±260 BC for sample OSL6, and 1700±270 BP; 300±270 AD for OSL7. These results should be taken with caution in the absence of fading tests. However, they are in good agreement with the rest of the dating evidence for the canal, and the agreement between the feldspar (150±240 AD) and quartz (120±410 AD)) coarse grain results from sample OSL3 may imply that fading is not relevant in this case.

Table 2
Equivalent dose (Gy) as a function of grain size in feldspars from basal samples in section 2

	OSL6		OSL7	
Grain size (μm)	IRSL	OSL	IRSL	OSL
<10	12.2±3.8	6.0±0.5	14.4±3.9	8.33±0.85
10–30	18.3±10.8	6.05±0.2	11.1±3.5	6.54±0.3
90–125	11.7±2.5	7.4±0.5	37.7±8.2	14.2±3.6

5. Discussion and conclusions

In summary, samples were obtained from the first ancient canal to be excavated in the southern Cambodian Mekong Delta. This study represents the first use of luminescence to date archaeological canals in southeast Asia, and makes a significant methodological contribution to the field. It has been convincingly demonstrated that luminescence profiling can recognise stratigraphic features such as the early canal excavation, thus identifying promising sedimentary units for dating. The profiling data give insight into the depositional context for many of the units, and also provide the first independent confirmation of the antiquity of the canal section. Quartz SAR data have provided age estimates for upper units in the 1st millennium AD (595 ± 140 AD OSL1; 120 ± 410 AD OSL3; 630 ± 130 AD OSL4), which are consistent with the expected Funan association, and fit in well with the pattern of emerging archaeological evidence for associated activities in the area. The basal units are more problematical, since SAR dose-distributional analysis and small-aliquot analysis provide compelling evidence for mixing of canal sediments with the unbleached substrate, resulting in erroneously high age estimates. The lower units of the canal infill most probably date from the late 1st millennium BC or early 1st millennium AD, based on the combination of small aliquot SAR data (290 ± 240 AD–750 ± 650 BC from OSL7) and the feldspar data (50 ± 260 BC from OSL 6 and 300 ± 270 AD from OSL 7). These OSL ages are entirely consistent with recently received radiocarbon age determinations on the following charcoal samples (Fig. 2) which we note here in a preliminary way prior to a full report elsewhere (Bishop et al., in preparation). These 95% confidence calibrated ages are: CH06 (430 ± 110 AD); CH07 (515 ± 95 AD); CH08 (455 ± 115 AD); CH11 (515 ± 105 AD); and CH12(475 ± 95 AD).

The dates obtained represent the first absolute luminescence ages for an ancient canal section in the region, and imply that there is considerable potential for further work to examine the associated network, and also to date other features associated with the hydraulic monuments of these pre-Angkor Khmer regimes.

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