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Tracing the source of recent sediment using environmental magnetism and radionuclides in the karst of the Jenolan Caves, Australia

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ABSTRACT This study examines sediment sources and chronology in underground sediment sinks in the Jenolan Caves system, N.S.W., Australia. Relationships between mineral magnetic ratios are used to identify the sources of modern sediment to the cave system. Correlation between the naturally occurring radionuclides ^{226}Ra and ^{232}Th quantify these findings. When considered with historical evidence and fallout ^{137}Cs chronology, a detailed description of the variations in source contributions with time is developed. It is concluded that catchment disturbance associated with forestry activity in the early 1950s significantly changed the relative contributions of the two contributing subcatchments. However, subsequent changes in sediment deposition rate, and by implication sediment supply, were probably more dependent on rainfall changes than relative variations in supply from the two catchments.

INTRODUCTION

This paper reports on recent sediment transport and deposition at Jenolan Caves, the premier tourist caves in Australia. Over recent years, concern has been expressed by the cave's management that the mean water level has risen and the amount of fine sediment being transported within the caves has increased. The major problem lies within Imperial Cave which is part of the underground channel of the Jenolan River. Upstream this river passes through several long cave systems fed by non-specific sources in the incised valleys upstream of the karst.

Mineral magnetic parameters and naturally occurring radionuclide concentrations are used to identify the sources of sediments within the drainage system. These parameters are considered with a sediment chronology, based on fallout ^{137}Cs, radiocarbon dating, rainfall records and correlations with historical evidence, to reconstruct the recent sediment source history of the Jenolan River.

Magnetic parameters and correlations between ^{226}Ra and ^{232}Th (Murray, 1991), are used to characterise the potential sources, and determine the relative contribution of these sources to the sediment sinks. The presence of the fallout nuclide ^{137}Cs near the top of a sediment profile or in grab samples is used to identify material eroded from surface sources after the late 1950s, when ^{137}Cs first reached levels detectable today (Olley et al., 1990).

SITE DESCRIPTION AND SAMPLING

The Jenolan Caves lie in an impounded karst (Jennings, 1985) the catchment of which is highly variable in both lithology and relief. Approximately 320 cave entrances have been recorded. The best known caves are included in the system of underground passages, containing Imperial Cave, that are used as a tourist attraction (Fig. 1).

The Jenolan karst is located in the South Eastern Highlands of New South Wales, an irregular, dissected erosion surface at approximately 1100 to 1200 metres altitude. The geology of the area consists of early Paleozoic sediments and volcanics intruded by a few small igneous bodies and overlain by a sequence of sediments and volcanics which ranges in age up into the lower Devonian. Immediately to the west of the

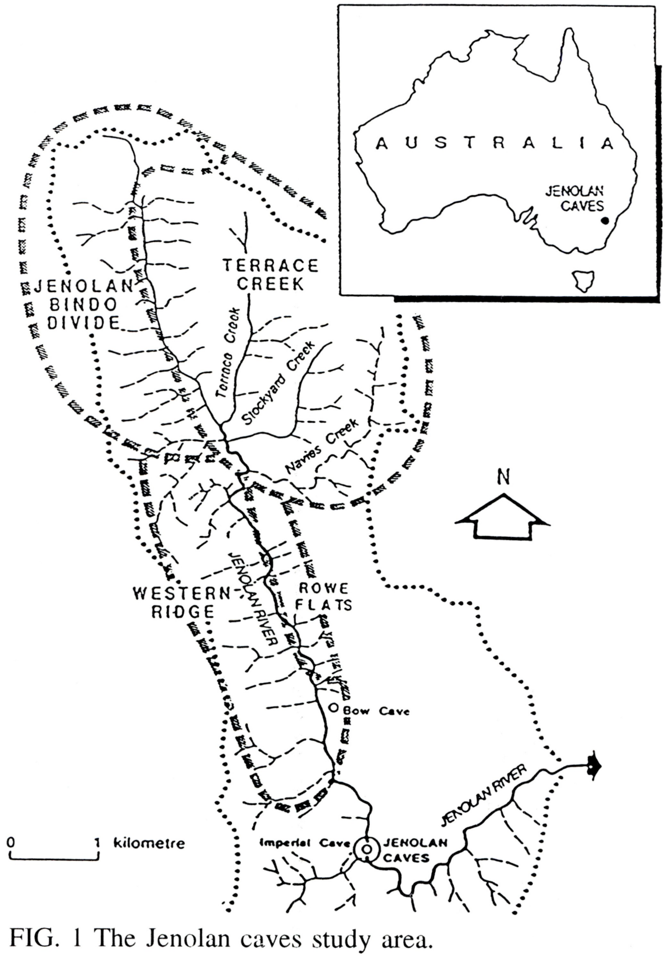

FIG. 1 The Jenolan caves study area.

outcrop of the Jenolan Caves Limestone, and apparently overlying it, is a unit of black mudstones and interbedded andesitic lava and tuff (Allan, 1986). To the east of the Jenolan River Valley and forming the surface lithology of the ridge is a fine grained Upper Silurian slate (Geological Survey of N.S.W., 1971). The alluvial floor of the valley consists mainly of reworked colluvium derived from nearby slopes, from rockfalls and debris flows on the eastern side of the valley, and outwash and slopewash on the western side (Stewart, 1987).

The soils of the area are red or yellow podsolics and lithosols. Most of the catchment area is dominated by tall Eucalyptus forest with some areas of tussock grassland in the valley bottoms.

In 1953 and 1954 native forest in the Terrace Creek catchment, was felled to allow establishment of Pinus radiata (Fig. 1). Apart from some controlled burning the valley has experienced no significant fires for at least several decades; the last major wildfire appears to have been in 1939 .

On average, rainfall is uniformly distributed throughout the year. However, the area is subject to very intense, although sometimes very localised rainstorms.

The major underground stream is the Jenolan Lower River and the surface stream is known as either Jenolan River or McKeowns Creek. From its source at the Jenolan River / Bindo Creek Divide, the surface course of the Jenolan River flows slightly to the east of the limestone belt for the first 6km, and then through the limestone belt for the last 5km to the tourist caves area. All but one of the tributaries on the western side of the valley sink before reaching the main valley, indicating that the limestone extends beneath this area as well.

In normal rainfall conditions the surface river bed is dry everywhere south of the northern end of Rowe Flat (Fig. 1); the flow sinks through gravel/sand stretches in the river bed, and is carried by Lower River. Lower River becomes accessible in Mammoth Cave and has been traced from there to Imperial Cave.

With increasing flood discharge the Jenolan River flows progressively further on the surface until it reaches Bow Cave. Bow Cave is the only inlet capable of accepting large quantities of sediment directly from the river. Shannon (1976) suggested that sediments were entering the cave system by way of Bow Cave, however, until now the only direct evidence for this has been from personal observation by Tourist Commission staff. In June and July 1988, one author (Stanton) observed floods delivering about one third of the total discharge to Bow Cave, which in turn is known to feed water directly into Mammoth Cave via a conduit known as Sand Passage. After the July floods the surface of the sediment in Sand Passage , first studied in February 1988, was covered by 20mm of new sediment by these floods. Furthermore, in the preceding February the surface of the deposit had also contained newly germinated seeds, suggesting that sediment had been deposited by the previous floods in October 1987. Pine bark was also found in surface sediments adjacent to Lower River, confirming the presence of modern sediment.

Bow Cave is the only known significant entry point for modern sediment. Thus only the catchment upstream can be considered a likely source of modern sediment to Imperial Cave. This catchment was divided into four subcatchments (Fig. 1) for the purposes of this study.

(1) The Western Ridge, an area with lithosols formed on interbedded black mudstone, andesitic lava and tuff on the ridge to the west of Jenolan River.

(2) Jenolan River/ Bindo Creek divide, which forms the head of the McKeowns valley with soils formed on Silurian metasediments.
(3) Terrace Creek catchment, to the north-east of Jenolan River. An area with deep yellow podsols, also of Silurian metasediment origin. This creek is the principle surface tributary of the Jenolan River.
(4) Rowe Flats. Mainly alluvial sediment, in some places consisting of, or overlain by colluvial deposits or outwash fans, and dissected by the Jenolan River to a depth of up to two metres.

Grab samples of soils and sediments were taken from within each subcatchment to characterise the potential sources. Samples of laminated sediments in Sand Passage and adjacent to Lower River in Mammoth Cave were taken by coring, and from an exposed face. Further grab samples of mobilized sediments were taken in Imperial Cave. A more detailed description of the sampling procedures is given by Murray et al. (in prep).

RESULTS

The results of the mineral magnetics measurements are shown in Fig. 2. A detailed discussion of the parameters used, and their mineralogical interpretation, is given by Thompson and Oldfield (1986).

In Fig. 2, the three bulked soil samples from the Western Ridge catchment have low frequency dependent susceptibility (X), and low arm/sirm ratios. This is in contrast to the Jenolan/Bindo divide and Terrace Creek data, which have high values for both parameters. The Jenolan/Bindo Divide data are also derived from bulked soil samples, whereas the Terrace Creek data are from individual samples, which probably explains the greater scatter in the Terrace Creek data. The data from the various sediment sinks are all consistent with mixtures of these three source catchments.

Figure 3 presents the radionuclide data. The concentrations of ^{226}Ra and ^{232}Th in the bulked and individual soil samples group as predicted by the magnetic results, with

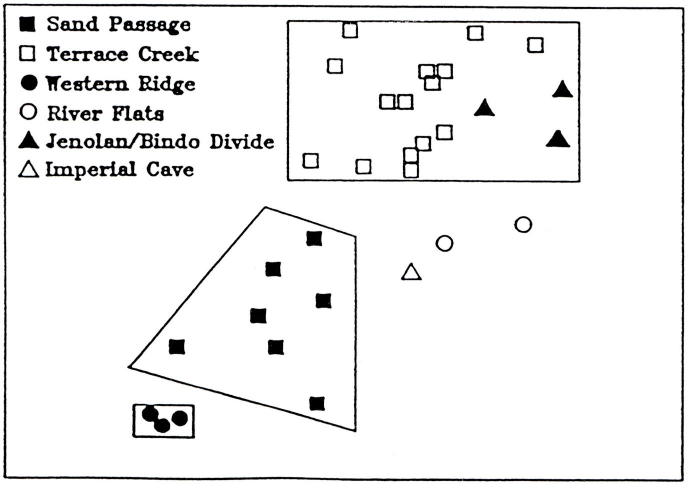

FIG. 2 Magnetic ratios showing signatures of sources and sinks.

pronounced linear correlations distinguishing the Terrace Creek and Jenolan/Bindo Divide data from the Western Ridge. Similar correlations distinguish deposition mixtures in the underground sediment sinks. It appears likely that a more detailed interpretation may be possible than with the magnetics data; at least three source mixtures can be identified. By moving the numerical origin of the concentration data to the mixing origin determined by the intersection of the various correlations, as discussed in Murray et al. (in prep), these data can be presented as activity ratios, and thus compared with stratigraphy and with ^{137}Cs concentrations in Fig. 4. The numbers on the Lower River data points in Fig. 3 also represent the stratigraphic order shown in Fig. 4.

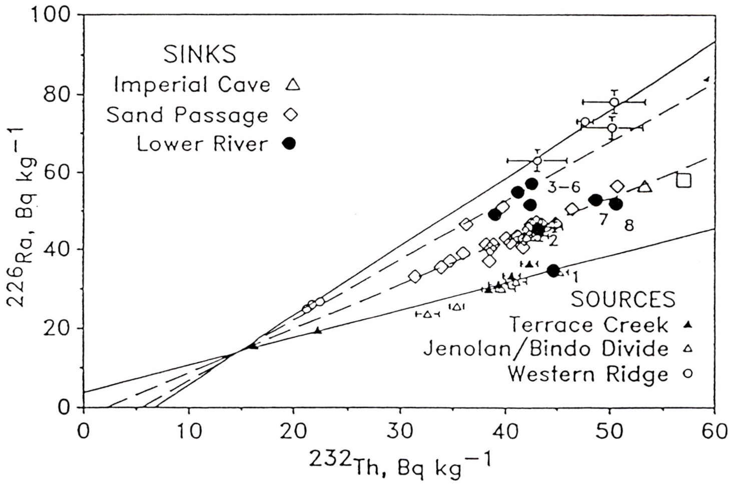

FIG. 3 ^{226}Ra and ^{232}Th correlations between sources and sinks.

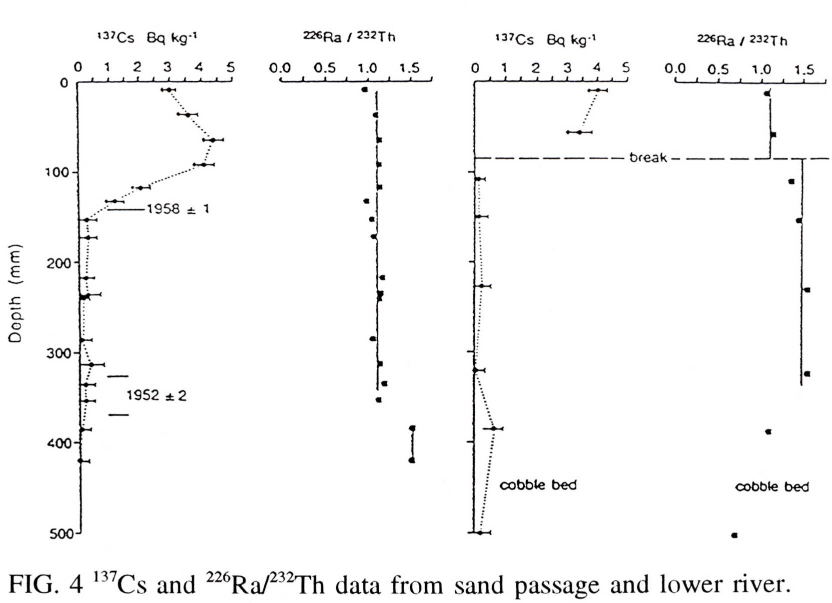

FIG. 4 ^{137}Cs and $^{226}Ra/^{232}Th$ data from sand passage and lower river.

The surface layers at both the Sand Passage and Lower River are consistent with each other both in terms of 137 Cs concentrations and radionuclide ratios. Reference to Fig. 3, (points 7 and 8), suggests that Terrace Creek has contributed a little more than 50% of the material in these sinks in the period. Below 385mm in Sand Passage, and below the 100mm break in stratigraphy Lower River, (points 3-6 in Fig. 3), there appears to have been a period of greater contribution from Western Ridge. In the Lower River data set two earlier phases may also be represented, one close to the present day mixture (point 2, Fig. 3), and the earliest, stratigraphically below the present cobbled bed of the underground river, completely dominated by the Terrace Creek signature (point 1, Fig. 3). All the above assumes that the erosion from Rowe Flats is not contributing significantly to the sediment sinks; this is further considered below. It is also assumed that any sediment trapped in the upstream section of Lower River is not being significantly reworked. However such sediment would not contain any ^{137}Cs, and appears unable to be contributing significantly to the modern phase of deposition which is shown to contain significant levels of 137 Cs.

DISCUSSION

No turbidity or flow records are available for the Terrace Creek/Jenolan River confluence, but direct observation by Stanton during the 1988 floods found that the Jenolan River upstream of Terrace Creek ran clear, in contrast to the turbid water flowing in Terrace Creek. This observation is supported by Tourism Commission staff, who claim that for many years they have found Terrace Creek to be more muddy than either the upstream Jenolan River or Stockyard Creek (Fig. 1). Given these observations and that Terrace Creek is a disturbed catchment, the Jenolan/Bindo divide is probably not as important a source of sediment to the Jenolan River as is Terrace Creek.

As the dissected river banks (up to 2m deep) in Rowe Flats erode and collapse, the top few centimetres of sediment containing ^{137}Cs will mix with subsoil containing no ^{137}Cs resulting in very low ^{137}Cs concentrations, which are probably undetectable. These concentrations would certainly be less than those found in the modern sediments in both Sand Passage and Lower River. Given these concentrations of ^{137}Cs in Sand Passage and Lower River, it is most unlikely that the river flats have contributed a relatively high proportion to the underground sediment sinks. In any case erosion of these flats was not evident, even after the large flood of 1988. The flats appear to be sites of nett accumulation of sediment rather than a source. Aerial photographs from 1935 and 1970 show no change in the meander loops through the flats compared with the present. It is thus concluded that the river flats are unlikely to be significant sources of sediment.

It now remains to develop a chronology for the phases of deposition identified in the previous section. The first time marker is the arrival of ^{137}Cs in both sediment sequences. Olley et al. (1990) suggest from a consideration of detection limits that 1958 is now the most appropriate date for the southern hemisphere to associate with the first detection of ^{137}Cs in a sedimentary profile; this is marked on the Sand Passage profile in Fig. 4. The second marker is based on circumstantial evidence. During the early 1950s and for several years thereafter, it was possible to enter Sand Passage via

Bow Cave (E. Holland, pers comm.). At the same time it was noticed that sediment was accumulating in Bow Cave, and speleological society members attempted to dig out the entrance twice over the next ten years. Nevertheless only voice contact is now possible, and it is suggested that Bow Cave received less sediment from major floods prior to the 1950s than afterwards. This same period saw the establishment of a pine plantation in the Terrace Creek catchment. It is considered likely that the catchment disturbances associated with this forestry operation account for the change in relative contributions of Western Ridge and Terrace Creek catchments at about 385mm in Sand Passage, and by implication the corresponding change across the stratigraphic break in the Lower River sequence. Using these two dates, sedimentation rates in Sand Passage appear to have decreased from about 35+/-14mm per year between 1952 and 1958, to 4.7+/-0.2mm per year after 1958. Partial destruction of the sedimentary record by extreme flood events is considered unlikely, at least in the recent past; the 1988 floods are estimated to have a return probability of more than 1 in 100 years (Holland, 1988, pers. comm.), and yet direct observation showed no apparent damage to the existing record and significant new deposition. It is deduced that the variation in deposition rates is due to a change in sediment delivery, either because of changes in catchment stability, or because of fluctuations in flood frequency.

The daily rainfall record for this location extents back to 1896, and this data set was subjected to trend analysis (Fig. 5). In addition to some cyclic behaviour, there is an increase in average rainfall from about the 1940s with a peaks in the 1950s and 1960s. There is thus the potential for increased erosion, sediment transport and flood frequency in this period.

Whatever the cause of the change in sedimentation rate, as the disturbed catchment recovered and sediment delivery from this subcatchment decreased, the relative mixture of Terrace Creek and Western Ridge sources should have tended to the predisturbance proportions. However, the radionuclide ratios suggest that after the change in mixture

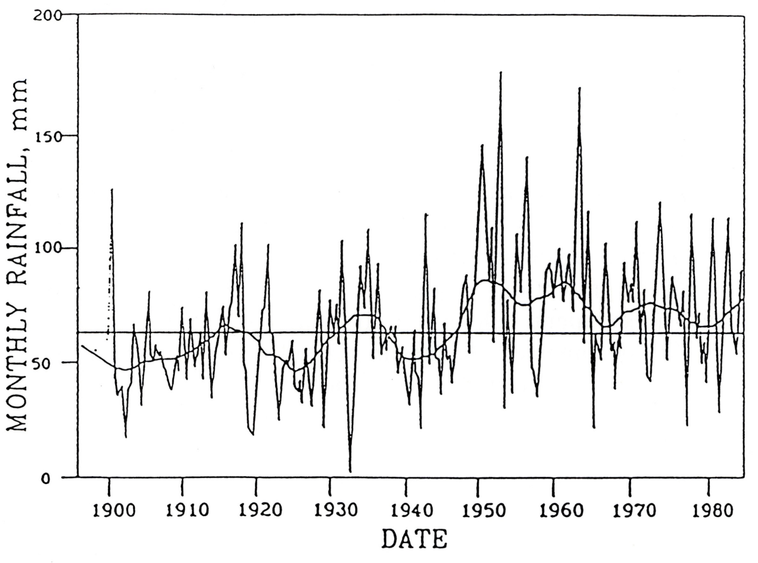

FIG. 5 Jenolan rainfall.

in the early 1950s the relative importance of the two sources has remained constant despite the overall reductions in sedimentation rate.

Although rainfall trends may explain the change in the rate of sediment supply from all sources, an explanation of the constancy of the sediment mixture of undisturbed Western Ridge and disturbed Terrace Creek is still required. It is known from several studies (e.g. Heede, 1984; Mackay & Cornish, 1982) that plantation roads, constructed for maintenance, thinning and fire fighting, are major sources of sediment because of constant traffic. In this case, the roads were established before ^{137}Cs fallout commenced, and so sediment derived from road surfaces can be expected to be indistinguishable from a modern surface soil source. If these roads indeed became the dominant source of sediment shortly after the establishment of the plantation, then it entirely possible that the relative contribution from Terrace Creek could have remained constant thereafter. Then rainfall changes in the 1950s would account for the changes in sedimentation rate, rather than stabilization of the disturbed catchment.

CONCLUSIONS

This study has successfully distinguished the two major areas from which sediment could have been derived in the Jenolan Caves catchment. Both mineral magnetics and naturally occurring radionuclides clearly separated Western Ridge from the Terrace Creek and Jenolan/Bindo divide soils and sediments. Sedimentary sequences, sampled at two locations within the underground system contained modern sediment. This was demonstrated by the presence of freshly germinated seeds, pine bark from a post 1950s plantation, and fallout ^{137}Cs (Post 1958). This information, coupled with historical descriptions and correlations of the $^{226}Ra/^{232}Th$ rates in the sediment profiles with the potential sources, enabled the construction of a chronology of sediment deposition and source.

It is concluded that at some time in the past, prior to a period of fluvial activity identified by the cobble bed in the underground river, the Terrace Creek catchment completely dominated the sediment supply. After this period the Western Ridge started to contribute more. Immediately prior to the early 1950s and the establishment of the pine plantation the dominant sediment source was the Western Ridge. After the catchment disturbance associated with the establishment of the plantation, the Terrace Creek contribution again increased, and the relative mixture of sources remained constant until the present day. There is, however, a decrease in sedimentation rate and presumably in sediment delivery; it is concluded that this is more likely to be associated with documented changes in rainfall than in sediment source.

This study has demonstrated the value of source tracers in reconstructing the sedimentation history of underground sediment sinks. It has also shown that, the establishment of the pine forest plantation probably did disturb the existing relative sediment sources. However, the increases (and decreases) in sedimentation rate and supply are probably not largely associated with this disturbance. Thus we conclude that the plantation is probably not the main cause of change in sediment fluxes moving through the cave system.

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