

Dating of coal fires in Xinjiang, north-west China

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ABSTRACT

Coal fires in China consume vast amounts of fuel and cause serious environmental problems. Most of these coal fires are related to mining activity. However, naturally produced palaeo coal fires in Xinjiang, north-west China, have been recognized via burnt rocks. The burnt rocks in the study area are found at different river terraces underlying unburnt alluvial and river terrace deposits. Several age groups of coal fires have been identified based on the positions of burnt rocks at river terraces and the relationship between the burnt rocks and the terrace

deposits. These palaeo coal fires are: (1) Pliocene – Early Quaternary in age at 200 m above present river terrace deposits; (2) Middle Pleistocene in age, at >90 m; (3) Late Pleistocene, at 90–70 m; (4) Holocene; (5) burnt rocks relating to active coal fires. Palaeomagnetic data of the burnt rocks from different terraces give normal remanent magnetization and help further to constrain the ages of the coal fires.

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Introduction

Coal fires are one of the most serious problems for the Chinese coal industry. The estimated annual loss of coal by fires in China ranges from about 10–20 million tonnes (Guan *et al.*, 1998) to 100–200 million tonnes (Schalke *et al.*, 1993; Cassells and Van Genderen, 1995). Besides the huge loss of coal resources and mining safety, coal fires cause considerable environmental problems, such as air pollution and land degradation. Coal fires have a global impact as well; the emission of CO₂ might contribute considerably to the increase in greenhouse gases in the atmosphere. If the latter estimate for annual loss of coal is correct, CO₂ emission by coal fires in China would account for 2–3% of the world CO₂ output from the burning of fossil fuels for the year 1992 (Cassells and Van Genderen, 1995).

Active coal fires in China are usually related to mining activity; however, the direct cause of the coal fires is essentially spontaneous combustion. Spontaneous combustion is a process of oxidation of coal in which the temperature of the coal increases until a fire starts. Fires can also start at surface outcrops as a result of natural processes such as forest fires, lightning or even solar heating. Exposure of the coal seam is essential for these types of

coal fire. Several geological processes, such as faulting, folding and erosion by river action, can bring the coal to the surface thus lead to coal fires. In our study area, coal fires have repeatedly occurred because of river down-cutting and exposure of coal seams. The cap rocks and sediments enclosing the seams have been greatly altered thermally by the coal fires. These thermally altered rocks (burnt rocks) indicate that the palaeo coal fires occurred during geological history. The ages of the palaeo coal fires can be constrained from the ages of the river denudation that exposed the coal seam and from the terrace deposits overlying the burnt rocks. The temperature of the burnt rocks is believed to have exceeded the Curie point (Guan, 1963) and hence they record the geomagnetic direction of that point in time. Ten orientated specimens of burnt rock from different age groups were collected and examined in the laboratory. The palaeomagnetic data provide further constraints on the absolute ages of the coal fires. Our study shows that coal fires have repeatedly occurred since the Pliocene and that most of the burnt rocks are of Pleistocene age.

Geological setting

The Toutunhe study area is situated 30 km south-west of Urumqi, the capital city of Xinjiang, China, in the transition zone between the Tianshan mountain range and the Junggar basin, at an altitude of 1000–1400 m. It is crossed by the Toutunhe river,

which is fed by the glaciers of the Tianshan Mountains and by its tributary rivers the Qianshuihe, Gangou and Haojiagou (Fig. 1).

The core of the E–W-trending Tianshan Mountain range consists of pre-Mesozoic basement rocks (Peng and Zhang, 1989; BGXJ, 1993; Carroll *et al.*, 1995). On the northern side of the Tianshan, Mesozoic and Cenozoic sedimentary rocks have been detached from the underlying pre-Mesozoic rocks and folded into three lines of E–W-trending anticlines and synclines. The Kelazha anticline in the study area is situated in the first line, with Jurassic strata forming the core of the folds. Unfolded Pliocene sediments unconformably cover the Jurassic and Cretaceous rocks. The main coal-bearing strata that have burnt out belong to the Middle Jurassic Xishanyao Group, which consists of freshwater deltaic sediments (BGXJ, 1993; Schneider, 1996). The coal layers are concentrated in the lower parts of the Xishanyao Group, with thickness varying from 1 to 27 m. The lowest mineable layer is the Dacao coal layer, with a constant thickness of 15–17 m.

The Toutunhe river dissects the folded Jurassic rocks and has a flight of at least six river terraces in the valley (Fig. 2; Huang and Zhao, 1981; Qiao, 1981; Molnar *et al.*, 1994). The uppermost terraces are situated about 90 m above the river, the lowermost one about 15 m above the present river level. The other terraces are situated between these, with a regular height interval of about 10–15 m. Most of the terraces are cut into

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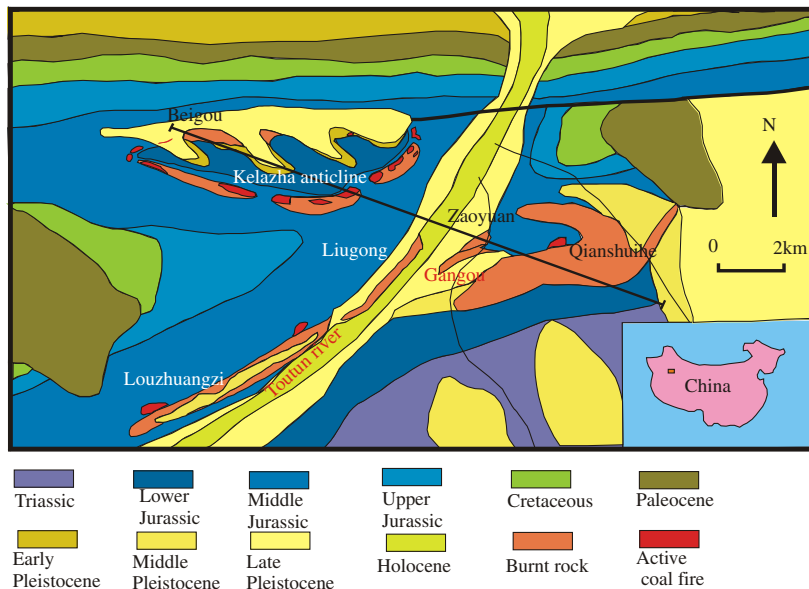


Fig. 1 Geological map of the study area with distribution of burnt rocks and active coal fires. The straight line from Beigou to Qianshuihe indicates the location of the section shown in Fig. 2.

bedrock and capped by 1–3 m of coarse gravel.

Field characteristics of burnt rocks

Burnt rock (pyrometamorphosed rock) is a general term for thermally metamorphosed rocks (Tyráček, 1994)

originating from heating by burning coal seams. Burnt rocks can be classified according to characteristics such as colour, texture, structure and metamorphic temperatures (Guan, 1963). In a scarp-slope exposure of slightly dipping burnt rocks, a characteristic three-layer profile is developed. (1) At

the bottom are the unburnt rocks underlying the coal seams. Nearing the contact with the burnt coal seam, the rocks become gradually baked in appearance; in mudstones this is obvious from the brick-red colour, ceramic character and sound, and sometimes with a characteristic millimetre-sized six-sided columnar structure ('chopstick rock') caused by shrinkage joints arranged in a sheaf-like pattern, like jointing in basaltic lava flows. Locally, the presence of a characteristic hardened kaolin layer (baked under clay) seems to have acted as an insulator, thus protecting the underlying rocks from baking. Sandstones appear less affected by baking alone. (2) The coal seam itself has been reduced to a thin ash layer of only a few centimetres thickness, often rich in gypsum. (3) Above the ash layer the roof of the coal seam has usually collapsed, resulting in a breccia-like structure. As the temperature of coal fires usually increases upwards as a result of increased oxygen supply, these rocks are also partially molten: between the partly molten fragments of collapsed roof rocks, a dark vesicular glassy matrix is often found, sometimes with microflow structures as in ropy lavas. Loess overlying burnt rock may have been baked to brick-like substances. The maximum thickness of the burnt

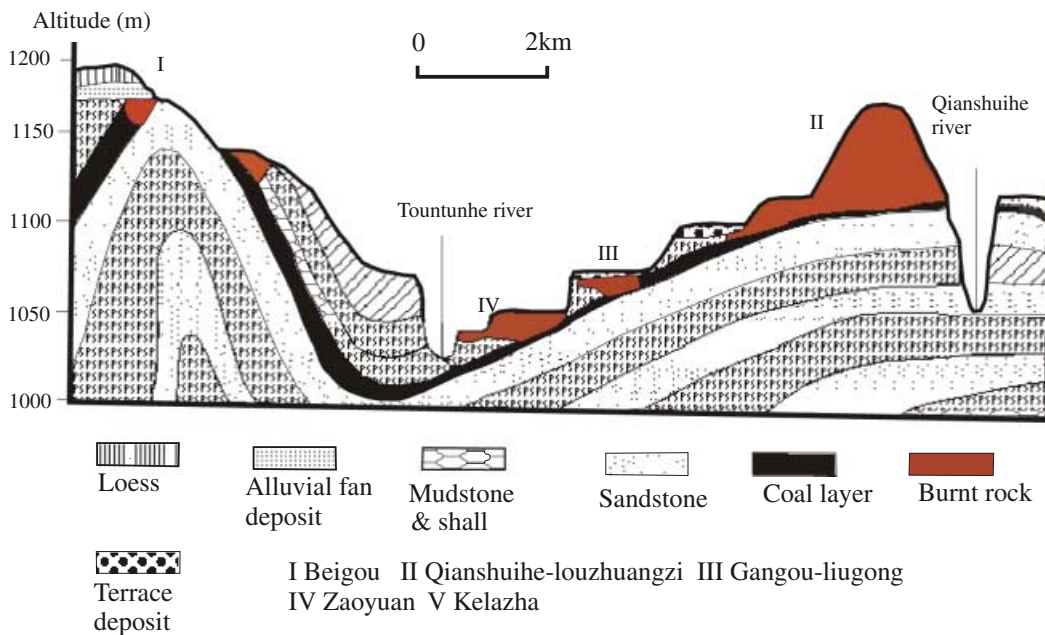


Fig. 2 Cross-section (from Beigou to Qianshuihe) of Tountunhe river terraces and burnt rock occurrences.

rocks in the study area is about 100–150 m. The reddish–yellowish colour enables unequivocal identification of burnt rocks from remote sensing imagery. Hence burnt rocks are usually used as an indicator of underground coal fires (Kang, 1991; Zhang *et al.*, 1999, 2003).

River terraces and dating of palaeo coal fires

The outcrop conditions of the palaeo coal fires in our study area are intimately related to the development of different river terraces (Fig. 2). The relative age of the palaeo coal fires can be distinguished according to their positions at different terraces and the relation between the burnt rocks and terrace deposits. A general age classification of the terrace deposits spanning the whole Quaternary has been obtained by correlation with morainic stages in the Tian Shan Mountains in the upper reaches of the Toutunhe rivers (Bo, 1981; Qiao, 1981; BGXJ, 1993). Five age groups of burnt rocks have been recognized in this area:

(1) The Beigou burnt rocks occur at an unconformity between steeply dipping Jurassic coals and black shales and unbaked deposits of a dissected alluvial fan, 200 m above the level of the Beigou tributary of the Toutunhe river. The alluvial fan could be Late Pliocene or Early Pleistocene age (Q1 high terrace, in Chinese terminology, 0.7–2 Ma). These deposits might correspond to the Xiyu Formation, exposures of which elsewhere have produced abundant Late Pliocene fauna have been found, and which is generally associated with the inception of glaciation (Qiao, 1981; Molnar *et al.*, 1994). Because the alluvial fan deposits are not baked, the coal fires occurred before deposition of these sediments.

(2) In the Qianshuihe–Louzhuangzi area a classic profile of burnt rocks shows 20 m of molten scoriaceous breccias on top of a burnt-out Dacao coal layer, in turn underlain by a baked kaolin ('porcellanite') layer, possibly of volcanic ash origin. Their position in the field suggests them to be older than the 90-m terrace nearby, as the deposits are in contact with the burnt rock and show no signs of baking. A similar situation is found in the south-western part of the area

near Louzhuangzi along the western side of the Toutunhe river. The Qianshuihe and Louzhuangzi 90-m terraces are fluvio-glacial in origin, and of Middle Pleistocene age (Q2, 0.7–0.1 Ma). The only published 'age' control comes from a specimen of *Palaeoloxodon*, a fossil elephant (now generally included in the genus *Elephas*; Nilsson, 1983) in the Middle Pleistocene gravels at Yaomoushan, about 15 km east of the study area (Qiao, 1981).

(3) Along the lowermost reach of the Gangou tributary of the Toutunhe river, 15–20 m of burnt rocks, molten breccias and small lava-like glassy flows are overlain by unbaked gravel in a 70-m terrace of the Toutunhe river (Figs 2 and 3). The burnt rocks contain strongly deformed, molten and baked pebbles derived from an older cover of terrace gravel deposited prior to the coal fire, probably from the collapsed roof of the 90-m terrace. The Gangou 70-m fluvio-glacial terrace is estimated by Qiao (1981) to be of Late Pleistocene age (Q3, 100–10 ka).

(4) The Zaoyuan burnt rocks lie on the first and second terrace of the Toutunhe river (Fig. 2). Terrace deposits such as pebbles on top of the burnt rocks are completely baked, and are even partially molten. No unbaked sediments are present above these. The Zaoyuan coal fires are probably of Holocene age (Q4, < 10 ka).

(5) The Kelazha burnt rocks are directly related to active coal fires. These burnt rocks occur above,

around or close to the active coal fires. These are the only burnt rocks that are revealed by thermal infra-red imagery. In the field these rocks differ in a number of aspects from the rocks of the palaeo coal fires. No complete sections can be seen, as most fires are ongoing below the ground surface. Characteristically these rocks differ in their surface mineralogy as related to temperatures at the vents, as measured with the thermal radiometer in the field (Zhang *et al.*, 1997, 2003). On a horizontal surface, coal fire vents below 80–90 °C have a halo around them consisting of tarry substances mixed with sulphur. Between 90 and 120 °C the halo consists of native sulphur alone, and above 120 °C, which is above the sublimation point of sulphur, white linings of salmiac can be found. None of these materials has thus far been found in palaeo coal fire rocks.

Palaeomagnetic dating of coal fires

Palaeomagnetic measurements were carried out on rock samples collected in the field to constrain the age estimates of the coal fires magnetostratigraphically. The characteristic remanent magnetization (ChRM) of the samples was determined to obtain their magnetic polarity. The magnetic polarity pattern of the burnt rocks can then be correlated with the geomagnetic polarity time-scale (Fig. 4), which is constructed based on irregular reversals of the Earth's

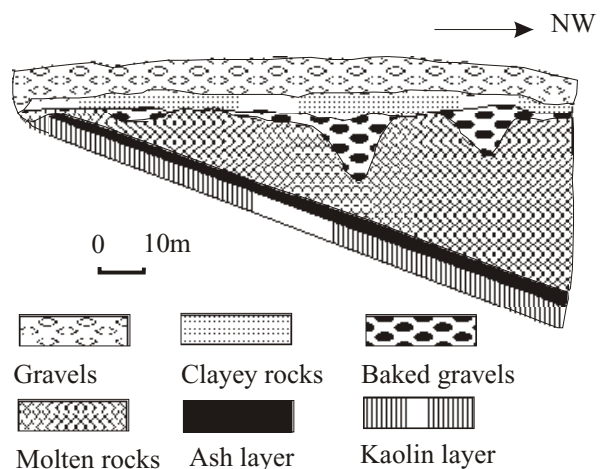


Fig. 3 Gangou burnt rock profile. Note the coal fires occurred before the terrace deposits.

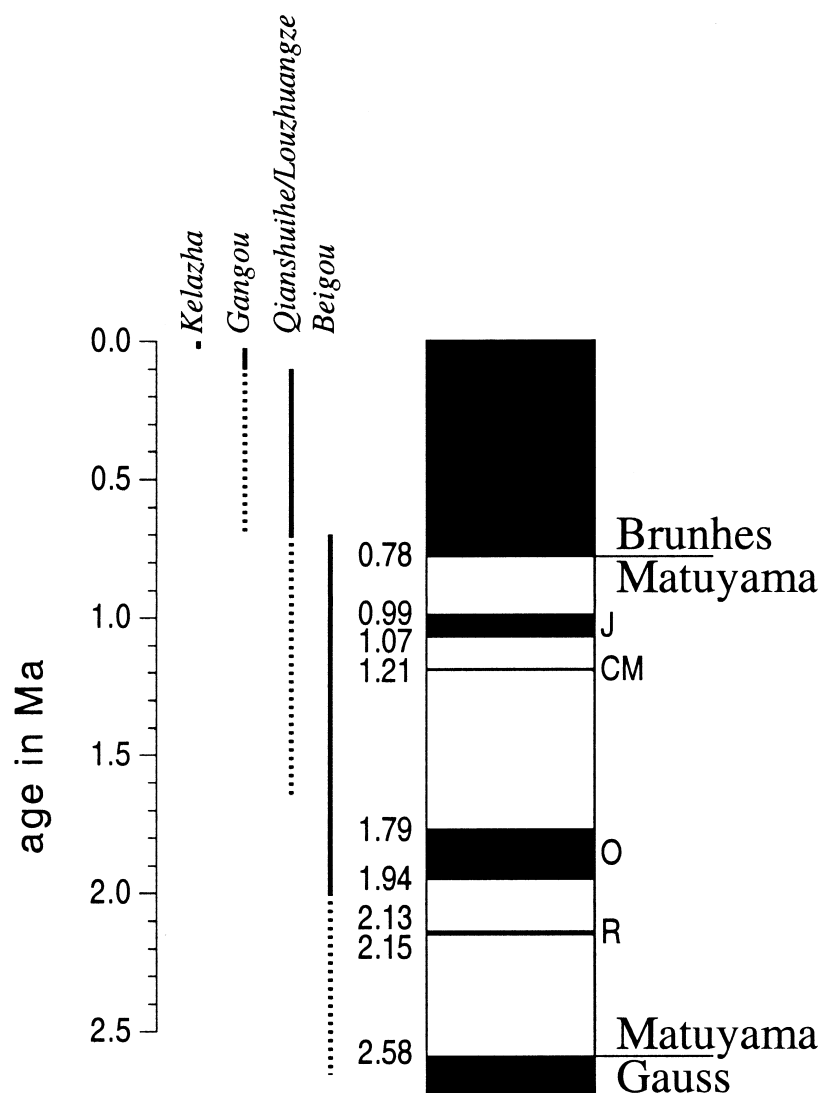


Fig. 4 Geomagnetic polarity timescale of the late Pliocene to Holocene according to Lourens *et al.* (1996). Black (white) blocks denote periods with normal (reversed) directions of the geomagnetic field. J: Jaramillo; CM: Cobb Mountain; O: Olduvai; R: Reunion. Vertical lines represent the age estimates based on stratigraphy.

magnetic field. This method has been used successfully in dating porcellanities from the North Bohemian Coal Basins (Tyráček, 1994).

Ten orientated hand samples were taken in the field: two from each of the Beigou, Qianshuihe–Louzhuangzi and Kelazha groups, and four from the Gangou–Liugong group. From each hand sample, one core (diameter of 25 mm) was drilled in the laboratory; several specimens with a length of 22 mm were cut from each core. At least one of the specimens was stepwise demagnetized with alternating magnetic fields. All cores showed normal

ChRM directions (Fig. 5). The directions of the ChRM in these burnt rocks may well have resulted from a thermomagnetic remanent magnetization (TRM) acquired at the time of final cooling. The pyrometamorphosed rocks of the Xinjiang region, in particular the breccia-type rocks above the burnt coal seams, show field evidence of having reached temperatures well above 770 °C, i.e. higher than the Curie points (T_C) of all magnetic minerals. On cooling below their T_C , magnetic minerals acquire a magnetization parallel to the ambient geomagnetic field. If the measured remanence is indeed a

primary TRM, it implies that the sampled rocks all cooled during a normal period of the geomagnetic field.

On the basis of the general stratigraphy outlined above, normal directions of the ChRM are expected for the samples from the Holocene (< 10 ka) Kelazha group and the middle to late Pleistocene (0.7–0.01 Ma) Gangou–Liugong group, because these groups of burnt rocks are younger than the beginning of the last normal polarity interval (Brunhes Chron: 0–0.780 Ma). The normal polarities of the relatively older Qianshuihe–Louzhuangzi and Beigou groups yield various options for their palaeomagnetic age: slightly younger than 0.780 Ma (beginning of the normal Brunhes Chron), between 0.990 and 1.070 Ma (Jaramillo subchron) or 1.21 Ma (Cobb Mountain cryptochron). Older options for the burnt rocks from the Beigou group are the normal polarity intervals recorded during the late Pliocene: Olduvai subchron (1.785 and 1.942 Ma), Reunion subchron (2.129–2.149 Ma) and the end of the normal Gauss Chron (≥ 2.582 Ma) (Lourens *et al.*, 1996).

The significance of these palaeomagnetic dates for the end of the coal fires, however, must be regarded with some caution. Trace amounts of native iron ($T_C = 770$ °C), especially in the Kelazha and Gangou–Liugong samples, were detected during thermomagnetic runs on a Curie balance (Fig. 6; de Boer *et al.*, 1998). A remanence carried by metallic iron is magnetically not particularly stable, and thus the observed magnetization is more likely to be the result of viscous resetting. Viscous magnetizations conform to new field conditions in a relatively short time, up to about 10 000 years. This suggests that the measured normal directions of the ChRM were acquired recently instead of representing a primary TRM. Moreover, native iron is thermodynamically metastable; it usually progressively oxidizes to magnetite (Fe_3O_4), maghaemite ($\gamma\text{-Fe}_2\text{O}_3$) and haematite ($\alpha\text{-Fe}_2\text{O}_3$). Because the much more stable ChRM of the older Qianshuihe–Louzhuangzi and Beigou groups is carried by these iron oxides, they may have recorded oxidation during a normal polarity interval any time after burning, rather than expressing a primary TRM.

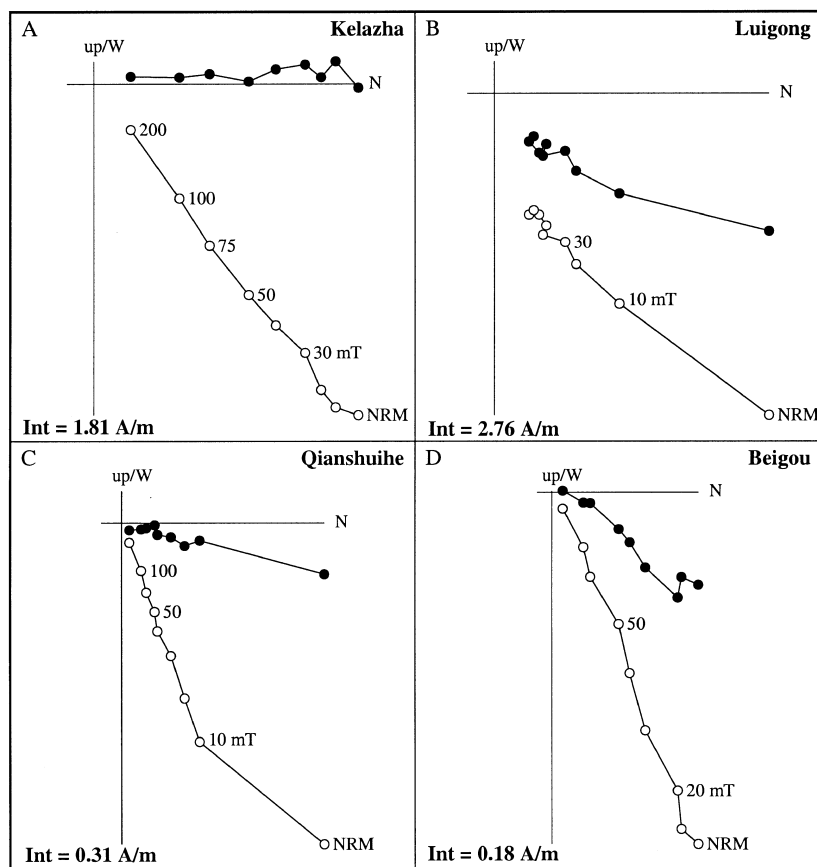


Fig. 5 Examples of alternating field demagnetization diagrams for samples of the burnt rock groups from the Xinjiang region, showing their normal polarity. Closed (open) symbols represent the projection of the NRM vector end-points on the horizontal (vertical) plane, respectively; values represent alternating fields in mT. Int = initial NRM intensity.

Discussions and implications

The combined remote sensing and field data show that coal fires have occurred in the area for a large part of the Pleistocene. Under natural conditions a coal fire can start wherever a coal seam crops out near the surface. Natural exposure of coal seams can be caused by processes such as faulting, folding and denudation or valley incision by streams. Once exposed, spontaneous combustion can start, as this is an exothermic oxidation process as soon as a certain threshold temperature is surpassed (Banerjee, 1985). Under natural conditions the threshold temperature for specific types of coal can be exceeded by forest fires, lightning and even by solar heating for favourably exposed coal seams.

In the study area the process that led to exposure of the coal seam is intimately related to the formation of

river terraces from the Pliocene onward. Using ¹⁰Be exposure age dating of deformed river terraces in the uplifting Kuitun He and Qiurgou He valleys nearby, Molnar *et al.* (1994) concluded that cyclivity in terrace deposition and dissection is probably tuned to the 100-kyr cyclicality of global climate change. This is consistent with modelling studies on terrace formation (Boll *et al.*, 1988; Veldkamp and Vermeulen, 1989; Veldkamp, 1992).

Taking this into account, and based on the Plio-Pleistocene age of the Beigou terrace at 200 m, terrace steps at 10–15-m intervals would indeed coincide with the major 100-kyr global climate cycles. It would imply as well that the 70 m Gangou/Liugong terraces are around 700 kyr old, i.e. considerably older than traditionally considered in Chinese Quaternary stratigraphy (Qiao, 1981). Uplift rates here are a factor of ten lower than in

the area studied by Molnar *et al.* (1994), and more in line with the uplift rate of 0.1 mm yr⁻¹ considered optimal for river terrace formation (Veldkamp and Van Dijke, 1998).

Terrace deposition probably took place during arid glacial periods and early deglaciation, while dissection predominated in the interglacials. Exposure of coal seams and concomitant spontaneous combustion of coal seams therefore must be largely an interglacial phenomenon.

Implications

The coal fires in north-west China, as well as in other places such as in India, have been studied for more than a decade using remote sensing data acquired from optical, thermal infrared or the short-wave wavelength of the electromagnetism spectrum. Detection of the coal fire relies on picking up one either the reflectance, temperature anomalies, surface cracks or subsidence of associated with the fire (Zhang *et al.*, 1999, 2003; Prakash *et al.*, 2001). Among these remote sensing detection indicators, burnt rocks are the most important, and these can be easily recognized from remote sensing acquired in the optical wavelength. In addition, the optical remote sensing data are usually of higher spatial resolution. Hence optical remote sensing has been normally used to delineate the boundaries of the coal fires. This research shows, however, that many of the burnt rock areas are palaeo coal fires. Distinguishing between palaeo coal fires and present active coal fires is necessary to estimate their current environmental impacts.

Conclusions

- 1 Spontaneous combustion of coal seams is a natural phenomenon that has occurred repeatedly during the recent geological past. It can occur at any site where deformation, uplift and dissection have exposed coal to the air. Spontaneous coal fires are especially likely to occur during interglacial dissection of river valleys at moderate uplift rates.
- 2 A large part of the burnt rocks identified from remote sensing imagery and in the field in the study area appears to be of Pleistocene

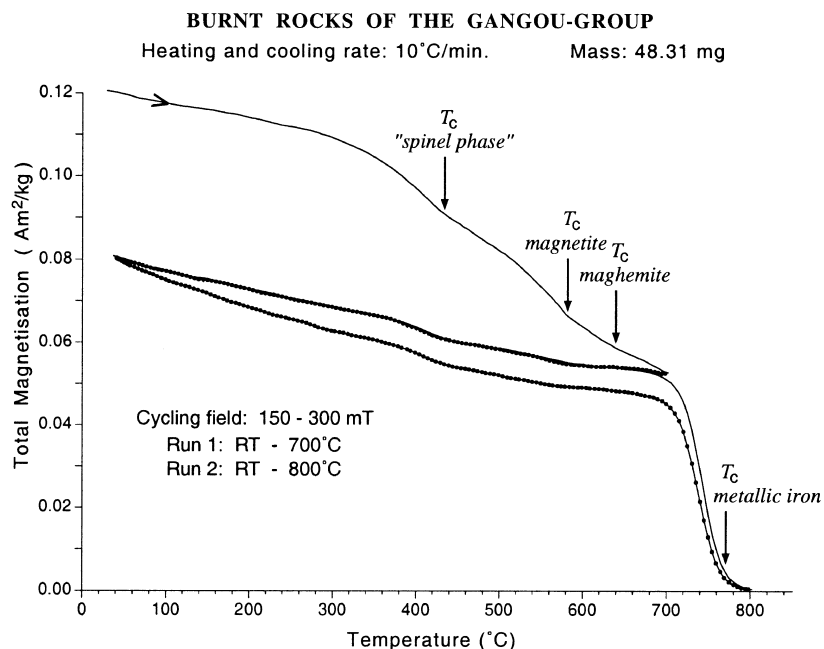


Fig. 6 Example showing a typical thermomagnetic analysis of burnt rocks from the Gangou group, clearly indicating the presence of metallic iron ($T_C = 770^\circ\text{C}$). Minor inflection points around 440, 580 and 640 °C suggest the presence of a magnetic spinel phase, magnetite and maghaematite, respectively.

age. Care needs to be exercised when delineating active coal fire areas using burnt rocks as an indicator from remote sensing data to avoid overestimating the contribution of coal fires to the global CO_2 budget.

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