

SOME EFFECTS OF FIRE ON THE REGOLITH

G. S. Humphreys¹, R.A. Shakesby², S.H. Doerr², W.H. Blake³, P. Wallbrink⁴ & D.M. Hart¹

¹Department of Physical Geography, Macquarie University, NSW, 2109

²Department of Geography, University of Wales Swansea, Swansea SA2 8PP, UK

³Department of Geographical Sciences, University of Plymouth, Plymouth PL4 8AA, UK

⁴CSIRO Land & Water, PO Box 1666, Canberra, ACT, 2601

INTRODUCTION

Fire is a compelling factor over the Australian continent. With sufficient fuel and fanned by strong winds, fire dramatically alters the appearance of the landscape in which charred trees and scorched earth are omnipresent. Charred litter remains are readily swept away by wind or become part of the floating load in post-fire runoff events. Thereafter mineral grains become increasingly exposed to wind and especially rain splash and slope wash. Nevertheless, it is clear that the Australian biota and landscape recovers quickly. This is not surprising since much of Australia's vegetation is adapted to periodic burning at both species and community levels. These adaptations are reflected in the fossil record, which indicates the co-development of traits that deal with periodic droughts and associated fire as the continent began drying out from the mid-Tertiary. Whilst these effects are well known there are a number of other effects that are not. The purpose of this contribution is to consider some lesser-known and unusual influences of fire on the regolith.

EROSION AND LANDSCAPE DENUDATION

Spalling

Various commentators have drawn attention to the spalling (flaking) of rock when subjected to intense heat from fire but there are few measurements of the amount of rock so removed. Up to 6 kg of flakes per square metre of exposed sandstone has been recorded in the Blue Mountains (Adamson *et al.* 1983). This is a very high value but without information on the extent of affected exposed rock the full significance of this cannot be evaluated. Nevertheless, if 1% of this area was so affected every 20 years a spalling rate of $3 \text{ g m}^{-2} \text{ y}^{-1}$ results, which translates to a denudation rate of about 6 m My^{-1} assuming a rock density of 2 g cm^{-3} . This is probably a conservative estimate that does not take into account charring of the cement-weakened algal coating of exposed rock. Subsequent rain fall events, falling twigs, wind and water flow dislodges the weaken crust and 1-2 mm layer is removed (Adamson *et al.* 1983), which equates to another 5-10 m My^{-1} if on average 10% of the sandstone terrain is affected. Conservative estimates such as these are geomorphologically significant since they are similar to rates of landscape lowering estimated by various methods in which erosional processes are subsumed under terms like incision by knickpoint retreat, valley widening, cliff retreat and plateau lowering (e.g., van der Beek *et al.* 2001).

Soil water repellency and associated effects

The heating of soil during a fire has a significant effect on the soil in several ways. Biological disruptions of living tissue (stems, roots and especially root hairs) begins at temperatures of 40-70°C and microbes begin to be affected at 50-120°C. At higher temperatures physico-chemical changes occur with the aggregation of silt and clay into sand sized entities at temperatures >220°C, distillation of organic matter at 200-315°C and nutrient volatilisation at 200-400°C (Neary *et al.* 1999). It is under these conditions that water repellency develops and/or is enhanced. This property reduces infiltration and can lead to accelerated runoff and erosion by wind and water (Doerr *et al.* 2000). The development of repellency during fire is attributed to the polymerisation of organic molecules into more hydrophobic ones (Giovannini & Lucchesi 1983), the improved bonding of such substances to soil grains (Savage 1974), and the melting and redistribution of waxes from interstitial organic matter onto soil aggregates and mineral grains (Franco *et al.* 2000). These temperatures are often achieved at the surface but it is only under severe burn conditions that temperatures of 200-300°C penetrate more than 2 cm depth (Chandler *et al.* 1983). A soil's water repellency status can become more complex during burning since repellency can be destroyed in the topsoil where a critical temperature of between 280-400°C (depending on heating duration) is exceeded. This has been observed and confirmed experimentally (e.g., DeBano 2000, Doerr *et al.* in press) and is attributed to the volatilization and combustion of organic compounds (DeBano *et al.* 1976, Chandler *et al.* 1983). In many Australian situations, soils already exhibit water repellency if long unburnt, such that fire may lead to its intensification, or its destruction in the topsoil, while repellency is enhanced a few mm to cm below the surface. Irrespective of the specific effects of fire on the location of the enhanced repellent layer, it is the combination of repellency with the removal of the protective vegetation and litter cover that can create a considerable erosion potential. Thus

measured erosion rates in the immediate post-fire period (6-12 months) are often an order of magnitude or more greater than for pre-fire or well recovered situations (e.g. Prosser & Williams 1998, Shakesby *et al.* 2003).

EFFECTS ON MINERALS USED AS TRACERS AND IN PROVENANCE STUDIES

The products of fire have proved useful as a means of tracing the origin and transport of sediment and provenance studies. The most visible effect of fire is on the production of copious amounts of charcoal, which eventually becomes incorporated into sediment and can be used for dating purposes and as an index of fire prevalence in the contributing catchment. However, there are other fire-induced changes to the soil mineral and organic constituents that can be used for the above purposes.

Magnetic enhancement of burnt soils

The most commonly occurring soil iron oxides are haematite, goethite, maghaemite and magnetite, and their nature and form within soil can be attributed to various environmental factors including fire (Maher 1988). Fire leads to changes in the properties of the magnetic minerals by forming an overprint of secondary minerals that can be distinguished from the primary magnetic signature of the host grain. Secondary overprinting also occurs via pedogenic and bacterial processes, but it is possible to separate these. At soil temperatures in excess of 400°C Fe-rich substrates, in the presence of a reducing agent such as organic matter, may generate large quantities of secondary magnetic minerals, especially very fine magnetite or maghaemite (e.g., Longworth *et al.* 1979, Rummery *et al.* 1979, Oldfield *et al.* 1981). These pyrogenic minerals generally take the form of ultra-fine superparamagnetic (SP) grains (magnetic grain size < 0.05 µm), viscous single domain grains (0.05 – 0.07 µm) and fine stable single domain (0.07 – 0.1 µm) grains, though it is the SP grain size that dominates. Fire, therefore, often leads to increases in magnetic susceptibility and saturation isothermal remanent magnetisation values (by up to three orders of magnitude) (Table 1). This enhancement is preserved in some lake sediments but it raises a particular paradox in fire-prone Australian landscapes, which according to this view might be expected to attain a uniform magnetic signature. Recent work in the Sydney area shows that this is not the case (Blake *et al.* *subm.*) although the underlying reasons have yet to be established.

Table 1: Fire induced new minerals and changes in mineral properties.

Mineral/material	Temperature	Product
haematite, goethite, maghaemite, and magnetite	>400°C	secondary magnetic mineralisation especially very fine magnetite or maghaemite
opal-phytolith	450-550°C	Refractive index increases from 1.427-1.440 (unburnt) to 1.427-1.487 (burnt)
wood-ash	400-750/815 °C	buetschliite (in wood-ash stone) and other carbonates but not calcinite which decomposes at 100-200°C
Ca-Ka carbonates (in wood-ash stone)	>750-815°C	carbonates decompose – wood ash forms oxides and silicates (if sufficient Si)
calcium oxalate (whewellite & weddellite)	430-510°C	calcite in plant cells

Phytoliths

Plant opal (SiO₂.nH₂O), or phytoliths, are freed from surrounding plant tissue during decomposition and especially by fire. In fire-prone parts of the Australian landscape burning is probably the most effective means of providing phytoliths as discrete particles to the soil surface, especially in forested landscapes. In grasslands fire is also effective although natural decay is probably equally effective, especially where fires are less regular. However, burning can hasten both the destruction of more fragile (platy) phytoliths and their removal in subsequent rainfall events and hence the characteristics of the assemblage changes between burnt and unburnt vegetation even though the species composition has remained the same (Hart 1997). Indeed it is likely that the magnitude of the change increases with fire severity. Again, this additional effect is likely to be more significant in forests than grasslands since the phytoliths in grass tend to be larger and more robust, and therefore more resistant to modification. Changes to the characteristics of the assemblage provides a challenging complication in using phytoliths to re-construct paleoenvironments. However, burning also increases the refractive index of phytoliths (Table 1) and this property makes it possible to distinguish between unburnt and burnt vegetation. This effect has been applied successfully to archaeological studies (Elbrum *et al.* 2003) but it has potential in regolith studies too.

PYRO-BIOMINERALISATION

Buetschliite and other wood-ash stone minerals

An unusual form of mineralisation may take place in the burning of trees in which carbonate stone is produced. Known as wood-ash stone or fused wood-ash stone it results from the combustion of wood and the fusion of mostly alkali and alkaline-earth metals. To date it has been reported from North America and Australia in a variety of conifers and angiosperms (Table 2), and in most cases it occurs within the trunks of trees that have slowly burnt downwards (Kienholz 1929). The resulting mass of stone, often in excess of 20 kg, is normally an off-white colour and may contain inclusions of charcoal. Often the cast of wood and flow structures are present (Figure 1). Apart from carbon and oxygen the main elements in stones are Ca and K with lesser and more variable amounts of Mn, Mg, Na and P, which matches the composition of wood-ash (Table 3). Calcite [CaCO_3] has been recorded in all samples subjected to mineralogical testing but rare potassium-calcium carbonates also occur. Buetschliite [$\text{K}_2\text{Ca}(\text{CO}_3)_2$] and kalcinite [KHCO_3] have been reported from North America (Milton & Axelrod 1947, Dietrich 1971). Australian samples exhibit appreciable calcite and in one sample a carbonate involving Na, K and Ca. In addition, Humphreys *et al.* (in press) report minor substitution of Mg /Fe in the calcite and the possible presence of dolomite and aragonite, small amounts of periclase (native magnesia, MgO) as well as quartz, which occurs mostly as sand-sized grains within infilled insect burrow features. The presence of buetschliite, calcite, portlandite [$\text{Ca}(\text{OH})_2$] and periclase has also been reported in furnace slag deposits where wood chips have been used as fuel providing that temperatures do not exceed about 750 °C (Mistra *et al.* 1993, Olanders & Steenari 1995) (Table 1). The same slag material heated to 1300°C revealed a variety of silicates in the presence of sufficient Si. Silicon may be uncommon in trees but is abundant in straw, another biofuel, where Si is most likely derived from opal phytolith.

Table 2: Trees known to yield wood-ash stone (all trees are from North America except for *A. costata*).

Conifers: <i>Abies concolor</i> (White Fir), <i>Abies grandis</i> (White Fir), <i>Abies procera</i> (Noble Fir), <i>Pseudotsuga taxifolia</i> (Douglas Fir), <i>Thuja plicata</i> (Western Red Cedar), <i>Tsuga heterophylla</i> (Western Hemlock), <i>Pinus monticola</i> (White Pine)
Deciduous angiosperms: <i>Betula</i> sp. (Birch), <i>Carya</i> sp. (Hickory), <i>Quercus prinus</i> (Chestnut oak)
Evergreen angiosperm: <i>Angophora costata</i> (Smooth-barked apple)

Table 3: Composition of wood-ash stones and tree wood.

	Australian ¹		North American ²	
	stone (n=4)	wood (n=4)	stone (n=5)	wood (n=1)
CaO	25.7-32.8	12.5-38.5	16.2-22.0	20.1
K ₂ O	2.5-13.3	7.8-35.4	23.6-40.4	34.9
MgO	7.6-13.1	5.3-9.6	0.51-6.3	10.4
Na ₂ O	0.72-2.60	1.09-5.9	1.8-10.7	8.0
SiO ₂	1.05-28.2	nd	0.32-0.43	
Al ₂ O ₃	0.16-1.24	nd	0.19-0.34	4.4
Fe ₂ O ₃	0.08-0.21	0.33-0.81	0.15-1.68	nd
P ₂ O ₅	0.08-0.52	0.03-5.32	1.96-7.0	10.5
MnO	0.06-0.33	nd	0.22-6.7	nd
TiO ₂	0.01-0.32	nd	nd	nd
S	0.02-0.08	nd	tr -0.28	nd
CO ₂	nd	nd	19.7-35.3	nd
LOI	31.6-49.6	nd	nd	nd
Total	99.8-100.9			

¹Humphreys *et al.* 1987 & in press; ²Englis & Day 1929; Milton & Axelrod 1947; Dietrich 1971. nd = no data

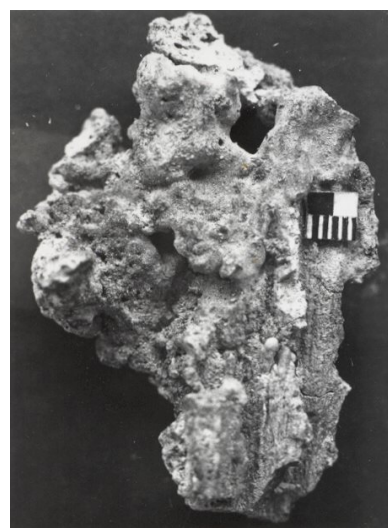


Figure 1: Wood-ash stone. Note wood impression on right side. Bar scale 1 cm

Weddellite / whewellite to calcite

Calcium oxalate is a very common salt in plants (Franceschi & Horner 1980). It is thought that oxalate, an end product of photosynthesis, is rendered harmless by combining with calcium to form insoluble monoclinic monohydrate whewellite ($\text{CaC}_2\text{O}_4 \cdot \text{H}_2\text{O}$) or tetragonal dihydrate weddellite ($\text{CaC}_2\text{O}_4 \cdot 2\text{H}_2\text{O}$). In contrast, oxalates formed with other common plant alkali metals (Na, K etc.) are soluble. Pyrolysis of calcium oxalate

crystals leads to the formation of calcium carbonate (Table 1), a transition that occurs at temperatures of 430-510°C (Podequin 1943) with the transposed crystals exhibiting a micritic microstructure (Bouchier & Thinon 2003). This transformation is expected to occur in burning wood but the calcite is unlikely to survive hot fires.

Other examples of plant calcite

Apart from calcium oxalate many plants contain micro-crystals of calcite that develop without any involvement of fire (Franceschi & Horner 1980). Presumably these crystals are released into the soil upon plant decay or during low temperature burning, though none have been detected. Also, their small size renders them very susceptible to leaching. Calcite is also known to form around the injured parts of some tropical trees especially *Chlorophora excelsa* and *Millettia* sp (Harris 1933). In the case of *C. excelsa* the injury may be caused by fire. The calcite appears to precipitate from a gel that oozes from the injured tissue resulting in large, partly rounded masses protruding into any central cavity of the tree and weighing several kilograms and more. The gel may penetrate surrounding regolith as Carozzi (1967) reports the occurrence of a calcite cemented quartz sandstone at the base of *C. excelsa* growing on sandy granitic regolith.

Fired clay

Fallen burnt tree trunks often reveal a central core of baked soil. This soil originates as infill deposited by termites, such as *Coptotermes* sps in south-east Australia. The baked soil is typically crumbly, white to orange in colour and consists of clay with variable amounts of finer quartz sand that sometimes resembles fired pottery fragments. This material has yet to be investigated but it may appear in soil and sediments. Perhaps some of the papules (terminology of Brewer 1964) in topsoils are derived this way.

Secondary fused rock and silica-glass

Baker & Gaskin (1946) report examples of trachyte and basalt with smooth glassy surfaces, inclusions of carbonised wood and impressions of wood tissue. The basalt examples were found within and at the base of a burnt tree, which indicates that the required secondary phase of partial fusion occurs during bushfires. In addition fired haystacks can yield silica-glass (straw-silica) fragments that in appearance resemble other silica glass such as fulgurites and tektites but differ in the lower silica but higher RO and R₂O content (Milton & Davidson 1946). Other examples of silica-glass from Macedon and also Darwin glass are attributed to burning trees by Baker & Gaskin (1946) but the low content of silica in most trees makes this unlikely. An alternative source is the clay and sand mix deposited in trees by termites as noted above.

SUMMARY

Fire imposes both direct and indirect effects on the regolith. Direct effects include enhanced mineral magnetic properties, the development of new minerals and the transformation of existing ones. The development of wood-ash stone, though rare, provides an excellent example. Secondary effects include reduction of protective ground cover and the development, enhancement and/or translocation of soil water repellency, which may influence hydrological response, resulting in increased runoff and erosion potential. In addition fire releases copious amounts of charcoal and phytoliths that are useful in paleoenvironmental studies.

REFERENCES

- ADAMSON D., SELKIRK P. & MITCHELL P. 1983. Fire, lyrebirds and landscape in the Sydney Region. *In*: YOUNG R. & NANSON G. eds. *Aspects of Australian Sandstone Landscapes* Aust. & NZ Geomorph. Group Spec. Publ. No. 1, 81-93.
- BAKER G & GASKIN A.J. 1946. Natural glass from Macedon, Victoria, and its relationships to other natural glasses. *J. Geology* **54**, 88-104.
- BLAKE W.H., WALLBRINK P.J., DOERR S.H., HUMPHREYS G.S. & SHAKESBY R.A. subm. The extent and nature of magnetic enhancement in burnt topsoil and its potential for sediment-source ascription in reservoir catchments, Australia. *Earth Surface Processes & Landforms*.
- BREWER R. 1964. *Fabric and mineral analysis of soils*. J Wiley & Sons, New York.
- BROCHIER J.É. & THINON M. 2003. Calcite crystals, starch grains aggregates or ... POOC? Comment on "Calcite crystals inside archaeological plant tissues". *Journal Archaeological Science* **30**, 1211-14.
- CHANDLER C., CHENEY P., THOMAS P., TRABAUD L. & WILLIAMS D. 1983. Fire effects on soil, water and air. *In*: *Fire in Forestry. I. Forest Fire Behaviour and Effects* (Wiley & Sons, New Jersey).
- CAROZZI A.V. 1967. Recent calcite-cemented sandstone generated by the equatorial tree Iroko (*Chlorophora excelsa*), Daloa, Ivory Coast. *J. Sediment. Petrol.* **37**, 597-600
- DEBANO L.F. 2000. The role of fire and soil heating on water repellency in wildland environments: a review. *Journal of Hydrology* **231-232**, 195-206.

- DEBANO L.F., SAVAGE S.M. & HAMILTON D.A. 1976. The transfer of heat and hydrophobic substances during burning. *Soil Science Society of America Journal* **40**, 779-782.
- DIETRICH R.V. 1971. An occurrence of buetschliite east of the Rocky Mountains. *Min Records* **2**, 130-132.
- DOERR S.H., SHAKESBY R.A. & WALSH R.P.D. 2000. Soil hydrophobicity: its causes, characteristics and hydro-geomorphological significance. *Earth Science Reviews* **51**, 33-65.
- ELBRAUM R., WEINER S., ROSA M.A. & ELBRAUM M. 2003. Detection of burning of plant materials in the archaeological record by changes in the refractive indices of siliceous phytoliths. *J Archae Sci* **30**, 217-226.
- ENGLIS D.T. & DAY W.M. 1929. The composition of peculiar clinkers found in snags after forest fires. *Science* **69**, 605-606.
- FRANCESCHI V.R. & HORNER H.T. 1980. Calcium oxalate crystals in plants. *Botanical Review* **46**, 361-427.
- GIOVANNINI G. 1992. The effect of fire on soil quality-physical and chemical aspects. In: Eftichidis G. & Fantechi R. eds. *Forest Fire Risk and Management*. Proceedings of the European School of Climatology and Natural Hazards Course. European Commission, Brussels, 241-278.
- GIOVANNINI G. & LUCCHESI S. 1983. Effect of fire on hydrophobic and cementing substances of soil aggregates. *Soil Science* **136**, 231-236.
- HARRIS C.M. 1933. Stone in *Chlorophora excelsa* B and H, Iroko. *Empire Forestry Journal* **12**, 229-238.
- HART D.M. 1997. Phytoliths and fire in the Sydney Basin, New South Wales, Australia. In: Pinilla A., Juan-Tresserras J. & Machado M.J. eds. *The state-of-the-art of phytoliths in soils and plants*. CSIC Monographs **4**, 101-110.
- HUMPHREYS G.S., HUNT P.A. & BUCHANAN R. 1987. Fused wood-ash stone near Sydney, NSW; an example of an unusual bio-pedological process. *Australian Journal of Soil Research* **25**, 115-124.
- HUMPHREYS G.S., RAVEN M.D. & FIELD R.J. in press. Wood-ash stone in *Angophora costata* (Gaertn.) J. Britt. following Sydney bushfires. *Australian Forestry*.
- KIENHOLZ R. 1929. On the occurrence of rock-like clinkers in burning snags. *J. of Forestry* **27**, 527-531.
- LONGWORTH G., BECKER L.W., THOMPSON R., OLDFIELD F., DEARING J.A. & RUMMERY T.A. 1979. Mossbauer and magnetic studies of secondary iron oxides in soils. *J. Soil Science* **30**, 93-110.
- MAHER B. 1986. Characterisation of soils by mineral magnetic measurements. *Physics of the Earth and planetary interiors*, **42**, 76-92.
- MILTON C. & AXELROD J. 1947. Fused wood-ash stones: fairchildite (n.sp.) $K_2CO_3 \cdot CaCO_3$, buetschliite (n.sp.) $3K_2CaCO_3 \cdot 6H_2O$, and calcite $CaCO_3$, their essential components. *Amer Miner* **32**, 607-624.
- MILTON C. & DAVIDSON N. 1946. Note on straw-silica glass from California. *Amer Miner* **31**, 495-498.
- MISRA M.K., RAGLAND K.W. & BAKER A.J. 1993. Wood ash composition as a function of furnace temperature. *Biomass and Bioenergy* **4**, 103-116.
- NEARY D.G., KLOPATEK C.C., DEBANO L.F. & FFOLIOTT P.F. 1999. Fire effects on belowground sustainability: a review and synthesis. *Forest Ecology and Management* **122**, 51-71.
- OLANDERS B. & STEENARI B-M. 1995. Characterization of ashes from wood and straw. *Biomass & Bioenergy* **8**, 105-115.
- OLDFIELD F., THOMPSON R. & DICKSON D.P.E. 1981. Artificial enhancement of stream bedload: a hydrological application of superparamagnetism. *Physics of the Earth and Plan Inter* **26**, 107-124.
- POBEQUIN T. 1943. Les oxaltes de calcium chez quelques angiospermes. *Annales des Sciences, Naturelles, Botanique*, 1^{ème} série **4**, 1-95.
- PROSSER I.P. & WILLIAMS L. 1998. The effect of wildfire on runoff and erosion in native *Eucalyptus* forest. *Hydrological Processes* **12**, 251-265.
- RUMMERY T.A., BLOEMENDAL J., DEARING J. & OLDFIELD F. 1979. The persistence of fire-induced magnetic oxides in soils and lake sediments. *Ann. Geophys.* **35**, 103-107.
- SHAKESBY R.A., CHAFER C., DOERR S.H., BLAKE W.H., WALLBRINK P., HUMPHREYS G.S., HARRINGTON B.A. 2003. Fire severity, water repellency characteristics and hydrogeomorphological changes following the Christmas 2001 Sydney forest fires. *Australian Geographer* **34**, 147-175.
- VAN DER BEEK P., PULFORD A. & BRAUN J. 2001. Cenozoic landscape development in the Blue Mountains (SE Australia): lithological and tectonic controls on rifted margin morphology. *J. Geol.* **109**, 35-56.