Sediment Transfer through the Fluvial System (Proceedings of a symposium held in Moscow, August 2004).
IAHS Publ. 288, 2004

Sediment redistribution following wildfire in the Sydney region, Australia: a mineral magnetic tracing approach

WILLIAM H. BLAKE[1], **PETER J. WALLBRINK**[2], **STEFAN H. DOERR**[3], **RICHARD A. SHAKESBY**[3] & **GEOFFREY S. HUMPHREYS**[4]

1 *School of Geography, University of Plymouth, Drake Circus, Plymouth PL4 8AA, UK*
william.blake@plymouth.ac.uk
2 *CSIRO Land & Water, PO Box 1666, ACT 2601, Australia*
3 *Department of Geography, University of Wales Swansea, Singleton Park, Swansea SA2 8PP, UK*
4 *Department of Physical Geography, Macquarie University, North Ryde, Sydney, NSW 2109, Australia*

Abstract Increased sediment and nutrient fluxes arising after wildfires may affect downstream water quality. We use mineral magnetic tracers to elucidate linkage between different slope units, river channel and a reservoir sediment column in the gorge-dissected landscape of a burnt water supply basin. Comparison of magnetic properties of source areas with downstream (sub-aerially stored) channel deposits suggests predominantly ridge-top origin with significant storage of sediment within footslopes. Magnetic properties of the sediment column provide insight into the nature of sediment accumulation on the reservoir floor and the role of immediate post-fire rainfall events. Comparison of source signatures with sub-aqueously stored sediment is complicated by the apparent fragility of some fine pyrogenic mineral grains; these may have to be accounted for in sediment column interpretation. Tracing tools provide river basin managers with important process-based evidence of post-fire sediment redistribution, useful for more effective mitigation of these infrequent, but significant, sediment redistribution events.

Key words Australia; downstream impacts; erosion; mineral magnetics; rainstorm; reservoir; sediment; tracer; wildfire

INTRODUCTION

The dynamics of sediment redistribution following wildfire events, particularly with respect to the timing and intensity of post-fire rainfall, are not well understood. These require attention since post-fire sediment and nutrient fluxes affect downstream water quality. Sediment tracing approaches provide information on river basin sediment dynamics unavailable through direct monitoring approaches (e.g. Walling *et al.*, 1979; Blake *et al.*, 2003). In the context of fire-related sediment redistribution, mineral magnetic tracers have received attention since large quantities of pyrogenic iron minerals, with magnetic properties that can be used to distinguish burnt from unburnt sediment sources, are produced at high temperatures, in the presence of organic matter (Rummery *et al.*, 1979; Gedye *et al.*, 2000; Blake *et al.*, 2004).

The aim of this paper is to explore the potential for using mineral magnetic tracers to elucidate slope–channel–reservoir linkages in water supply basins, near Sydney Australia, which were affected by recent wildfire events (Christmas 2001–2002). Clarification of the link between slope and sediment column provides an opportunity, as a secondary aim, to interpret recent reservoir deposits in the context of the erosional response of the landscape to fire events of variable severity. This is important in the context of both changing hydrological (water repellency) properties of soil with variable fire severity (Doerr *et al.*, 2000) and the increased frequency and severity of ENSO-driven drought. The immediate basin area of the reservoir, Lake Burragorang, is dominated by dry sclerophyllous eucalypt forests which have a history of recurring wildfire. Consequently, we also aim to establish the influence that any sediment eroded after such fires would have on Burragorang water quality over the longer term. We assess this by determining the contribution of fire-eroded soils to the sediment archive deposited on the reservoir floor.

STUDY AREA

Research was undertaken in the Nattai River drainage basin, which flows into the Warragamba River, which in turn forms part of Lake Burragorang (Fig. 1). Lake Burragorang was formed in 1960 by the impoundment of Warragamba Dam and is Sydney's principal water supply reservoir. The basin is underlain by Hawksbury Sandstone and is characterized as a plateau-gorge type landscape. Surface soil materials are typically sandy to sandy loam. The basin is largely forested with a variety of native eucalypt species (Shakesby *et al.*, 2003).

This investigation was prompted by extreme wildfire events of Christmas 2001–2002. Fire events were followed by moderate intensity rainstorm events from January to May 2002 which triggered significant sediment redistribution within the basin (Shakesby *et al.*, 2003).

METHODS

Sampling locations are shown in Fig. 1 and reflect the need to (a) establish the link between slope–channel–reservoir, and (b) interpret the magnetic properties of the sedimentary archive in terms of any temporal trends in fire-driven sediment and nutrient flux to the reservoir.

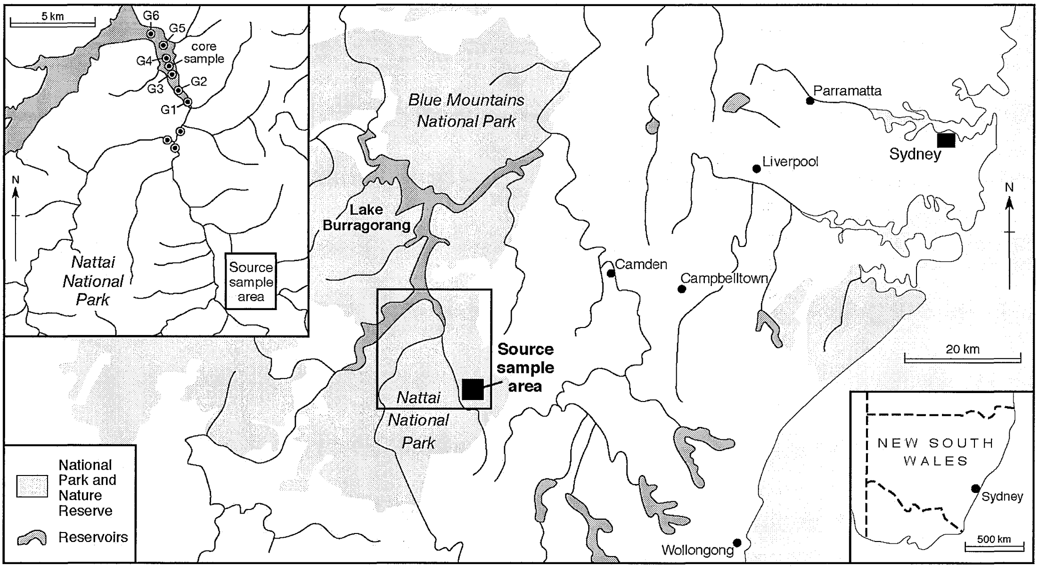

Fig. 1 Location of study area and sediment sampling sites (inset).

Samples of sediment source material were collected within the gorge-dissected landscape, from ridge-top and footslope units representative of areas experiencing contrasting fire severity across the catchment, as described in Shakesby *et al.* (2003) and Blake *et al.* (2004). Each sample population was combined. Samples of recent sediment deposits were collected from the downstream channel network (Fig. 1). A series of grab samples were collected from the mouth of the Nattai River through the Nattai arm of Lake Burragorang (Fig. 1). The <10 μm fraction was extracted from each sample.

A sediment core was taken from the reservoir floor of the Nattai arm (Fig. 2) (the former River Nattai floodplain) using a percussion coring device. The core was divided into stratigraphic units (A–G, Fig. 2) and the <10 μm fraction extracted from each. Units A, C and E displayed characteristics of immediate post-fire-derived material similar to those observed in the recent channel deposits, i.e. black, massive silty clays. Units B and D comprised slightly coarser material with laminations of dark sediment. Units F and G were similar to B and D but with less distinct laminae of finer sediment.

A full suite of mineral magnetic analyses was undertaken following standard procedure. In brief, low-frequency mass-specific magnetic susceptibility (χ_{lf}) is an indicator of the total magnetic concentration of the sample. Frequency-dependent susceptibility ($\chi_{fd\%}$) indicates the proportion of superparamagnetic (SP) (<0.05 μm) minerals present in the assemblage with values ranging from 0 to 14%. Susceptibility of anhysteretic remanent magnetization (χARM) is an indicator of the concentration of magnetic minerals of the 0.02–0.4 μm fraction. Saturation isothermal remanence magnetization (SIRM) indicates the ability of the mineral assemblage to hold a magnetic remanence which in turn can be linked to magnetite concentrations, mineralogy and magnetic grain size (Walden *et al.*, 1999).

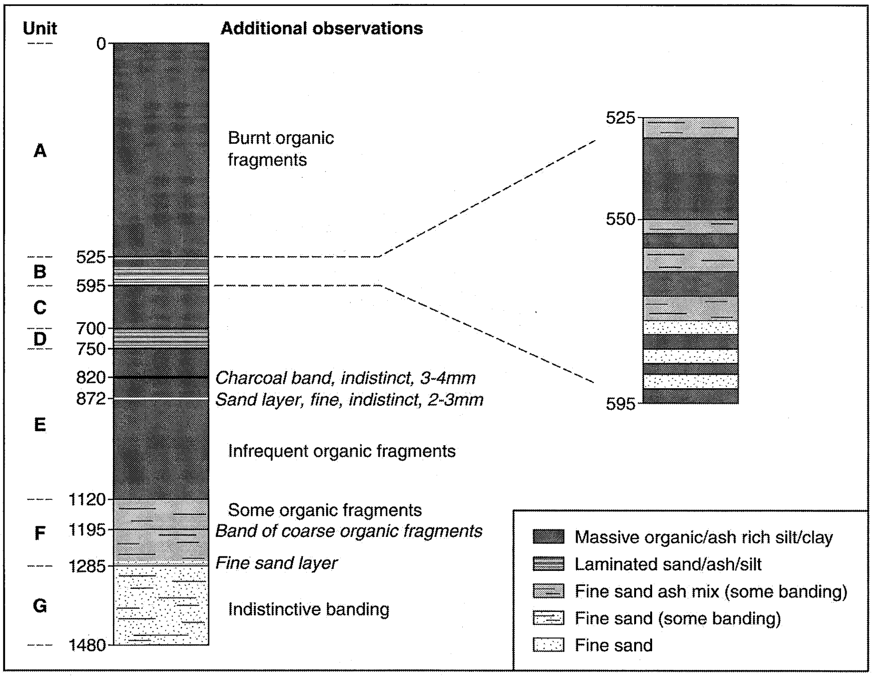

Fig. 2 Schematic representation of the Lake Burragorang sediment core

RESULTS AND DISCUSSION

Linking slope to channel

The main mineral magnetic properties of each sample set (i.e. source, channel, grab sediment and sediment core) are shown in Table 1 (a)–(d).

Comparison of slope material (Table 1(a)) and channel sediment (Table 1(b)) from the Little River channel (using multivariate analysis of the mineral magnetic properties discussed by Blake *et al.* (2004), summarized in Fig. 3) suggests (qualitatively) that the burnt ridge-top area (irrespective of fire severity) dominates as the source of material deposited in the channel of the near-burnt-slope environment (i.e. Little River). This implies that sediment is delivered to the channels via concentrated overland flows directed through existing ephemeral gully features. Conversely, the lower slope locations tend to act as areas of sediment storage rather than source, forming an unusual soil profile where subsurface material carries a fire-enhanced signature as a relic of material burnt and eroded from upslope locations following previous fires. The effect of secondary burn events on this pre-enhanced, stored material appears to be one of further enhancement (compare magnetic concentration severely burnt ridge-top to severely burnt footslope in Table 1(a)) where magnetic grain-size indicators suggest a coarsening of the mineral population (compare χARM and χARM/SIRM in Table 1(a)). However, it is unknown whether the "coarsening" of slope-stored magnetic mineral assemblages reflects "storage diagenesis" (loss of finer grains through dissolution processes; cf. Oldfield *et al.*, 1992) or a mineral formation process linked to multiple burning.

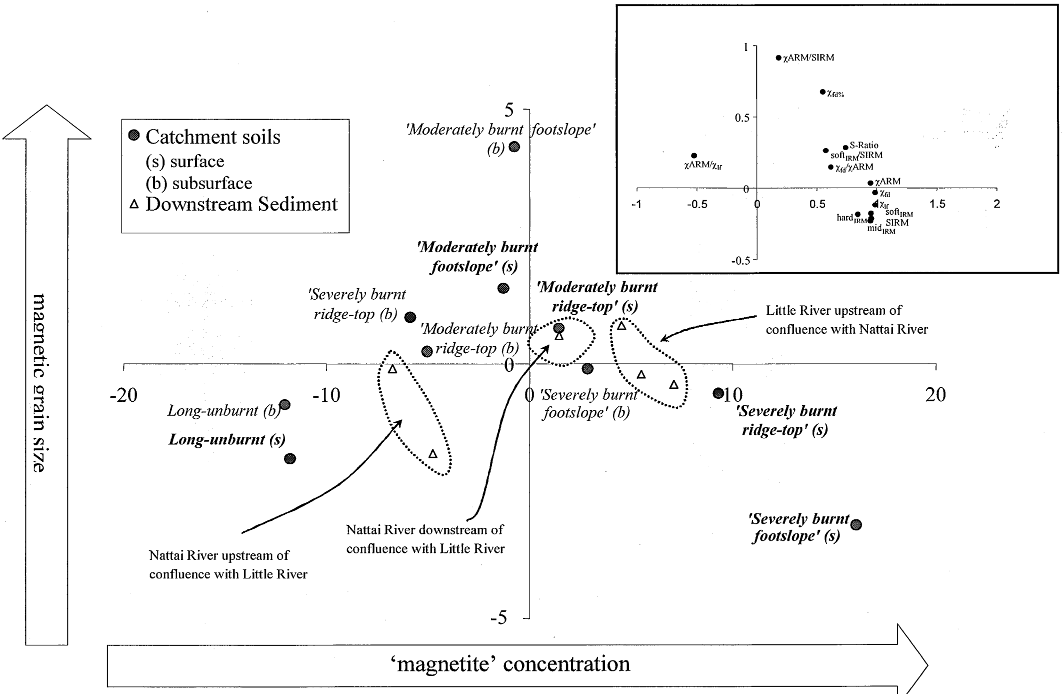

Fig. 3 Multivariate plot (principal components analysis) of sediment source area and downstream sediment properties where proximity within plot space indicates similarity in magnetic signatures after Blake *et al.* (2004).

Table 1 Mineral magnetic characteristics of: (a) source materials on the burnt slopes, (b) channel deposits around the Little River/Nattai River confluence, (c) grab samples of recent lake sediment and (d) stratigraphic units of the lake sediment core.

Table 1(a) *Landscape unit soil*	χ_{lf} (10^{-6} m^3 kg^{-1})	χ_{fd} %	χARM (10^{-5} m^3 kg^{-1})	soft$_{IRM}$ (10^{-5} Am^2 kg^{-1})	hard$_{IRM}$ (10^{-5} Am^2 kg^{-1})	SIRM (10^{-5} Am^2 kg^{-1})	χARM/SIRM (10^{-3} Am)	χ_{fd}/χARM	S-ratio
Unburnt	0.77	8.84	0.35	177	112	829	0.42	0.19	0.79
Mod. burnt footslope	4.06	10.65	1.82	610	378	2368	0.77	0.24	0.96
Mod. burnt ridge-top	4.59	11.18	1.21	676	180	2104	0.58	0.42	0.94
Sev. burnt footslope	10.39	10.68	3.36	1868	746	6700	0.50	0.33	0.97
Sev. burnt ridge-top	8.03	11.24	2.92	1386	399	4751	0.61	0.31	0.99
Table 1(b) *Downstream channel sediment*									
Nattai R. u/s Little R.	2.25	8.54	1.10	562	99	1831	0.60	0.17	0.91
Nattai R. u/s Little R.	3.42	7.32	1.28	666	150	2292	0.56	0.20	0.92
Little R. u/s Nattai R.	6.84	10.82	2.68	1418	317	4478	0.60	0.28	0.93
Little R. u/s Nattai R.	6.10	10.86	2.57	1223	213	3799	0.68	0.26	0.95
Little R. u/s Nattai R.	6.42	10.89	2.41	1235	282	3991	0.60	0.29	0.95
Nattai R. d/s Little R. (*reservoir inlet*)	4.78	10.44	2.08	1015	232	3190	0.65	0.24	0.92
Table 1(c) *Reservoir sediment (grab samples)*									
Grab 1	0.72	9.42	0.64	179.49	23.36	721.75	0.89	0.105	0.89
Grab 2	0.51	8.75	0.57	144.00	17.01	590.35	0.96	0.079	0.89
Grab 3	0.82	7.66	0.62	228.41	18.34	992.79	0.63	0.101	0.93
Grab 4	0.54	7.55	0.70	163.12	23.03	803.27	0.87	0.059	0.92
Grab 5	0.95	8.16	0.92	267.33	44.60	1138.49	0.80	0.085	0.91
Grab 6	0.72	9.42	0.64	179.49	23.36	721.75	0.89	0.105	0.89
Table 1(d) *Reservoir sediment (core samples)*									
Unit A	0.92	6.25	0.70	292	32.5	1347	0.52	0.081	0.93
Unit B	0.67	6.08	0.56	177	30.3	987	0.57	0.071	0.91
Unit C	0.49	5.81	0.40	123	7.8	610	0.65	0.072	0.89
Unit D	0.49	4.75	0.41	119	28.5	611	0.68	0.056	0.86
Unit E	0.34	5.42	0.25	70	25.9	380	0.65	0.075	0.79
Unit F	0.56	7.81	0.35	111	27.5	491	0.71	0.126	0.82
Unit G	1.06	9.25	0.67	251	26.6	903	0.74	0.146	0.90

In contrast, comparison of slope (Table 1(a)) and channel sediment (Table 1(b)) from the Nattai River suggests dilution of the fire-enhanced signal by upstream Nattai River sediment that generally records lower values for each magnetic parameter (Table 1(b)). Possibly, the less-enhanced Nattai River signal results from dilution by unburnt sediment sources, most likely agricultural and urban areas that, in contrast to the Little River basin, form a substantial part of the Nattai basin land use. Fire-related magnetic properties of sediment delivered to the lake have been slightly diluted prior to deposition but carry a significant fire-related signal.

Linking channel to lake

Comparison of the Nattai River channel sediment with surface grab samples of sub-aqueously stored recent sediment suggests a further reduction of the fire-enhanced mineral magnetic signature. However, in this case it is more difficult to reconcile these changes in terms of physical mixing or dilution. Magnetic susceptibility values fall from 4.78 (at the inlet (Table 1(b)) to 0.51–0.95 10^{-6} m^3 kg^{-1} in the surface lake sediment (Table 1(c)). Values of χARM similarly fall from 2.08 to 0.57–0.92 10^{-5} m^3 kg^{-1} and SIRM values fall from 3190 to 590–1138 10^{-5} Am^2 kg^{-1}, but to a lesser degree. These reductions in measures of magnetic concentration coincide with changes in magnetic grain size indicators. Comparison of lake and the Nattai River input sediment shows lower χ_{fd}% values (cf. Table 1(b) and (c)) and lower χ_{fd}/χARM values in the lake sediment, which indicate a "coarser" magnetic assemblage.

This coarser magnetic assemblage could be linked to some loss of the finer grained (SP) fraction of the mineral population to dissolution processes during subaqueous storage (cf. Oldfield *et al.*, 1992). Alternatively, comminution or sorting processes could modify signatures although the effect of the latter should be accounted for with comparison of <10 μm fractions. SP grains will contribute to χ values and also χ_{fd} both of which are significantly reduced. The (less dramatic) reduction in the value of χARM and SIRM indicates that dissolution or distortion might not be restricted to SP grains alone. A loss of pyrogenic grains has important implications for tracing applications both in terms of signal preservation and interpretation of the sediment column. It also contributes to understanding the lack of a "magnetic memory" in soils from surfaces experiencing a fire-event in 1994 but remaining unburnt during the recent event (see unburnt soil in Table 1(a)). Dissolution processes potentially contribute to a resetting of the source signal, together with denudation and bioturbation processes, albeit at a slower pace than in sub-aqueously stored fine sediment.

Interpreting the sedimentary record

The bulk mineral magnetic properties of the reservoir sediment column are shown in Fig. 4. The high values for all properties of units F and G are consistent with results reported for slope-stored eroded burnt material that had potentially been subjected to multiple burnings (Blake *et al.*, 2004). These differences imply that these units represent the former flood plain surface comprising subaerially stored burnt and reburnt material mobilized from upstream. If this assumption is correct, sediment from 0 through to 1020 mm depth can be considered to be lacustrine sediment deposits spanning from the present back to 1960. Dating evidence is required to support this.

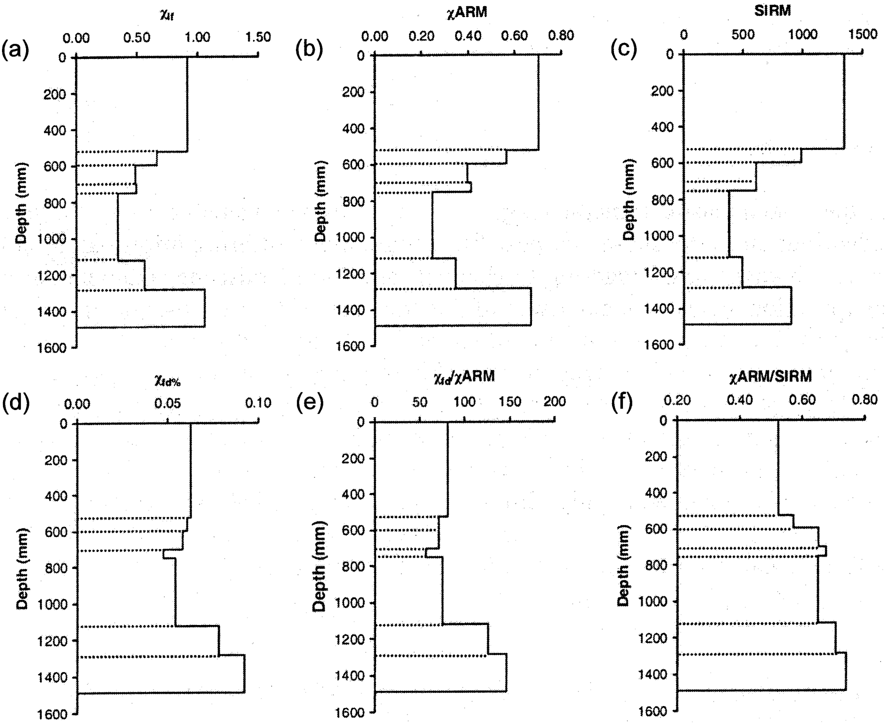

Fig. 4 Depth profiles of average mineral magnetic properties for lake core units A–E (see Table 1 for measurement units).

Stratigraphic evidence (Fig. 2) suggests that during this period there have been at least two additional fire-related, major deposition events (units C and E) of similar character to that of the 2001 erosion events (unit A). Domination of the record by these units, assuming they represent similar conditions to those observed following the study events, demonstrates the importance of immediate post-fire rainstorms in terms of sediment flux in this system.

The magnetic properties of units A, C and E are, however, not similar. A progressive and consistent decline in the magnetic concentration properties (χ_{lf}, χARM and SIRM, Fig. 4 (a)–(c)) is seen with depth. This could imply that either: (a) the dissolution of fine-grained magnetite in sub-aqueously stored sediment, as suggested by comparison of channel and surface lake sediment data above, continues with time, or (b) the fire-events that triggered major redistribution of sediment within the river basin were of different severity and hence led to different levels of enhancement in the source areas (cf. range of values in Table 1(a)). The decline in the proportion of fine magnetic grains in these units with depth suggests the former is more likely (see $\chi_{fd\%}$, χ_{fd}/χARM and χARM/SIRM, Fig. 4(d)–(f)). Evidence from Table 1(a) ($\chi_{fd\%}$) supports this showing that although different severities of fire produce different concentration-related signatures, all are represented by a high proportion of fine SP grains. Spatial variability in the magnetic properties of recent deposits (grab samples in Table 1 (c)), however, should also be noted.

The consistent decline in magnetic properties of the intermediate units (B and D) with depth, which we regard as representing non-immediate post-fire-rainfall and non-fire driven sediment mobilization, supports the above assertion. Interpretation of sediment column mineral magnetic evidence must, therefore, account for possible sub-aqueous distortion of the tracer signal.

CONCLUSION

In the Nattai basin, mineral magnetic properties are valuable tools for tracing sediment redistribution in the sub-aerial post-fire environment, offering information on both sediment source linkages (e.g. ridge-top to channel) and intra-landscape sediment storage. However, complication arises with extension of this tracing tool to the sub-aqueous environment where the pyrogenic magnetic signature of stored burnt sediment appears distorted by loss of some fine-grained pyrogenic magnetite, probably through dissolution.

Our data suggest that substantial post-fire rainstorm events account for 89% of total reservoir sedimentation in the Nattai arm of Lake Burragorang and that, unexpectedly, a significant proportion of that material is sourced from burnt ridge-tops and transported directly, via ephemeral gully flows, to the river channel. Mineral magnetic tracing tools provide river basin managers with important process-based evidence of post-fire sediment redistribution, useful for more effective mitigation of these infrequent, but significant, sediment redistribution events.

Acknowledgements NERC Grant NER/A/S/2002/00143 and NERC advanced fellowship NERC/J/S2002/00662 (SHD); Macquarie University for financial contribution (GSH); Sydney Catchment Authority for logistical support (Glen Capararo) and data (Chris Chafer); Danny Hunt (CSIRO L & W) and Vicky Farwig (UWS) for assistance with field sampling; Gareth James (UWS) for sample analysis; Wirrimbirra Nature Reserve for laboratory space; Nicola Jones (Fig. 1); Jamie Quinn (Fig. 2).

REFERENCES

Blake, W. H., Walling, D. E. & He, Q. (2003) The use of ^{7}Be as a tracer in sediment budget investigations. *Catena* **82A**(2), 89–102.

Blake, W. H., Wallbrink, P. J., Doerr, S. H., Shakesby, R. A. & Humphreys, G. S. (2004) Magnetic enhancement in fire-affect soil and its potential for sediment source-ascription. *Earth Surf. Processes Landf.* (submitted).

Doerr, S. H., Shakesby, R. A. & Walsh R. P. D. (2000) Soil hydrophobicity: its causes, characteristics and hydro-geomorphological significance. *Earth Sci. Rev.* **51**, 33–65.

Gedye, S. J., Jones, R. T., Tinner, W., Ammann, B. & Oldfield, F. (2000) Use of mineral magnetism in the reconstruction of fire history. *Paleogeo. Paleoclim. Paleoeco.* **164**, 101–110.

Oldfield, F., Darnley, I., Yates, G., France, D. E. & Hilton, J. (1992) Storage diagenesis *versus* sulphide authigenesis: implications in environmental magnetism. *J. Palaeolim.* **7**, 179–189

Rummery, T. A., Bloemendal, J., Dearing, J. A., Oldfield, F. & Thompson, R. (1979) The persistence of fire-induced magnetic oxides in soil and lake sediments. *Ann. Géophys.* **35**, 103–107.

Shakesby, R. A., Chafer, C. J., Doerr, S. H., Blake, W. H., Wallbrink, P. J., Humphreys, G. S. & Harrington, B. A. (2003) Fire severity, water repellency characteristics and hydrogeomorphological changes following the Christmas 2001 Sydney forest fires. *Austral. Geog.* **34**, 147–175.

Walden, J., Oldfield, F. & Smith, J. (1999) *Environmental Magnetism a Practical Guide.* Quaternary Research Association Tech. Guide 6, UK.

Walling, D. E., Peart, M. R., Oldfield, F. & Thompson, R. (1979) Suspended sediment sources identified by magnetic measurements. *Nature* **281**, 110–113.