Clastic spring sediments: a tool for palaeoflood reconstruction?

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with 5 figures and 1 table

Summary. Clastic spring sediments, the product of groundwater transport by fissure or conduit flow, remain largely uninvestigated. Yet such sediments may be much more common than has generally been realised and examples within the stratigraphic record are likely to have been widely overlooked. This study investigates the potential of these deposits for preserving a history of past floods. Clastic spring sediments at Mount McKinlay Spring in the hot, arid Gammon Ranges of northeast South Australia were dated by ^{14}C analysis. Five samples of pollen grains taken from sediments interpreted on geomorphic grounds as post-dating European contact (AD 1843) all yielded dates of AD 1955–1958. These are likely to be the product of sedimentation in March 1956 following the greatest single day's rainfall in the instrumental record. This event, with a return period of around 100 years, may have caused the undercutting of the banks of the creek downstream of the springs, the collapse of mature River Red Gums growing adjacent to the channel and the accumulation of a jam of logs across the creek. The spring deposits appear to represent solely the product of high-magnitude, long return-period floods. A series of older spring sediments at the site dating from the first millennium BC to the mid-18th century may therefore provide an opportunity to establish event magnitude and frequency, to determine return periods, and to assess the role of climatic change and human environmental impact on flood frequency. This approach may offer a valuable means of reconstructing the chronology of floods, particularly in locations affording few other sources of palaeoenvironmental information.

Key words: Australia, Gammon Ranges, clastic spring sediments, large woody debris, flood chronology, springs

1   Introduction

This study aims to draw attention to a previously poorly described suite of deposits, clastic spring sediments, and to investigate their potential for preserving a record of past floods. Attempts to reconstruct flood frequency face significant challenges. This is particularly the case where rainfall and discharge gauging stations are rare and where those records that do exist are short. Even where instrumental records may be found, however, most provide only an unreliable measure of the frequency of large floods (SMITH & WARD 1998: 178–198), whilst the return period of truly catastrophic events may be so long that millennial-scale archives may be required to place them in their correct context. Several approaches have been employed to reconstruct long-timescale records of this sort (see, for example, COSTA [1978] and STEDINGER & BAKER [1987]). This study attempts to add to these by assessing the potential of pollen grains deposited coevally with clastic spring deposits to preserve a palaeoflood record in the remote and arid northeast of South Australia. The low population and short history of European contact in the region mean that instrumental records of environmental change are limited, whilst the paucity of natural archives makes it difficult to obtain alternative proxy records of past environmental conditions.

2   Clastic spring sediments

Although subsurface water may be discharged by a variety of mechanisms, true springs occur where the groundwater table intersects the land surface and where discharge is the result of hydrostatic pressure (MEINZER 1942: 417). The focussing of discharge at a discrete spring outlet is partly a consequence of flow localisation through the aquifer (very few aquifer media exhibit the fully diffuse flow of the theoretical ideal) and partly a product of the enlargement of flow routes near the surface. This enlargement may result from a complex mix of mechanisms including subaerial weathering, winnowing of fine particulate matter by subsurface flows and headward erosion.

Springs that are fed largely by diffuse flow appear to be characterised by a relatively uniform discharge and negligible particulate loads, and are not associated with accumulations of clastic sediment (WHITING & STAMM 1995, JEFFERSON et al. 2010). By contrast, springs fed by fissure or conduit flows display very different hydraulic and sedimentological characteristics. For a boundary roughness of 10^{-3} m and with hydraulic gradients typical of natural aquifers, the flow regime changes from laminar to turbulent once the hydraulic radius exceeds $\sim 10^{-2}$ m (WHITE 1988: 160–165). In natural conduits, turbulent flows at the lower end of the typical range of boundary-shear conditions might be expected to maintain particles of up to ~ 100 μm in suspension (GALE 1984a). By contrast, extreme flows are potentially capable of entraining particles of 10^{0} m in diameter (GALE 1984a). The dimensions of the inlets and flow routes may limit the size range of this material, but the transport of boulder-sized clasts is not unusual in the case of karstic conduits (GALE 1984b, VALEN et al. 1997). Clastic spring sediments may be derived from a variety of sources. They may be the product of weathering of the fissure or conduit walls, they may represent regolith material that has percolated from the ground surface through a network of fractures into the flow passage or they may have been transported directly into the conduit through large fissures that open directly onto the surface. This material may be stored more or less temporarily at a range of locations along the flow path.

It is only recently that studies have begun to be made of clastic sediment discharge from fissure- and conduit-fed springs (ATTEIA & KOZEL 1997, MAHLER & LYNCH 1999, DRYSDALE et al. 2001, CURRENS 2002, AMRAOUI et al. 2003, MASSEI et al. 2003, TORAN et al. 2006, HERMAN et al. 2008, REED et al. 2010). This work demonstrates that sediment transport in conduit flow aquifers is episodic and occurs primarily during floods (though the relationship with discharge is not always straightforward, with periodic supply exhaustion appearing to play a particular role). Although the period of sediment transport is brief, significant masses of material may be entrained (of the order of 10^{-1}–10^{1} tonnes per storm). The annual flux of clastic sediment is typically 10^{2}–10^{3} t a^{-1} (ATTEIA & KOZEL 1997, DRYSDALE et al. 2001, CURRENS 2002, HART & SCHURGER 2005). As the flood waters emerge from a confined flow path into unconfined open-channel flow, sediment transport capacity is reduced and substantial bodies of sediment may accumulate immediately downstream of the spring. These deposits may be much more common than is generally realised (OWEN et al. 2008, 190). Nevertheless, with the exception of the sand cones formed where upwelling groundwater sorts overlying unconsolidated sediments (GUHMAN & PEDERSON 1992, YOUNGER & McHUGH 1995), the depositional products of clastic sediment discharge from springs remain largely uninvestigated.

It is likely that fossil examples of clastic spring sediments have been widely overlooked. In part this may be because their geomorphology and stratigraphy vary widely depending on the topography and hydrology of the depositional site and fail to provide easily usable criteria for the recognition of ancient deposits. A better approach may be to consider the sedimentary petrology of the deposits. The composition of clastic spring sediments appears to be closely linked to that of distant source materials (STANTON et al. 1992, DRYSDALE et al. 2001, LYNCH et al. 2004). This may be sufficient to distinguish spring deposits from adjacent units. Alternatively, the presence of characteristic assemblages of (*inter alia*) snails, caddis flies, ostracods and diatoms in spring deposits may offer a means of identifying spring sediments in the rock record (see, for example, CANTONATI et al. [2006] and TAXBÖCK & PREISIG [2007]).

3   The study area

The Gammon Ranges of northeast South Australia form a deeply dissected plateau of Late Proterozoic sandstone lying at the northern end of the great north–south aligned mountain chain of the Flinders Ranges (fig. 1). The Gammons rise to an altitude of 1064 m at Benbonyathe Hill and are bounded on their eastern side by high cliffs dissected by a series of gorges. Groundwater flow occurs largely through discontinuities in the highly fractured sandstone (NORTHERN FLINDERS RANGES SOIL CONSERVATION BOARD 2004: 19). The study site, Mount McKinlay Spring, lies in the southeast corner of the massif at the exit from a deep and narrow canyon entrenched into the eastern wall of Mount McKinlay Bluff (figs 1–2). The canyon is normally dry, but is floored by boulder-sized braided channel deposits. Discharge from the springs takes place from three discrete outlets (fig. 2). All have been active on each of our (winter) visits, though channel flow was observed to extend only tens of metres beyond the springs and on one of these occasions we estimate total discharge to have been $\lesssim 1$ l s^{-1}. The springs are reported to dry up entirely at times of drought.
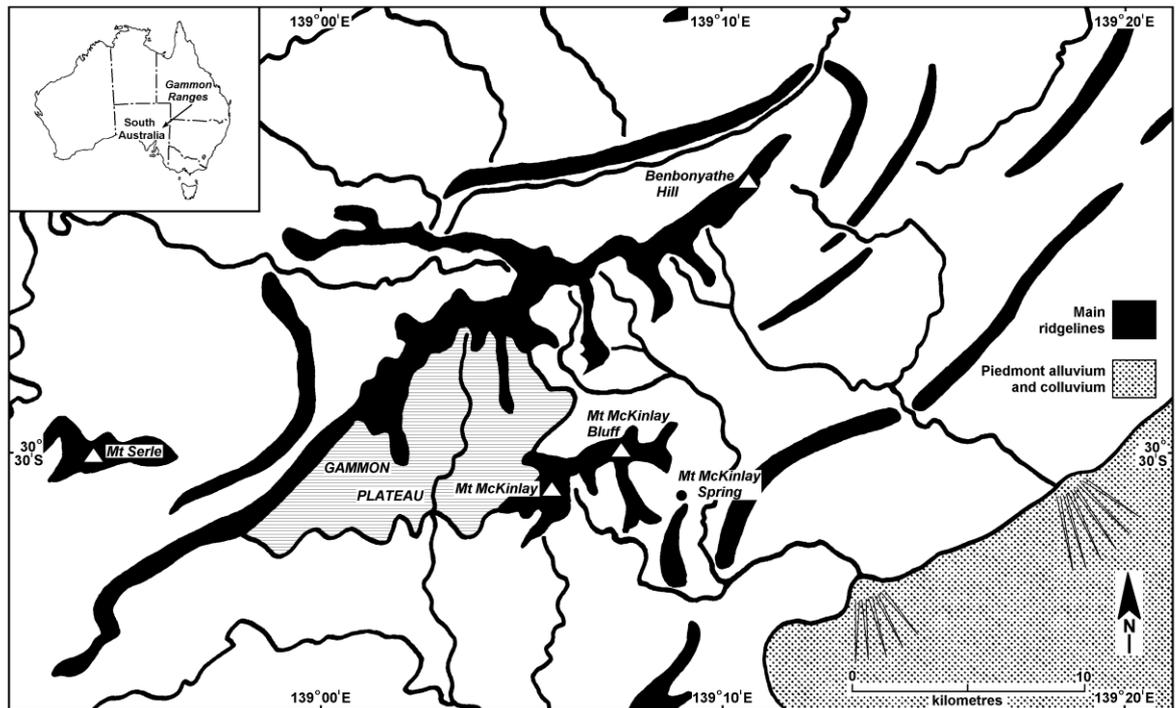
Fig. 1. The Gammon Ranges of northeast South Australia showing the location of Mount McKinlay Spring.
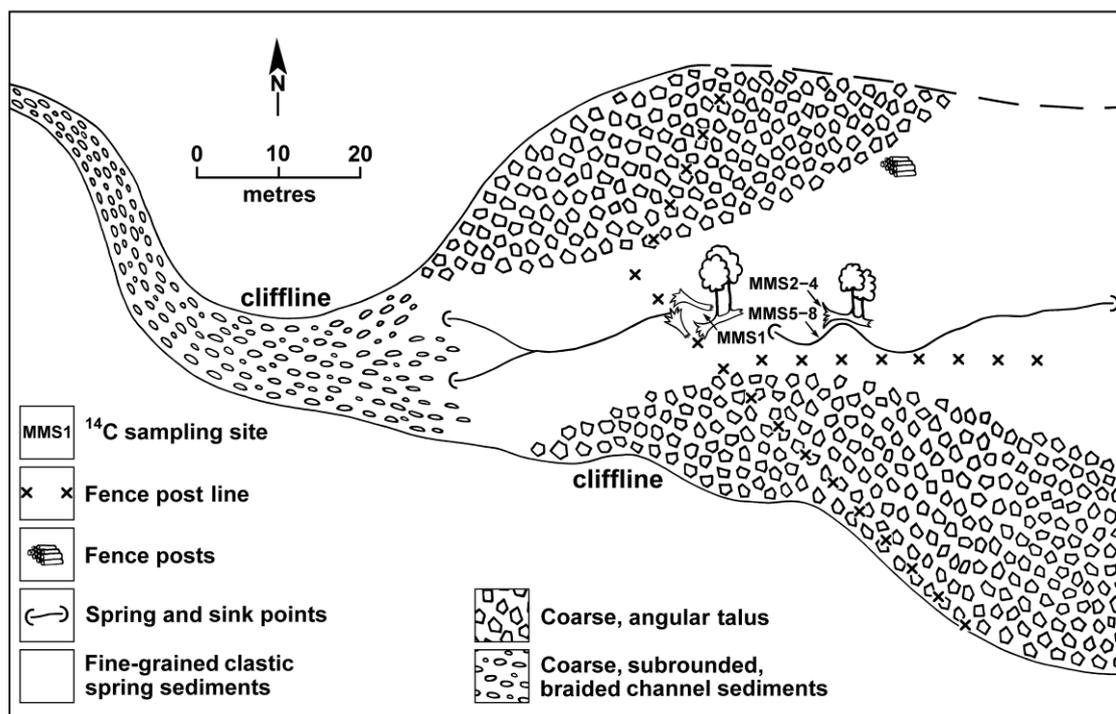
Fig. 2. Mount McKinlay Spring in the Gammon Ranges of northeast South Australia. The site was surveyed on 14 July 2005.

Below the springs, the valley becomes broader and the gradient markedly less steep. Immediately downstream of the springs, fine-grained sediments blanket the valley floor, extending 80 m downvalley before the braided, boulder-floored channel resumes. Sediments deposited in such a geomorphic context might be anticipated to represent alluvial fan deposits. The sediment body does not possess a conical form, however, distributary channels are absent, and there is little evidence of coarse bedload deposition, debris flows or mass wasting. Instead, from the indication of its location only at and immediately below the springs, its limited downstream extent and its fine particle-size distribution (likely to have been truncated by filtration through the narrow fissures of the aquifer), we interpret the fine alluvium as the product of groundwater transport.

The paucity of coarse sediments amongst the fine-grained sediments downstream of the springs suggests that surface flows capable of mobilising bedload in the canyon above the springs are rare. Although bedload-transporting events are well-known in the higher-order channels of the region (EARTH TECH *c*. 2007), there is evidence that the first- and second-order headwater streams experience sediment-transporting flows only during very high-magnitude events. This may be because of the coarse nature and high porosity of the channel beds, which means that most discharge occurs as underflow, reaching the surface only once the water leaves the confines of the gorges. Some support for this thesis comes from observations made at Arcoona Creek on the southwest side of the Gammon Ranges. In January 2009, an intense local storm yielded ~10 mm of rainfall in 15 minutes. This flooded the ground surface but generated no flow in the coarse, openwork deposits of the adjacent river channel (C.J. WRIGHT, Water Projects Officer, Adelaide and Mount Lofty Ranges Natural Resources Management Board, South Australia, personal communication, 12 December 2011). It is possible that some of the fine sediments deposited downstream of Mount McKinlay Spring were transported by storm-generated underflow through the coarse bed of the upstream channel, although no observations of this phenomenon have been undertaken.

At least three units may be identified within the spring sediments. The oldest deposits form low terraces on either side of the channel. The left-bank terrace is higher, and presumably older, than that on the right, though this simple morphology undoubtedly disguises a much more complex history of sediment accumulation.

Adjacent to the active channel and within the flanking terraces lies a series of younger deposits. The relationship of these sediments to cultural artefacts around the springs allows certain of these deposits to be attributed to pre-contact and post-contact times. Amongst the pre-contact sediments are deposits intimately bound within the roots of a fallen (but still growing) specimen of River Red Gum adjacent to the channel and 48 m downstream of the uppermost springs (fig. 2). That this tree and thus the sediments bound within its roots predate European contact is demonstrated by the vertical branches with diameters of ~0.2 m sprouting from the fallen trunk. These retain the marks of fencing wire twisted around the trunk and overgrown by bark. The undercutting of the Gum and its regrowth must have predated the fencing and is likely to have occurred many decades ago. The tree itself is likely to be considerably older than this.

Finally, a post-contact depositional unit may be identified at the springs. Amongst the post-contact sediments are those lying immediately adjacent to the active channel and those forming the uppermost unit of fine-grained alluvium at the site. The latter deposits include a 50 mm thick unit deposited in a sump between a second fallen (but still growing) River Red Gum and a jam of logs and branches trapped immediately upstream of the tree (fig. 2). This fine-grained unit overlies a bed of rounded cobbles set in a sandy matrix.

The closest long-term meteorological record to the field site comes from Arkaroola, 30 km to the northeast, where observations extend back to AD 1938. Mean annual rainfall here is 248.3 mm (range 55.9–949.4 mm), with a summer maximum. Mean daily minimum temperatures (AD 1977–2010) vary between 3.4°C (July) and 20.0°C (January), whilst mean daily maximum temperatures (AD 1977–2010) range from 16.5°C (July) to 34.2°C (January). The climate falls within the BWh (desert hot arid) category of the KÖPPEN (1936) classification.

The first European to enter the Gammon Ranges was Edward Charles Frome in 1843 (NEWLAND 1959, AUHL & MARFLEET *c*. 1977). By 1853, John McKinlay claimed several pastoral runs extending up to the southern margin of the Ranges, although it appears that many of these were never fully stocked. Within a few years, however, other runs surrounding the massif were taken up: the MacFarlane brothers settled on Owieandana (modern Yankaninna) in 1856, McTaggart took up Wooltana in 1857 and John McCallum claimed Nepowie (or Nepouie) the same year. The area encompassed by the Ranges has thus been pastoral land since the time of European settlement, although the region has been progressively incorporated into the Gammon Ranges National Park since 1968 (MINCHAM 1983: 63–64, 231–235).

4   Reconstructing palaeoflood conditions

The aim of this study was to investigate the potential of clastic spring sediments for preserving a record of past floods. This requires first a means of determining chronology. Unfortunately, very few of the techniques used to date the recent past are suitable for the direct dating of fluvially-transported materials (GALE 2009). Complicating the choice of dating procedures are the difficulties associated with determining the time of deposition of the sediment, as opposed to the time of formation of the materials of which the sediment is composed. This is an especial problem in Australia, where the long intervals between events capable of mobilising sediments may mean that datable material is retained in temporary stores for centuries before it finally reaches the site of deposition (BLONG & GILLESPIE 1978).

We tackled these problems by using accelerator mass spectrometric ^{14}C methods to date pollen grains extracted from the sediments. This procedure is predicated on the assumption that the pollen is contemporaneous with the deposits and not reworked from older soils and sediments. Pollen is susceptible to mechanical damage during wetting and drying cycles, and to destruction by oxidation under aerobic conditions (DELCOURT & DELCOURT 1980, CAMPBELL 1991). Under arid conditions, and particularly under the alternately moist and dry conditions experienced in the study area, pollen experiences significant degradation (BRYANT et al. 1994). Pollen grains are thus unlikely to remain undamaged either in the sediments and soils upstream of the springs or within deposits trapped in the fractures of the sandstone aquifer. Any

well-preserved pollen grains extracted from the spring deposits are therefore likely to have been either entrained into the groundwater sediment load from contemporaneous pollen fallout or incorporated into the material deposited at the spring outlet from vegetation growing at the site. In either case, the pollen will be contemporary with the time of sedimentation.

Having established a chronology of sedimentation, the magnitude of the event represented by each deposit must be determined. We attempted to calibrate flood magnitude by focussing initially on the post-contact sediments. We undertook a pilot study in which five samples were taken from different geomorphic contexts within those deposits interpreted on morphostratigraphic grounds as post-dating European contact. Since pollen is best preserved in fine-grained sediments under anaerobic conditions (HUNT & GALE 1986), sampling was restricted to those parts of the sediment body composed of fine-grained alluvium that is likely to have remained permanently moist. Sample MMS1 was taken from the 50 mm thick unit of fine alluvium retained in the sump between the upper of the fallen (but still growing) River Red Gums and a jam of logs and branches trapped immediately upstream of the tree (fig. 2). Samples MMS5–8 were taken 14 m downstream of MMS1 along the edge of the active channel (fig. 2). Pollen from each sample was extracted for accelerator mass spectrometric ^{14}C dating following the procedure of REGNÉLL (1992).

Table 1. Accelerator mass spectrometric ^{14}C determinations from Mount McKinlay Spring, Gammon Ranges, northeast South Australia. The modern ages have been calibrated to calendar years using the CALIBomb Radiocarbon Calibration Program of P.J. Reimer and R. Reimer, employing the SH1.14c data set of HUA & BARBETTI (2004) and a 0.5 a smoothing. The remaining ages have been calibrated to calendar years using the CALIB 6.0 Radiocarbon Calibration Program of M. Stuiver, P.J. Reimer and R. Reimer, employing the SHCal04 data set of McCORMAC et al. (2004). Following the recommendations of TELFORD et al. (2004), the central estimates of the pre-modern dates represent the medians of each calibrated range. The ranges of the pre-modern dates are determined from the complete 2 s range of the calibrated values.

Sample code	Laboratory code	Modern carbon (pmc) (%±1 s)	Radiocarbon age (a BP±1 s)	Calibrated date (BC/AD±2 s)
MMS1	OZL642	101.53±0.48	Modern	AD 1955.50–1957.37
MMS5	OZK578	107.37±0.47	Modern	AD 1957.76–1958.65
MMS6	OZK579	106.12±0.54	Modern	AD 1957.37–1958.35
MMS7	OZK580	103.14±0.46	Modern	AD 1956.13–1957.61
MMS8	OZK581	104.91±0.46	Modern	AD 1956.28–1956.42 AD 1957.15–1958.04
MMS3	OZL644	97.10±0.43	235±40	AD 1747+204/–114
MMS2	OZL643	95.70±0.47	355±40	AD 1560+85/–95
MMS4	OZK577	76.66±0.63	2140±70	104+169/–253 BC

The results of the dating exercise are tabulated in table 1. Samples MMS1 and MMS5–8 all yielded ages that lie in the range AD 1955–1958, confirming our field assessment of the morphostratigraphy of the deposits.

The narrow age range of the samples strongly suggests that they represent the product of an individual episode of sedimentation. The greatest single day's rainfall in the Arkaroola record occurred on 30 March 1956 (fig. 3) and it is highly probable that the deposits at the springs are the result of sedimentation associated with that event. A rainfall event of similar magnitude occurred at Arkaroola on 14 January 1984. This appears to have been much more localised in its impact, however, and rainfall at Mount McKinlay Spring during this event is likely to have been significantly less than that experienced in 1956 (fig. 4).
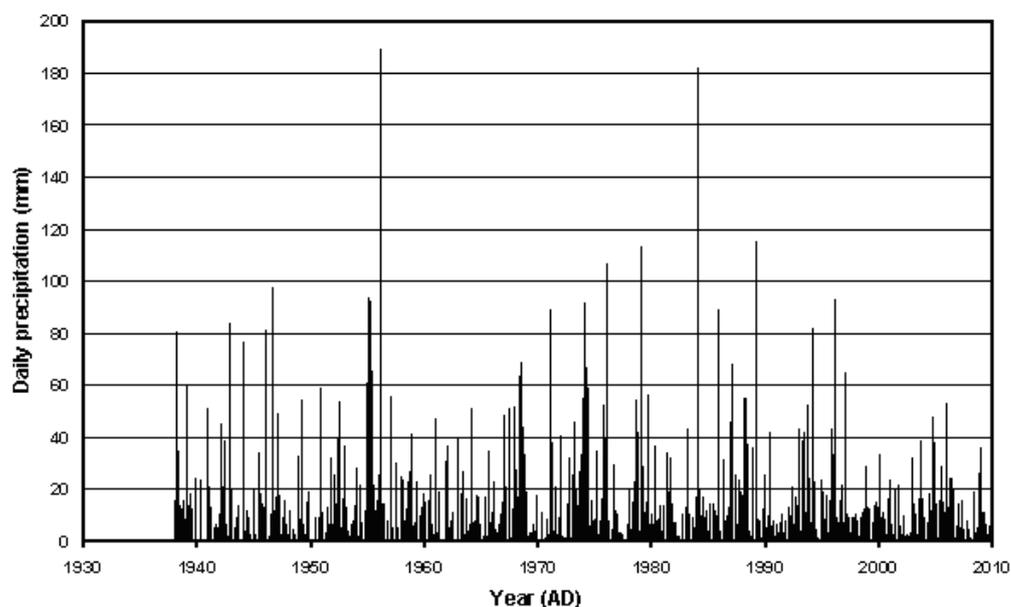
Fig. 3. Daily precipitation at Arkaroola, Gammon Ranges, northeast South Australia, AD 1938–2009 (source of data: Bureau of Meteorology, Melbourne).

The possibility that deposits of more recent high-magnitude events at the site have not been sampled or that they have been lost to erosion (or possibly that the floods failed to leave any depositional imprint, although this would seem highly unlikely) must be considered. However, given the derivation of the five dated samples from different geomorphological contexts within the post-contact unit, it is extremely unlikely that the deposit represents anything other than the product of a single episode of sedimentation. Instead, the 1956 flood is almost certainly the most recent event to have left any sedimentological and geomorphological signature at the site.

Since there is no evidence of deposition at the site in the last half century, it would appear that the spring deposits represent solely the product of high-magnitude, long return-period floods. If this is the case, the modern deposits may provide an analogue for earlier episodes of deposition at the site. The partial duration series of all daily precipitation events in the Arkaroola record is shown in fig. 5. Following the recommendations of CUNNANE (1978), their probability of occurrence has been

determined using GRINGORTEN's (1963) procedure. In the context of the data set shown in fig. 5, the 1956 flood has a return period of somewhat over a century (for comparison, the return period calculated using the widely used WEIBULL [1939] formula is around 71 years).
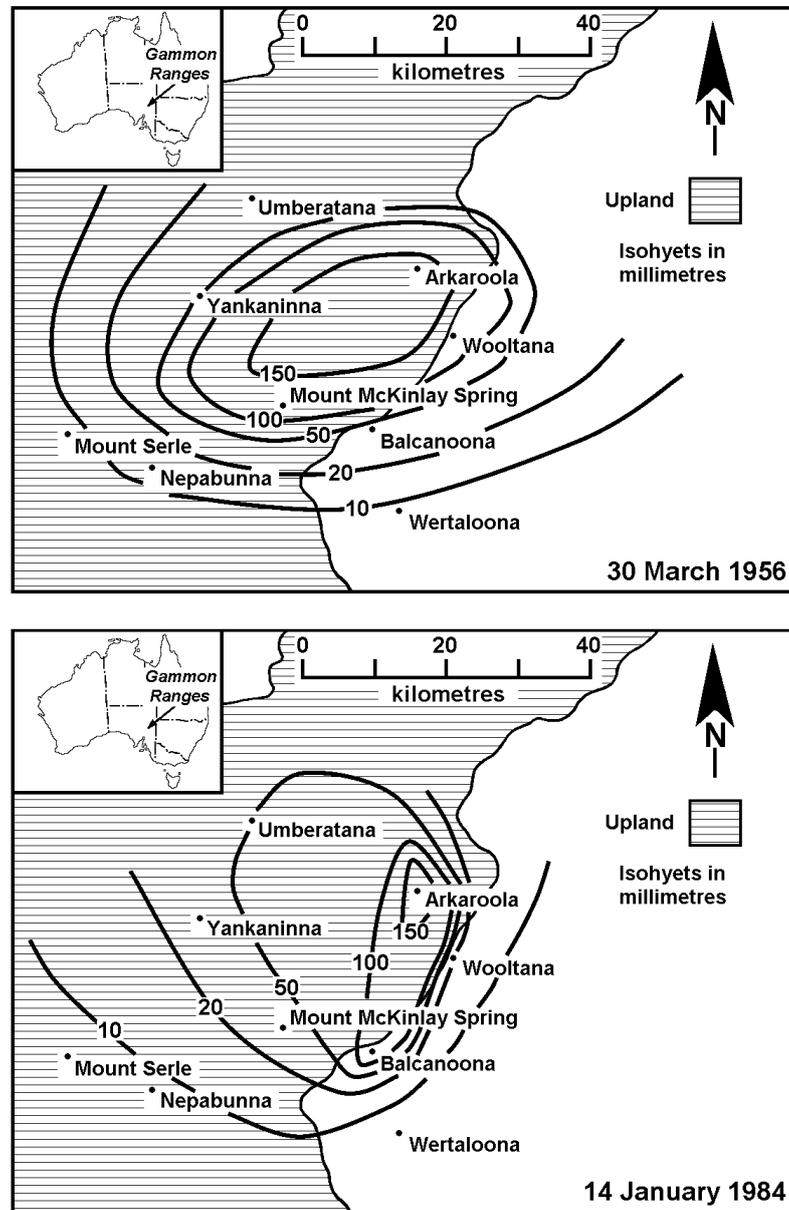
Fig. 4. Rainfall in the southeast Gammon Ranges, northeast South Australia in the 24 h preceding 0900 h on 30 March 1956 and 14 January 1984. With the exception of Mount McKinlay Spring, the sites shown represent the meteorological stations used in the construction of the isohyetal maps (source of data: Bureau of Meteorology, Melbourne).
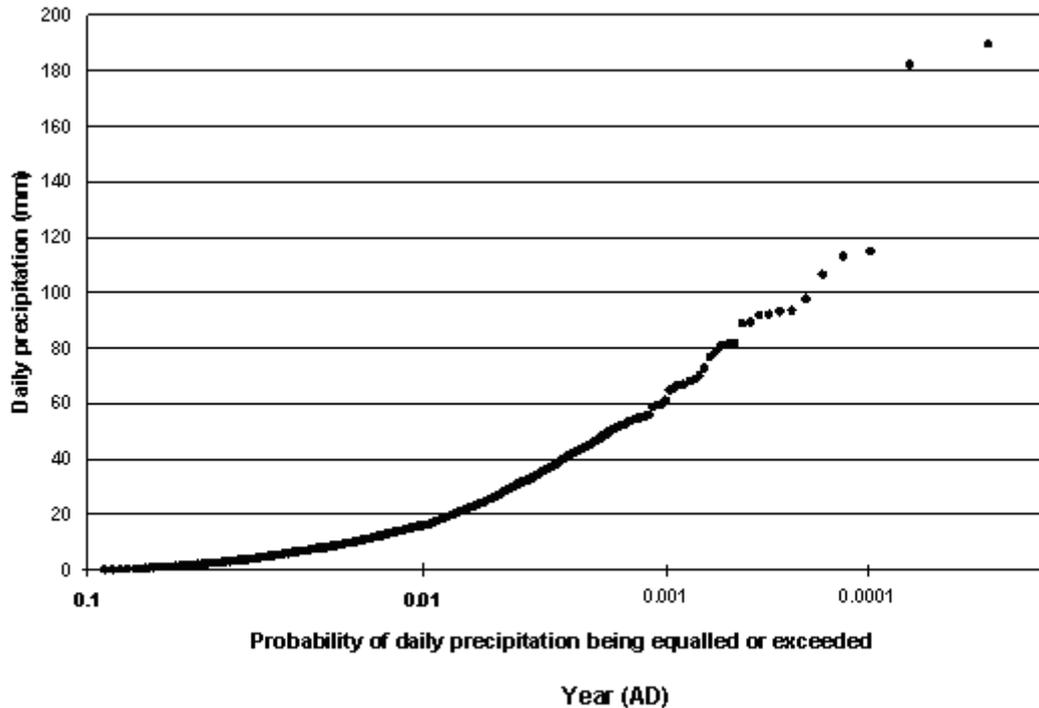
Fig. 5. The partial duration series of all daily precipitation events at Arkaroola, Gammon Ranges, northeast South Australia, AD 1938–2009 (source of data: Bureau of Meteorology, Melbourne). Thirty-two precipitation events were removed from the record because the available data represented cumulative totals of more than a single day's rain. The probability of occurrence was determined using the procedure of GRINGORTEN (1963).

The post-contact deposits may thus offer a means of calibrating the magnitude of the floods represented by earlier deposits at the site. The evidence of the pilot study suggests that the spring sediments represent the product of events with return periods of the order of a century or more. A comprehensive dating programme at the site would allow this thesis to be tested and would enable the flood record to be extended back through the pre-contact era. We tested our interpretation of the stratigraphy of the site by taking a series of samples from deposits interpreted as of pre-contact age. Samples MMS2–4 were obtained from sediments intimately bound within the roots of the fallen (but still growing) River Red Gum identified from its association with European artefacts as of pre-contact age (fig. 2). Pollen from these samples yielded dates ranging from the first millennium BC to the mid-18th century (table 1), supporting our field assessment of the stratigraphy of the deposits. The range of dates of the older samples, all taken from within the root bole of a single tree, confirm the stratigraphic complexity of the deposits. They also strengthen our assessment that the post-contact unit, composed by contrast of deposits of a narrow range of ages, represents the product of a single episode of sedimentation.

The earlier dated sediments may thus each represent the product of a high-magnitude flood, providing an opportunity to establish a picture of event magnitude and frequency, to determine return periods, and to assess the role of climatic change and human environmental impact on flood frequency at the site. A comprehensive programme of dating will be required to test this thesis. Nevertheless, the results

suggest that this approach may offer a valuable means of reconstructing the chronology of floods in an environment offering few other sources of palaeoenvironmental information.

It is likely that the fallen (but still living) River Red Gums that line the channel and the log jam just below the main springs are a product of channel scour associated with the 1956 event. This assessment is supported by the date of AD 1955.50–1957.37 obtained from fluvial sediments deposited in the sump between the upper fallen River Red Gum and the jam of logs trapped behind it, and by the date of AD 1747+204/– 114 from the root bole of one of the fallen trees adjacent to the channel. The fall of the trees is thus bracketed between the 18th century and the mid-20th century. The residence time of the logs in the creek is thus comparable with the ages of several centuries determined on large woody debris in Tonghi Creek in the far southeast of the continent (WEBB & ERSKINE 2003).

5   Conclusions

With the exception of those curious but rare phenomena known as sand cones, clastic spring sediments remain largely undocumented and uninvestigated. Yet these deposits may be far more common than is generally realised. It is likely that ancient examples of these features have been overlooked, in part because their geomorphology and stratigraphy are easily misinterpreted. An alternative approach to the identification of fossil spring deposits may be to consider the sedimentary petrology and palaeontology of the deposits, since both potentially offer a means of distinguishing spring deposits from adjacent units.

This pilot study has considered the potential of clastic spring sediments for preserving records of past flows. At Mount McKinlay Spring in the Gammon Ranges of northeast South Australia, the most recent sediments appear to have been deposited in March 1956 following the greatest single day's rainfall in the instrumental record. This event, with a return period of around 100 years, is likely to have resulted in the undercutting of the banks of the creek downstream of the springs, the consequent collapse of mature River Red Gums growing adjacent to the channel and the accumulation of a jam of logs across the creek. The sediments associated with this event may provide an analogue for earlier episodes of deposition at the site. Given that there is no evidence of sedimentation at this location in the *c.* 50 years since that event, it is possible that the spring deposits represent solely the product of high-magnitude, long return-period floods. If this is the case, clastic spring sediments may offer a valuable means of reconstructing the chronology of floods, particularly in locations affording few other sources of palaeoenvironmental information.

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