Remote thermal infrared surveying to detect abandoned mineshafts in former mining areas

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Abstract
In former mining areas it is critical to locate unknown, abandoned mineshafts prior to the development of a site. Abandoned mineshafts are ground disturbances that have very localised effects on the morphology, physical, chemical, drainage and moisture properties of the surface geological materials and thus thermo-physical properties. Remotely sensed thermal infrared surveys provide the potential for a rapid, inexpensive and non-intrusive technique for mineshaft detection. The key parameters of thermal infra-red radiation and the application of remote thermal infra-red surveys to planning are described, using case histories from former mining areas in Lancashire, Yorkshire and Nottinghamshire. Field-measured infrared temperature differences correlated well with different ground conditions caused by changes in vegetation, disturbance, compaction and moisture-drainage regimes. A thermal anomaly over an area of approximately 6 m^2 above a known mineshaft was characterised by traces of methane and increased temperatures of between 0.5 ^{o}C to 1 ^{o}C in comparison to the adjacent ground surface. Using thermal infrared images, collected with the Daedalus 1260 Airborne Thematic Mapper, a scheme was developed to classify and map mineshafts with and without any observed visual characteristics. When applied using commercially flown thermal imagery the scheme identified several potential sites of abandoned mineshafts in an area designated for the redevelopment of the Nottingham Business Park, East Midlands. The thermal anomalies were associated with minor topographic features such as mounds, depressions, dereliction and also, compositional features caused by coal enrichment and coal-measures mudstone infill. These features had very little surface expression and were only confirmed using soil stripping.

Introduction
Mining has been practised in the British Isles since pre-historic times and has been a significant industry for several centuries. Records indicate up to 170,000 mine entries have been known to have existed within the UK. It has been estimated that a further 150,000 mine entries may exist, many of which have since infilled (Caunt 2008), however, many of their locations are either unknown or inaccurate (Gunn *et al.* 2004). They can represent a significant environmental hazard, in the worse cases, posing the danger of collapse as well as the potential to leak noxious gases and acid mine waters. The benefits of detecting mineshafts before they are disturbed by construction or during site development are twofold: safety is increased and costs are reduced. No definitive technique exists that can reliably detect all such mineshafts. Geophysical techniques can be employed with some success, but they are not always effective and some professionals lack confidence in them. They also involve extensive ground surveying, which can be time consuming and expensive. Drilling and trenching can also be used but, as well as time and expense, this approach involves disruption to the ground under study and safety issues. The need for rapid, cost effective and non-intrusive techniques is clear.

Remote sensing techniques have been employed in several other aspects of geoscience to investigate large areas quickly, with a reduced reliance on field techniques (Sabins 1978; Lillesand & Keifer 1987). They are certainly rapid and are inexpensive when compared to extensive ground surveys. As they involve no contact with the matter under study they leave the site undisturbed. To realise the wider potential of remote sensing for the detection of mineshafts it is necessary to identify a characteristic that they exhibit which can be observed or recorded from an aircraft or satellite. Mineshafts with a clear surface expression can be recognised in aerial photographs, but do not form the target of this study. Abandoned mineshafts with no obvious surface expression require a different approach. Currently, many remain unrecorded and thus their existence is commonly unsuspected and their location unknown.

Using case histories from former mining areas in Lancashire, Yorkshire and Nottinghamshire, this paper presents a strategy for the use of remote thermal infra-red surveys prior to site development. Using a field site example from St. Helens, Lancashire, this paper reviews the application of thermal infra-red techniques to detect mineshafts. The effects of the ground conditions and disturbances about the mineshaft upon the thermal infrared radiation process are explained, and, remotely sensed images from Baildon Moor, Yorkshire are used to provide a correlation between the observed visual and the thermal characteristics of mineshafts. Finally, data from Nottinghamshire are used to demonstrate the application of commercially flown thermal infrared images to identify mining disturbances with no observed surface characteristics prior to the development of the Nottingham Business Park, where the existence of abandoned mineshafts was confirmed by soil stripping.

Effects of the ground conditions upon the thermal infrared radiation

A shaft in the ground can be thought of as an air-filled void, which is commonly capped to some degree. Air and solid rock have different thermal properties and hence, a temperature difference can be expected to occur between the two. Generally, mineshafts are cooler than their surroundings for much of the year, but in winter, at certain times of the diurnal cycle, mineshafts will be warmer than the enclosing ground, particularly during freezing conditions. Dependant on the effectiveness of the mineshaft capping a thermal anomaly may be produced at the earth's surface. Anomalously high temperatures have been observed to cause melting of frost over capped mineshafts, and measurements indicate that anomalies can average 2 ^{o}C – 3 ^{o}C under ideal conditions (Donnelly & Meldrum 1997; Donnelly & McCann 2000). Gases are associated with some mineshafts and can exert an influence on the strength of the thermal anomalies through possible exothermic reactions as they reach the surface. There is a tendency for gases to build up during periods of high atmospheric pressure and to be released on a drop in atmospheric pressure (Carter & Durst 1955; Durst 1956). Where abandoned mineshafts are open and have an obvious surface expression, the most likely cause of the thermal anomaly is the temperature contrast between the shaft-filling air and the surrounding ground. Where shafts have a less obvious surface expression, there is likely to be infill material between the shaft opening and the ground surface, or even an engineered capping. The thermal anomalies over such shafts may relate to the temperature contrast between ground disturbances and materials associated with the shaft and the surrounding ground. Ground disturbances can be due to excavation of a shaft or related actives of hauling, crushing, bagging and sorting, and transportation. Buildings and water pumping works would also disturb the ground and provide potentially anomalous surface areas. These ground disturbances have very localised effects on the physical, chemical, drainage and moisture properties of the surface geological materials. All of these properties have a direct and significant control on the diurnal heating and cooling cycles of the ground and on its ability to radiate heat energy. Soil density changes are caused by shaft excavations, compaction by heavy trafficking about the shaft, mixing of surface soils with deeper derived rock spoil and looser shaft infilling materials. Shafts and associated ground fractures can either drain surface waters or provide spring sources for rising mine-waters (Jackson *et al.* 1987; McCann *et al.* 1987). Thus, localised disturbances to water-flow, drainage and material density will create secondary moisture content changes in the vicinity of a mineshaft. Changes in soil chemistry are caused by the mixing of surface soils with the mining spoils, and also by shaft infilling with materials, sometimes borrowed from sources outside of the local area. Soil chemistry, density, drainage and moisture content changes affect the localised distribution of the flora, and thus the heat radiation pattern about mineshafts.

Case History: Pewfall Colliery, St. Helens

Site location, geology and ground conditions

The Pewfall Colliery was roughly mid-way between St. Helens and Wigan. Since the cessation of mining the site has been returned to agriculture, but some fenced off mineshafts remain in neighbouring fields. Bedrock geology consists of the Lower Coal Measures Formation, the Middle Coal Measures Formation and the Ravenshead Rock with a regional dip of 30° to the south-east. The site is cut by a normal fault that is downthrown to the south-west, with a dip of 70° and strikes to the south-east (Fig. 1a). The bedrock geology is overlain by Glacial Till to an unknown thickness but, possibly up to 10m thick. Two 50 m x 50 m survey grids were established and denoted Site B, which was on a gentle, south-west facing slope, and, Site C, which was in a shallow trough that widened and whose axis also dipped to the south-west (Fig. 1b). The focus of this paper is site C but the Gunn *et al.* 2006 provide detailed field methodologies and results for both sites. The x-axis of Grid C was orientated approximately west to east, but dipped to the south-east by 3°. The origin of the grid was located at BNG co-ordinates 355209E, 398346.88N. The elevation range across the grid was 3 m.

Looking across Grid C, long grass generally covered the area below y = 13 m and beyond x = 44 m (Fig. 1b); generally long grass gave way to very short grass up to y = 20 m and below x = 15 m; vehicle rutting was confined to a small zone near y = 50 m; an island of wet, disturbed and turfed up ground roughly 20 m in the x-dimension by 25 m in the y-dimension was centred about x=32 m, y=36 m; standing water / ice occurred over a 5 m wide island in the trough along a section of x = 40 m from y=15 m to 32 m, over the Coal Measures sub-crop; other areas comprised dry, flat ground with coarse brick and stone gravel sized rubble.

Survey conditions, equipment and methods

The survey over Grid C was undertaken from 01.00 to 05.20 on the 26th February 2004. Generally, the winter of 2003 – 2004 had been fairly mild, and in the weeks leading up to the survey, there were several rainy spells. However, the week before the survey was characterised by very clear, sunny days with freezing temperatures in the evening. There was only one spell of rain within this week, which occurred from 04.00 to 10.00 on the 24th February 2004. A decrease of 5mbars in barometric pressure was recorded during the survey.

A FLIR TERMCAM PM 675 was used for the survey. This had a minimum focal distance of 0.3 m, a spatial resolution of 1.3 mradians and a typical sensitivity of 0.1 ^{o}C at 30 ^{o}C. Measurements were taken over a 50 m by 50 m grid of points at every 2 m in both x and y directions (i.e. 26x26=676 points per grid). At each measuring point within the grid the camera was held directly above the ground at head height such that an area of approximately 1 m^2 could be imaged. The temperature attributed to the measurement point was the average of all the pixel values within the image (320x240). Thus, an overall averaged value of the ground was measured that was insensitive to the small-scale changes associated with footprints, grassy tufts, tyre ruts and so on. These values are presented as a contoured image covering the whole 50 m by 50 m grid. Control points were established where a series of repeat readings were taken throughout the duration of the survey. These repeat readings formed a baseline of temperature-time variation, which was used to correct the gridded survey for background temperature drift. The control point for Grid C was at x = 0 m, y = 0 m on the grid. The gridded image presented in Fig. 1c is corrected for background temperature drift.

Thermal infrared radiation from the ground

The thermal IR emitted from the ground over Grid C is shown in Fig. 1c. The line work overlay delineates the key surface and underlying geological features over the grid (from Fig. 1b). The confirmed position of a 3 m diameter brick-lined, back-filled mineshaft is denoted by the circular target with a diagonal cross at 28 m, 14 m. The coldest parts of the grid coincide with the dry, flat ground containing coarse brick rubble. In fact, the amount of brick rubble was sufficient to give this area of ground a brown-red colour. This ground appeared to be of low moisture content and very well draining. The low temperatures are suspected to be due to heat losses caused by evaporation. A large cold target centred approximately at x=21 m, y=25 m has been highlighted for possible further investigation, but it is suspected that the anomaly is due to the large amount of brick rubble in the ground, for example consistent with buildings located here formerly. Another notable cold target is centred along x=50 m from y=20 m to y=36 m. This is within the zone of long grass, within which there are areas of very long, dry wispy grass that had frosted up where pockets of cold air may have been trapped. It is possible that this cold zone is related to variability to the underlying ground, which may comprise made-ground associated with former railway works that were understood to have once occupied the site. The cold target within the wet, disturbed and turfed up ground coincides with a small island of brick rubble.

Warm targets of note include an oval zone roughly 5 m by 4 m centred at x=32 m, y=37 m, and also lesser targets at x=36 m, y=44 m; x=38 m, y=50 m and x=13 m, y=4 m. It was noted that the first three targets occur in grass-free areas, whereas the target at x=13 m, y=4 m occurred within the zone of long grass. The target at x=38 m, y=50 m coincided with standing water and ice that was observed during the survey, and it is suspected that the target at x=36 m, y=44 m was also associated with ice. Soil gas sampling across the largest anomaly at x=32 m, y=37 m indicated the presence of very minor amounts of methane and complete deficiency of oxygen in the ground that is compatible with methane oxidation. Fig. 2 shows a profile of analyses of gas samples taken along x = 32 m across the warm target at y=37 m. Exothermic oxidation of methane would provide additional heat into the ground and this is very compelling evidence for the presence of a mineshaft in the zone highlighted.

Application of remotely sensed thermal IR to detect mineshafts

Remotely sensed thermal infrared provides the potential for a low cost and non-intrusive technique that can aid mineshaft detection. It offers the benefit of providing rapid coverage over large swathes of ground. Using modern scanning technology, thermal infrared images can be gathered in the same way as aerial photographs. With the development of an appropriate scheme, localised thermal anomalies associated with ground disturbances can be analysed and mineshafts, both with and without any surface expression identified. Knowledge of the mining history of an area aids the identification of the coal seams that were mined and provides details of the size and structure, the approximate height above the seams and the geology of the mine entries. This information forms the basis for the criteria against which mine entries are interpreted on thermal images. It also provides a guide to the potential location of unrecorded mineshafts. Mineshaft location on thermal images is particularly successful in former mining areas where the land is derelict or returned to farming, where later ground disturbances have largely removed the obvious surface expression of a mine entry. However, the ground still holds a record of many of the ground disturbances related to the existence of the original mine entry, and these can be detected as anomalies on thermal images.

<u>Case History: Baildon Moor, Yorkshire</u>

Site location, geology and ground conditions

Baildon Moor comprises an outlier of Coal Measures resting conformably upon the Millstone Grit Group (Fig. 3). The word Baildon can be translated as ‘the hill of pits or mines’, where mining may have begun during the occupation of the Roman Legions, about 200 AD. Baildon town is located in West Yorkshire, England, about 10 km north of the City of Bradford. Baildon Moor covers about 20 km^2 and has an elevation of 280 m above sea level at the summit. It rises above Baildon town on a thick scarp of the hard Rough Rock sandstone (R in Fig. 3b). The flat top is formed by the 80 Yard Rock sandstone-capping layer. About 20 m below is an extensive plateau, which is formed in the 48 Yard Rock sandstone. Coal-bearing rocks of the Lower Coal Measures (Waters *et al.* 1996) are sandwiched between this lower plateau and the thick scarp above Baildon town. The Coal Measures show a gentle dip of between 1^o and 4^o to the south-south-west within the area of Baildon Moor. Therefore, over much of the study area the depth to coal seams, the Hard Bed (HB in Fig. 3b) and Soft Bed (SB in Fig. 3b), was largely a function of the surface topography. Shallow depth, bell pits into the Coal Measures are distributed around the perimeter of the lower plateau, and larger diameter, deeper mineshafts can be found in, and above the lower plateau. However, in the north and west of the study area the depth to coal is controlled by displacement along a series of steeply dipping normal faults (Fig. 3a).

Bell pits were usually initiated from shafts with a diameter of approximately 1 m - 2 m down to the coal seam with a maximum depth of around 10 m (Waters *et al.* 1996). Coal was then excavated at the base to a maximum diameter of around 6 m, limited only by the collapse potential of the roof. However Littlejohn (1979) does record excavations up to 20 m in diameter. The majority of bell pits are associated with working of the Hard Bed Coal. As bell pits were only excavated to approximately 10 m depth, it is presumed that they lie exclusively between the outcrop of the Hard Bed Coal seam and the base of the 48 Yard Rock sandstone. It is unlikely that any casual bell pit development would have been undertaken through this hard sandstone and so the base of the 48 Yard Rock can used as a reasonable upper boundary to presence of bell pits. Many of the bell pits were characterised by a conical depression of up to 4 m diameter and 2 m deep (Fig. 4 shows a typical example). Spoil rings when present, appeared as a low lying circular ring less than 0.5 m high with an outer diameter of up to 6 m.

Mining in excess of 25 m probably began occurring in the UK in the 18th or 19th Centuries, requiring more efficient winding gear and techniques of pumping out groundwater. It is believed that in the early works at Baildon, the coal would have been removed by a shafthead windlass. While the maximum depth of shaft using this method limited to 20 m – 25 m, it was still sufficient to mine the Hard Bed Coal. The shafts over the plateau formed by the 48 Yard Rock in the vicinity of Dobrudden Caravan Site appear to have been of this type. The arrangement of these mineshafts is in a grid of approximately 100 m dimensions. Mining was in the form of room and pillar away from each shaft centre. Also, ventilation of the deeper pits would have involved an up- and a down-shaft, to allow a through flow of air. Many of the abandoned shafts were characterised by a spoil ring with a 20 m outer diameter around a central zone of around 12 m diameter (an example is shown in Fig. 5). This central zone can be flat with infill soil, water filled or a conical depression up to 5 m deep. The spoil ring can be built up to 3 m above the outer ground level or a low lying annulus less than 0.5 m high.

Table 1. Classification of thermal anomalies based upon comparison with mapped shafts and surface features

Mapped shaft	Feature visible on aerial photo	Height class above HB coal	Geology of entrance	Brief Description of Features	Area Class (Visually Observable)
Yes	Yes	< 10 m Bell Pit	LCM	Thermal anomalies in this area were associated with bell pits that had been mapped and/or were visible in the aerial photographs. There were no thermal anomalies unaccounted for in this area. The bell pits had typical dimensions of between 1 and 4m diameter and a 2m deep depression at surface, with a small ring of vegetated spoil around them (Fig. 4).	1: Mapped visible feature.
Yes / No	Yes	> 20 m Mineshaft	On or above the 48 Yard Rock plateau	The known mineshafts in this area, approximately 12m shaft top diameter, surrounded by a vegetated ring of spoil to 20m dia., appeared to occur in a grid pattern with an approximate spacing of 100m (Fig. 5). This pattern suggested that an additional mineshaft could be located in the approximate position of the anomaly cluster in this area. The unaccountable thermal anomalies appeared to correspond either to an area of wet, boggy ground and reed grass or to 6m diameter circular areas of short grass. Two anomalies in the pre-dawn thermal image were particularly large and had potential to be mineshaft sites.	2: Not mapped as shaft when surface expression disturbed.
Yes / No	Yes	> 20 m Mineshaft	LCM in faulted zone	An area of mapped mineshafts, shafts visible on aerial photographs and several unaccountable thermal anomalies. Mapped shafts typically relatively small with an inner area reed grass of approximately 4m to 6m surrounded by shorter grass around the perimeter, with either no spoil around them or a small spoil ring. The ground appearance at the location of unaccountable thermal anomalies was similar to some of the mapped mineshafts, with shorter grass surrounding reed grass. There was potential for these to be mineshafts.	3: Infilled, or further disturbed. Not always mapped
Yes / No	No	> 20 m Mineshaft	48 Yard Rock	An area of mapped mineshafts and a small number of unaccountable thermal anomalies. Mapped mineshafts were wide and deep, with typical dimension of 12 to 15m diameter, with a 3 to 4m deep depression at the surface, but a wide ring of vegetated spoil around them makes them difficult to observe on aerial photographs (Fig. 7). Features mapped as mineshafts included surface workings cut into the hillside.	4: Obscured by vegetation. Not mapped due to access.
No	No	> 20 m Mineshaft	48 Yard Rock	Shafts or quarry openings mapped where features were obvious. Also present where thermal anomalies only observed in the daytime thermal image. In the field these features were not as obvious as other mineshafts on the Moor, but had a subtle surface expression, being approximately 12m in diameter with a slightly depressed appearance, and thus difficult to observe on aerial photographs (Fig. 8).	5: Not mapped No visible features. On set aside land.

Remote sensing conditions, equipment and methods

The Daedalus 1260 Airborne Thematic Mapper[1] (ATM) imagery records data in twelve wavebands spanning visible, short wave infrared and thermal infrared. Thermal infrared radiation at wavelengths of 8-14 microns are recorded as band eleven. High resolution data were acquired over Baildon Moor, Yorkshire on two days, 15 September 1996 and 2 May 1997. Data capture took place immediately pre-dawn on both dates, and there was an additional late morning capture on 2 May. Two flight lines of the 1997 data were required to cover Baildon Moor. For both the pre-dawn and daytime images the two flight lines were georeferenced, mosaiced together to make one image and a contrast stretch was applied (Fig. 6). The pre-dawn image was geocorrected to 1:10,000-scale Ordnance Survey maps and the daytime image geocorrected to the pre-dawn image. The data supplied by the NERC Airborne Remote Sensing Facility had been corrected radiometrically prior to delivery, using the relevant calibration data (this process transforms data from sensor digital numbers to an absolute scale of radiance).

Classification of features on remotely sensed thermal infrared image

Data available for the study, in addition to the thermal images, were a 1:2,500-scale mine abandonment plan, a 1:10,000-scale field survey map and a set of 1:25,000-scale aerial photographs acquired on the same date as the May 1997 thermal data. A comparison was made between the location of anomalies identified in the thermal images, the location of mapped mineshafts and mineshafts with a clear surface expression in the aerial photography. Examples of the criteria used in the comparison (as explained above) are summarised in Table 1. The classification of the thermal anomalies was based upon the degree of difficulty in observing the ground disturbances on aerial photographs and in the field. For example, areas 4 and 5 provide thermal evidence for the presence of shafts where there is little or no visible expression of the entry. Visual observation of mine entries in area 4 was obscured by very thick bracken cover. Shaft entries were characteristically a 12 m diameter depression of up to 3 m deep surrounded by a narrow spoil ring of about 15 m diameter. Where the bracken cover was thin, for example at the shoulder of the plateau formed by the 48 Yard Rock, mine entries were still visible and thus mappable (Fig. 7a). However, the bracken was very thick on the slope of the hill where mine entries were not necessarily observed and mapped. However, Fig. 7b shows the depression, believed to be an abandoned mineshaft, of approximately 15 m diameter associated with a cluster of thermal anomalies in this area.

Mine entries in area 5 have been disturbed by later farming activities, such as ploughing, and the ground in this area is generally flat with little obvious surface expression. Thus, field observation of abandoned shafts was very difficult, where only the subtlest of vegetation changes indicate the presence of a former shaft, such as a concentration of clover over a former spoil ring as shown in Fig. 8a. In this case, the change in vegetation was visible on the aerial photograph, but other abandoned shafts, such as Shafts 1, 3 and 4 in Fig. 8b were not so clear, and thus, missed during interpretation. However, the ‘bull’s-eye’ target features at the locations of Shafts 1 to 4 were visible on the late morning thermal image (Fig. 8c), and were interpreted as former shafts, but were not readily observed in the pre-dawn image (Fig. 8d).

[1] Supplied by the Natural Environment Research Council (NERC) Airborne Remote Sensing Facility

Note also, a cluster of former bell pits on the LCM between Shaft 3 and the small copse of trees to the east, which were not readily observed in the field.

Integration of remote thermal IR in site development planning

Planned construction of the Nottingham Business Park at a former mining site in west Nottingham highlighted the need for the abandoned mineshafts that underlay the site to be accurately located. Appropriate sealing of the shafts prior to site development could then take place. Coal Authority records indicated in excess of thirty abandoned mineshafts over the Chilwell Dam Farm Site, (see Table 2). Before designation for the development of the Nottingham Business Park in 2002, wheat was cultivated in the fields and fruit trees grew in the orchard next to the farm buildings at Chilwell Dam Farm. Thus, most of the mine entries were obscured and very difficult to observe in the field. Mineshaft locations transcribed from a British Geological Survey field slip (Table 2) were originally transcribed from Coal Authority records. However, the precision in their location could not be taken to be less than ±20 m on either the easting or the northing. The flight path of a planned commercial thermal infrared flight (by the Nottingham Energy Partnership for a building heat loss study) was extended to provide thermal images over the site. The scheme developed at Baildon Moor was applied to Chilwell Dam Farm to improve the existing information on shaft locations held by the developers BWB Consulting Ltd. This provided the opportunity to compare the effectiveness of the scheme using a commercial 8-bit sensor[2] from Chilwell Dam Farm with the data from the NERC 16-bit sensor from Baildon Moor.

Table 2. Approximate location of mineshafts at Chilwell Dam Farm

No.	BNG Grid Reference	No.	BNG Grid Reference
1	451005, 343135	19	451515, 342685
2	450815, 343015	20	451030, 342650
3	451220, 342985	21	451290, 342635
4	451395, 342955	22	451150, 342495
5	450875, 342945 *	23	451310, 342485
6	451030, 342930	24	451145, 342460
7	451335, 342910	25	451480, 342455
8	451145, 342895	26	451145, 342440
9	450920, 342890	27	451150, 342425
10	451430, 342880	28	451375, 342385
11	450830, 342875	29	451180, 342380
12	450995, 342830 *	30	451180, 342360
13	451220, 342815	31	451325, 342355
14	451075, 342805	32	451285, 342340
15	451485, 342790	33	451365, 342320
16	451455, 342785	34	451215, 342280
17	451015, 342740	35	451235, 342215
18	451380, 342730	36	451245, 342180

* Identified from aerial photograph

[2] Supplied by Infoterra Ltd.

Case History: Nottingham Business Park (formerly Chilwell Dam Farm), Nottinghamshire

Site location, geology and ground conditions

Chilwell Dam Farm was situated on the west side of Nottingham, within the city limits, as shown in Fig. 9a. It is approximately 800 m at its widest and 1.8 km at its longest. It comprised a roughly triangular area of farmland with its eastern boundary along the A6002, its northwestern boundary along the M1 motorway and other boundaries formed by hedgerows. Access to the site was via a slip road that runs off the A6002. Limestone of the Cadeby Formation carbonate facies (formerly the Lower Magnesian Limestone) outcropped over most of the site (Fig. 9b). Dip was sub 10^{o} with a prevailing easterly direction. A normal fault striking ESE – WNW with a northerly down throw side cut through the site. To the west of the site the Lenton Sandstone overlies the Edlington (Marl) Formation, which overlies the Cadeby Formation carbonate facies. At the NE corner of the site the Cadeby Formation carbonate facies is underlain by the Cadeby Formation mudstone facies (formerly the Lower Marl), which rests unconformably on Middle Coal Measures. A cover of Glacial Till was found on the small hill formed by the Lenton Sandstone on the west side of the site.

Coal has been mined west of Nottingham since at least the Middle Ages and probably considerably earlier (Charsley *et al.* 1990). Much of the wealth of the Willoughby family, who constructed Wollaton Hall in the 16th century, and other Nottingham landowners was founded on coal mining in the area of an exposed and shallowly concealed coalfield west of Wollaton Hall (*c.f.* Fig. 9a). By 1604 Huntington Beaumont constructed a wooden wagonway from bell pits at Strelley down to Wollaton Lane, for carriage to the Nottingham market (Healey 2001). During the 19th Century, mines were generally leased from landowners by partnerships of mining entrepreneurs, who raised the necessary capital for development. Villages like Hucknall and Bulwell in the Leen Valley grew to accommodate the workforce. Improved steam pumping could drain deeper shafts, and some of the first deep shafts were sunk in 1841 at Cinderhill, and in 1851 at Hucknall. Before the First World War, coal production from Britain's 3,024 mines was at its peak (Healey 2001). Nottinghamshire coalmines stretched the length of the county and in Eastwood alone 40% of the workforce were employed down the coal pits. After many pit closures in the 1980s, most of the sites have been completely cleared. Many spoil heaps have been reshaped and re-planted while others have been reused as industrial estates.

After the mining ceased, the site located at Chilwell Dam Farm (Fig. 9) was returned to orchards and plantations surrounded by pasturelands (Ordnance Survey, 1885). The shallowest coal at the site is Cinderhill Main Seam, which is a metre thick at a depth of 22 m, (National Coal Board 1959). The distribution of the abandoned mineshaft locations suggests an ad hoc approach to mining on the land where the landowner leased mining rights to several different co-operatives (as was the practice at the time). If this is the case then mining may have been via the use of unusually large bell pits (Whittaker & Reddish 1989). Some shafts would have been lined either to provide stability from collapse or spalling of the rock, or possibly, to control the ingress of water into the mine workings. Shafts have been commonly lined since the 17th Century and many materials have been used. Littlejohn (1979) reported the use of wooden planks arranged vertically like a barrel, and Boulton (1907) reported that it was common for shafts less than 3.5 m in diameter to use moulded brick linings in the 19th Century. Fig. 10 shows a brick-lined shaft of approximately 2m in diameter that was observed on the Chilwell Dam Farm site at BNG 51285, 42342; mineshaft no. 32 in Table 2. The lining is of dry-stacked red-brick and its collar is within 1.5m of the ground's surface.

Vegetation was lush where present but when viewed from a short distance (in June 2001), it was apparent that much of the ground surface was bare soil and for most of the area still in crop furrows. The north and northwest sections of the site, recently used as arable grazing, were covered in a lush growth of grasses and meadow plants. In some areas immediately surrounding the farm site and in the far northwest of the site, it appeared that no recent agricultural activity had taken place and as a result, a dense vegetation cover was present.

Table 3. Observed features corresponding to most thermal anomalies at Chilwell Dam Farm

Feature observed at or within top 100mm of ground surface	Example in Text (General increase in visual identification of shaft →)						
	S3	S6	S8	S10	S15	S20	S32
Soil Changes							
Coal fragments < 10 %				Yes	Yes		
Coal fragments > 10%							
Coal Measures Mudstone				Yes	Yes*		
Brick fragments	Yes*				Yes*		Yes
Vegetation Changes		Yes			Yes		
Topographic / Other Features							
Depressions						Yes	
Mounds					Yes		
Shafts (incl. linings etc)							Yes
Ground Conditions							
Soft Ground	Yes*						
Increased moisture / damp ground			Yes				
Thermal Anomaly (Yes / Obscured)	Yes	Yes	Obs	Yes	Yes	Obs	Obs
Visible on Aerial Photo (Yes / No)	No	No	No	No	No	No	No
Interpretation on the basis of features alone Shaft (Yes / Probable / No)	No	No	No	Prob	Prob	Yes	Yes

* Indicates that these features only became apparent after soil stripping.

Remote sensing conditions, equipment and methods

Thermal imagery was acquired at Chilwell Dam Farm on two dates as an extension to a building heat loss survey in Nottingham. Data were acquired pre-midnight on 15 February 2001 and pre-dawn on 12 March 2001. Pre-dawn was the preferred time of data acquisition for shaft detection hence the pre-dawn dataset was the focus of the research at the Chilwell Dam site. Two flight lines provided full coverage of the Chilwell site. The flight lines were georectified and mosaiced together prior to interpretation of the mosaiced image. Generally, thermal anomalies that seemed most likely to relate to mineshafts were dark relative to the rest of the image and circular in shape (Ager *et al.* 2004). Such anomalies were marked on the thermal image to be subjected to investigation in the field, prior to, during and after the top soil was stripped from the site. Several larger anomalously dark areas were also marked on the image, for field investigation.

Interpreted thermal infrared image

A comparison was made between the location of thermal anomalies, mineshafts with a clear surface expression on the 1:25,000 scale aerial photographs and the location of mapped mineshafts on a 1:10,000 field slip and from the Coal Authority records (Table 2 above). A comparison of the aerial photographs with the ‘known’ mineshaft locations revealed that some shaft sites were easily identified as areas of lighter tone of near-circular shape, approximately 10m in diameter, often with trees nearby. Using these criteria, the rest of the photograph coverage was examined for similar features. Only 17 potential shaft locations were identified, 15 of these were in agreement with known shaft locations. Over 50 thermal anomalies were identified across the site, which in general, corresponded to at least one of the following features that were observed in the field: soil, vegetation, topographic or ground condition changes (Table 3).

Thermal anomalies were identified to coincide with the expected position of approximately half of the known mineshafts listed in Table 2, as shown in Fig. 11. Generally, lack of detection was due to other features obscuring the localised anomaly caused by the shaft. For example, Shaft 8 was masked on the thermal image by a cold dark zone caused by very damp ground. Many of the shaft locations occurred beneath trees, whose warm thermal signatures would have obscured the effects of the shafts. Non-detected shafts included Shaft 20, which appeared in the field as a large oval of 12 m diameter up to 2 m deep with a pool of water 1m deep, and also, Shaft 32, which appeared as a lined opening (Fig. 10).

Over the site, spoil had been reused to backfill the shafts on closure, causing localised soil changes via introduction of mostly mudstone, coal and brick fragments. Backfilling with extraneous materials would have led to topographic changes leaving mounds and soft ground, and also, resulted in changes in local soil chemistry and ground conditions, thus favouring subtle differences in localised vegetation. Evidence of backfilling was more readily observed where the land had been very recently farmed, such as at Shaft 10. However, many of the primary soil changes were not completely detected until after the site was stripped of the top soil. The thermal anomaly related to Shaft 15 from Area 1 in Fig. 11 coincided with a 0.5 m high mound, approximately 30 m across, with a circumferential ring of nettles surrounding a central core of clover, dandelions and broad leave weeds (Fig. 12a). Only slight soil darkening by coal was noted during the initial site visit, but soil stripping revealed localised backfilling with light grey Coal Measures mudstone, brick and coal fragments (Fig. 12b). The changes in vegetation were very subtle resulting in many shaft locations, such as Shaft 3 coinciding with a cluster of anomalies. Soil stripping revealed this area to be of very variable stiffness, where soft patches coincided with backfilling of mudstone, coal and brick fragments. Shaft 5 coincided with a patch of nettles approximately 15 m in diameter. Shaft 6 coincided with a very minor vegetation change to lusher, longer grass over an area of about 3 m in diameter, where geophysical surveys revealed very large, localised perturbations in the electrical conductivity and magnetic field profiles indicative of magnetic materials such as bricks of scrap-iron (Fig 13).

Conclusions and recommended practices

Anomalies in thermal IR images are known to have been associated with mineshafts. These are either directly related to an air filled shaft but more often are related to the ground disturbances and materials associated with the shaft. Ground disturbances include effects due to density changes caused by soil mixing, moisture content changes caused by the presence of a shaft and also chemistry and related vegetation changes.

From Pewfall a warm thermal anomaly coinciding with a 3 m diameter brick-lined, backfilled shaft was found to be associated with methane oxidation. At Baildon Moor, thermal anomalies had a ‘bull’s-eye’ target structure of diameters to around 20 m related to the shaft and surrounding ground disturbance. The relative temperatures of these features depended upon the ground conditions and materials comprising the central core and surrounding annulus. The location and geology of the mine entries guided the determination of the style and depth of mining, i.e. to distinguish between bell pitting and pillar and stall mining. Abandoned shafts with clear surface expressions such as on the 48 Yard Rock plateau produced very clear thermal anomalies on pre-dawn and late-morning images. Also, in farmed areas thermal anomalies on the late-morning image were interpreted as shafts that were difficult to observe visually from aerial photos or in the field. The final case history at Chilwell Dam Farm typifies situations across the UK where development is being considered on newly acquired land that has been left derelict due to former mining and farming activities. Surface features related to mine entries are obscured making aerial and field observation extremely difficult, but leaving subtle changes in localised ground conditions that result in contrasts in the localised thermal infrared radiation. A scheme applying thermal imagery to aid the identification of abandoned shafts could be included as part of the planning process. It would be envisaged that the identification and location of thermal anomalies would lead to better planned field itineraries designed specifically to locate the more subtle disturbances related to former shafts, and thus, increase detection rate.

Remotely sensed data from Baildon Moor were acquired using a 16 bit (2^{16}) binary coding scale, whereas the data from Chilwell Dam Farm were acquired using an 8 bit (2^{8}) binary coding scale. This resulted in the images from Baildon Moor being far sharper due to a greater depth of grey-level providing far greater contrast within the image. Both pre-dawn and daytime thermal images have been shown to be useful for mineshaft detection. The information content of the images is distinct and complementary. Ideally both pre-dawn and daytime thermal data should be acquired for a mineshaft detection study. In addition to providing supplementary information on mineshaft location compared to single diurnal acquisition, acquisition of both pre-dawn and daytime data enables thermal inertia study to take place. Daytime acquisition should take place as close to noon as practicable. If cost or other limitations restrict acquisition to a single diurnal period then pre-dawn acquisition should be selected due to the minimal thermal shadowing; thermal shadowing can mask features within a daytime thermal image.

Successful data acquisition for mineshaft detection must take into account seasonal and meteorological conditions. Mineshaft detection performance of a thermal image is significantly influenced by precipitation receipt, temperature, and barometric pressure conditions in the period leading up to and during data acquisition. The study has confirmed that thermal data acquisition for shaft detection should be conducted during a period of dry weather. In particular, the study highlighted the significance of temperature in the period leading up to data acquisition on shaft detection capability. Colder conditions in the period leading up to data acquisition appear to result in the greatest contrast between mineshaft and surroundings in a thermal image. It is therefore preferable to conduct thermal data acquisition in Winter or Spring, not Summer or Autumn. Precipitation, temperature and pressure should be monitored in the field prior to and during thermal data acquisition, and significant weight given to meteorological conditions in the timing of data acquisition. Ground temperature measurements will also be required if airborne radiance data are to be calibrated to temperature.

Wherever possible, modern multi-spectral sensors should be used on all new airborne reconnaissance flights such that data in the visible and infrared band can be collected with the greatest level of binary coding scale. In order to maximise mineshaft detection from a thermal image precise geometric correction of the image must take place. Use of control based on GPS or Ordnance Survey 1: 1,250 scale Landline data should be considered. For data acquired by the NERC aircraft a digital elevation model should be used with the NERC geocorrection software.

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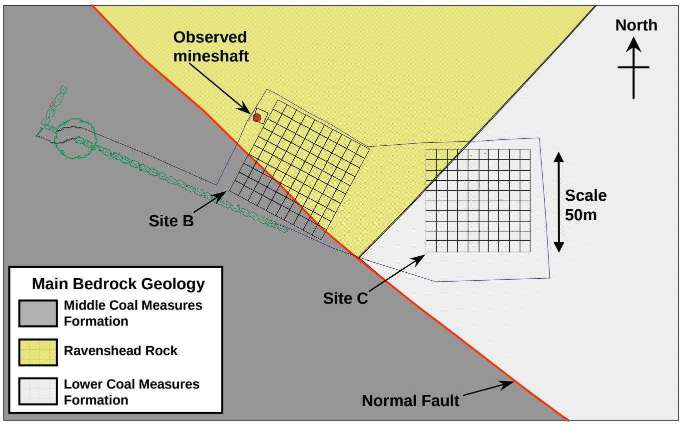
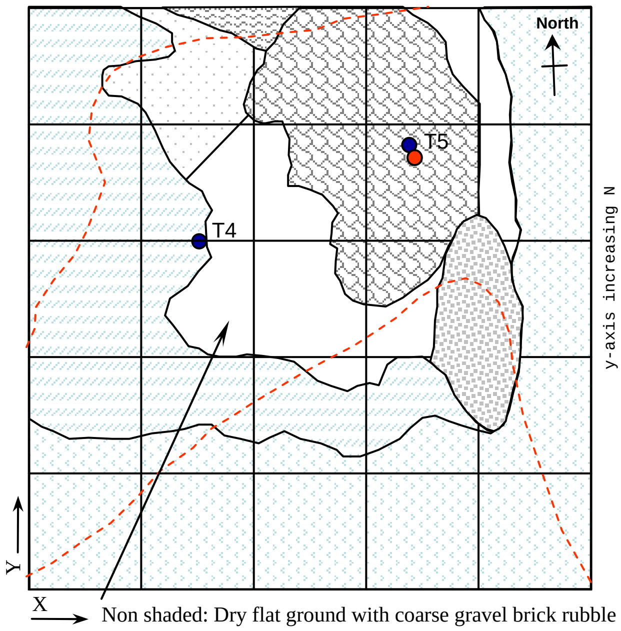
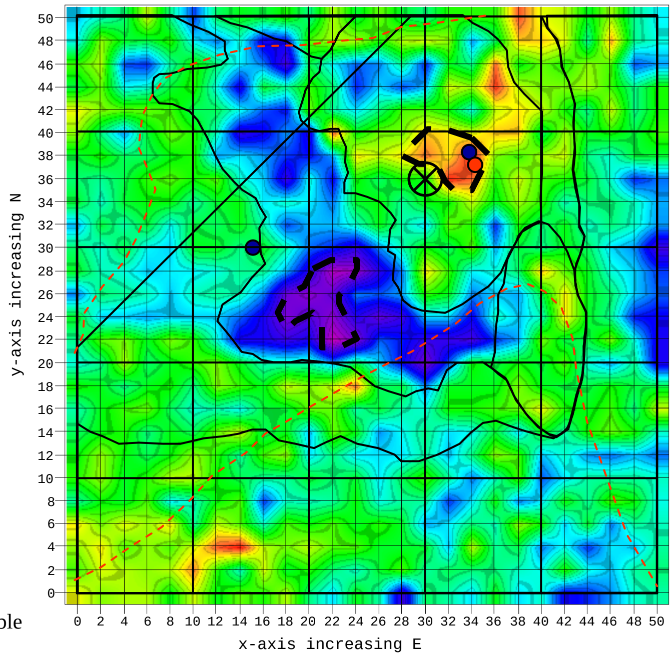


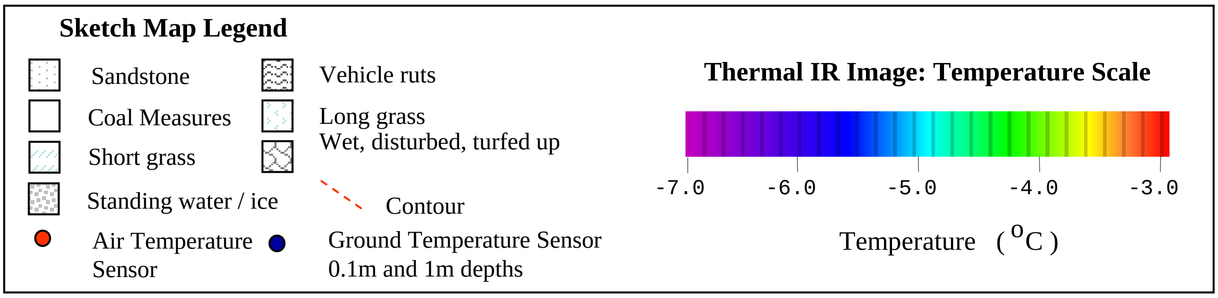
a. Orientation of survey grids relative to bedrock geology.
(arrows pointing to the origin on both Grid B and Grid C.)

b. Field sketch of the ground conditions over grid C.



c. Image of thermal IR radiation from ground at grid C.





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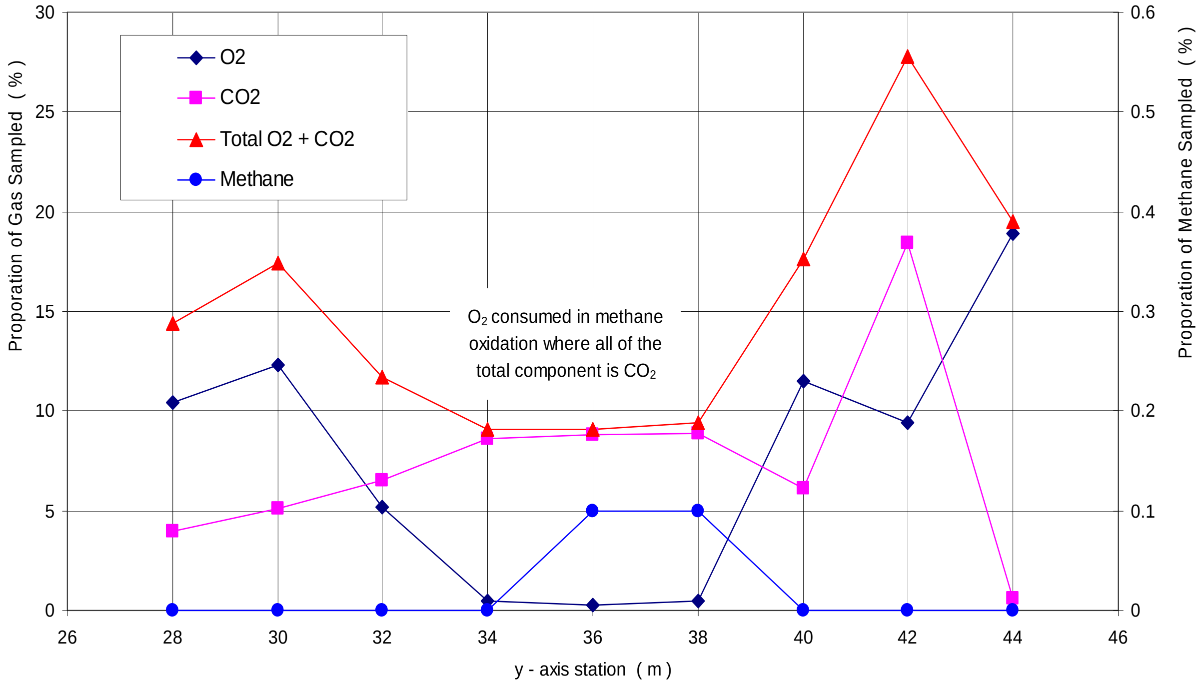

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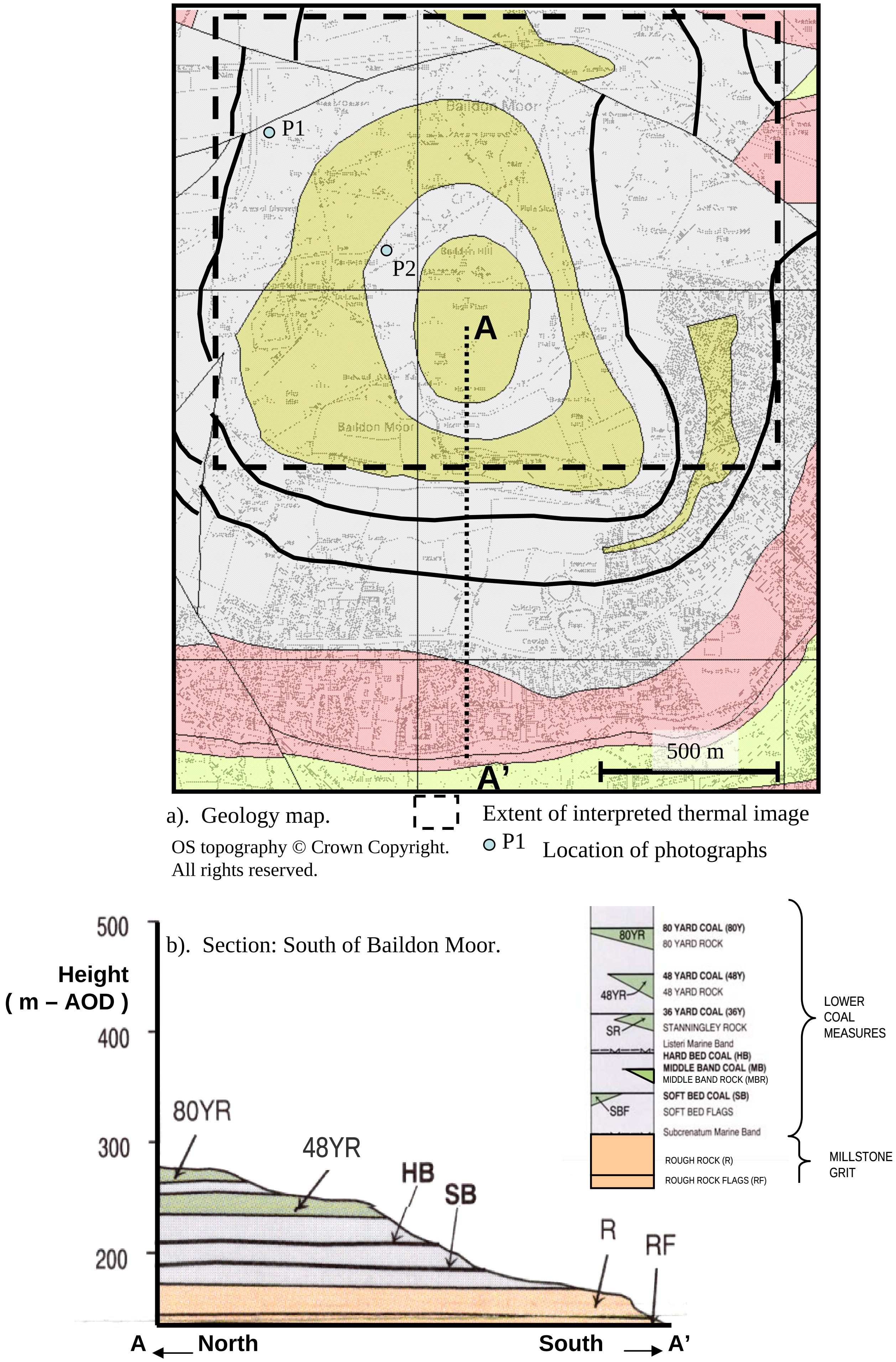

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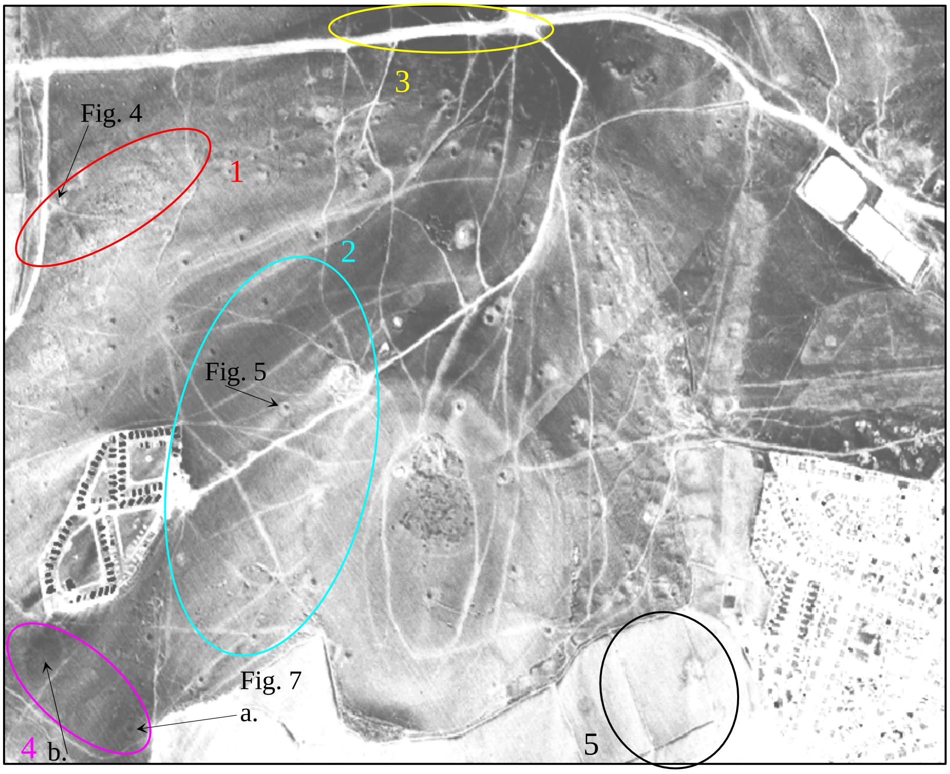
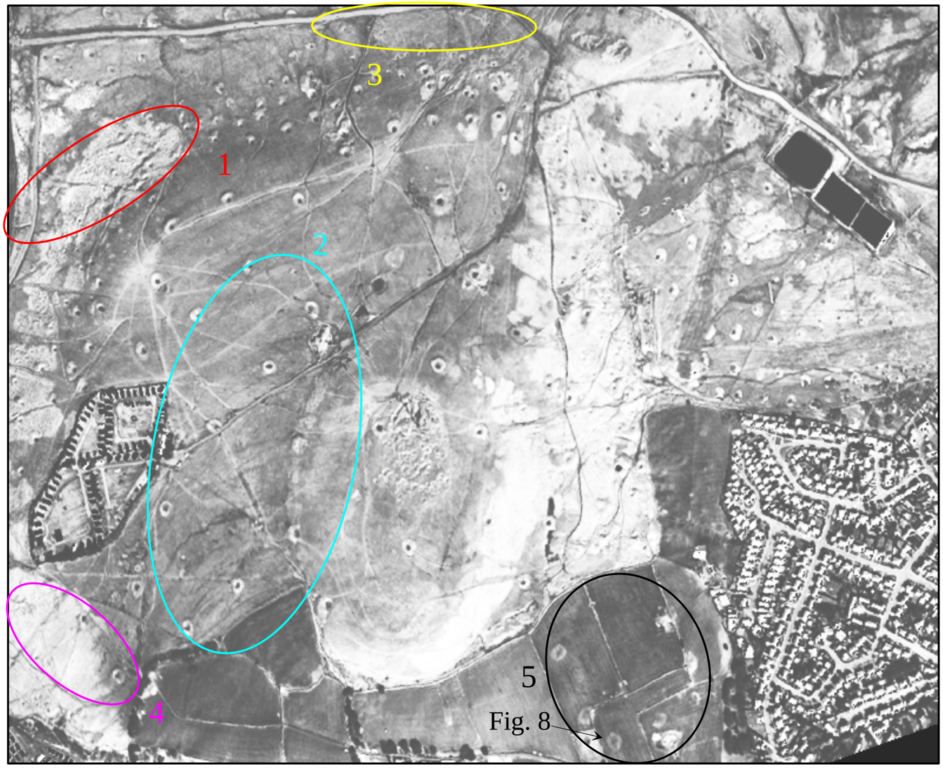


a. Pre-dawn image.



b. Late morning image.

Fig. 6. Thermal images of Baildon Moor, flown 2nd May, 1997.

(Darker tones represent cooler radiant temperatures, lighter tones represent warmer radiant temperatures.) Coloured rings indicate classes.

a. Shaft to Hard Bed coal: 12 m diameter / 2-3 m deep; low bracken cover but mapped.

b. Shaft to Hard Bed coal: 15 m diameter; dense bracken cover and unmapped.

Fig. 7. Degrees of masking by dense vegetation of mineshafts to Hard Bed coal.

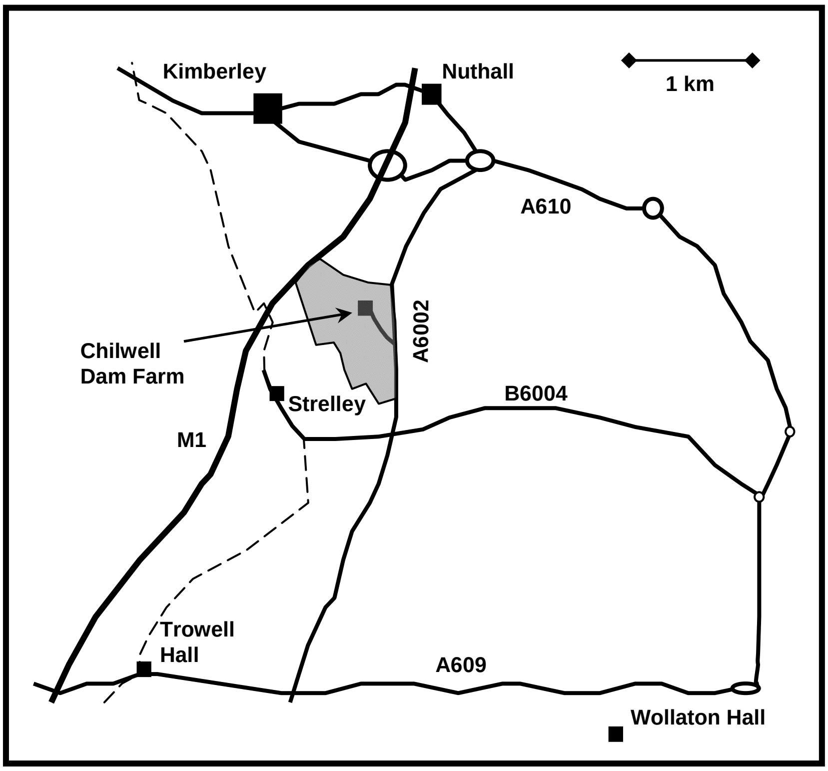
a. Photo of Shaft 2 in the Hope Farm area.

b. Aerial photograph

c. Late morning thermal image

d. Pre-dawn thermal image

Fig. 8. Mineshafts in farming areas. The four shafts were more clearly visible on the late morning thermal image than in aerial photographs and in the field.



a. Location of site in relation to the region mining communities, West Nottingham.

b. Solid and drft geology across the site.

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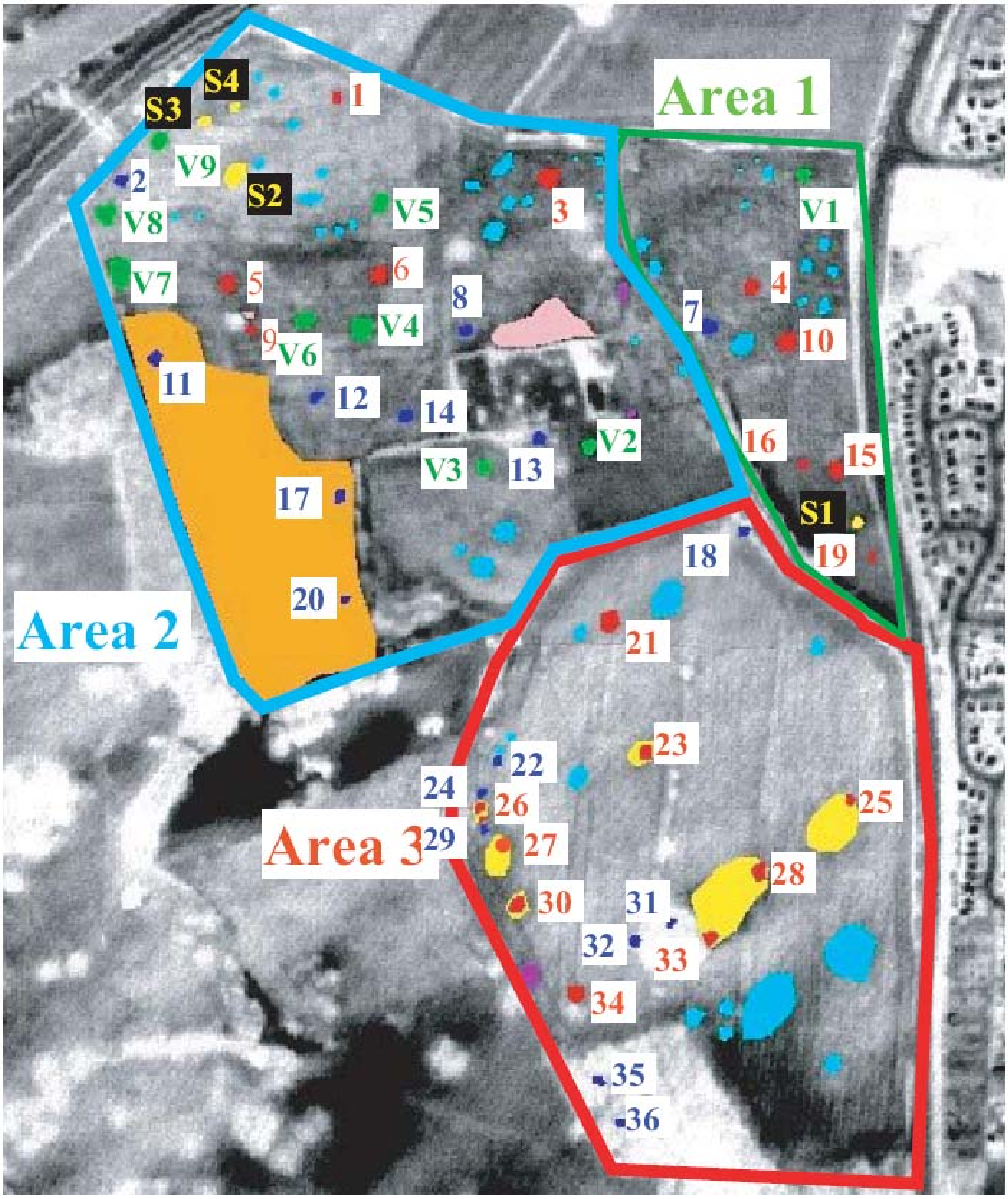


Thermal anomalies corresponding with:

- = mapped shafts
- = vegetation change
- = soil change
- = damp ground
- = geological change
- = no significant ground feature observed

- = location of a mapped shaft, but no thermal anomaly detected

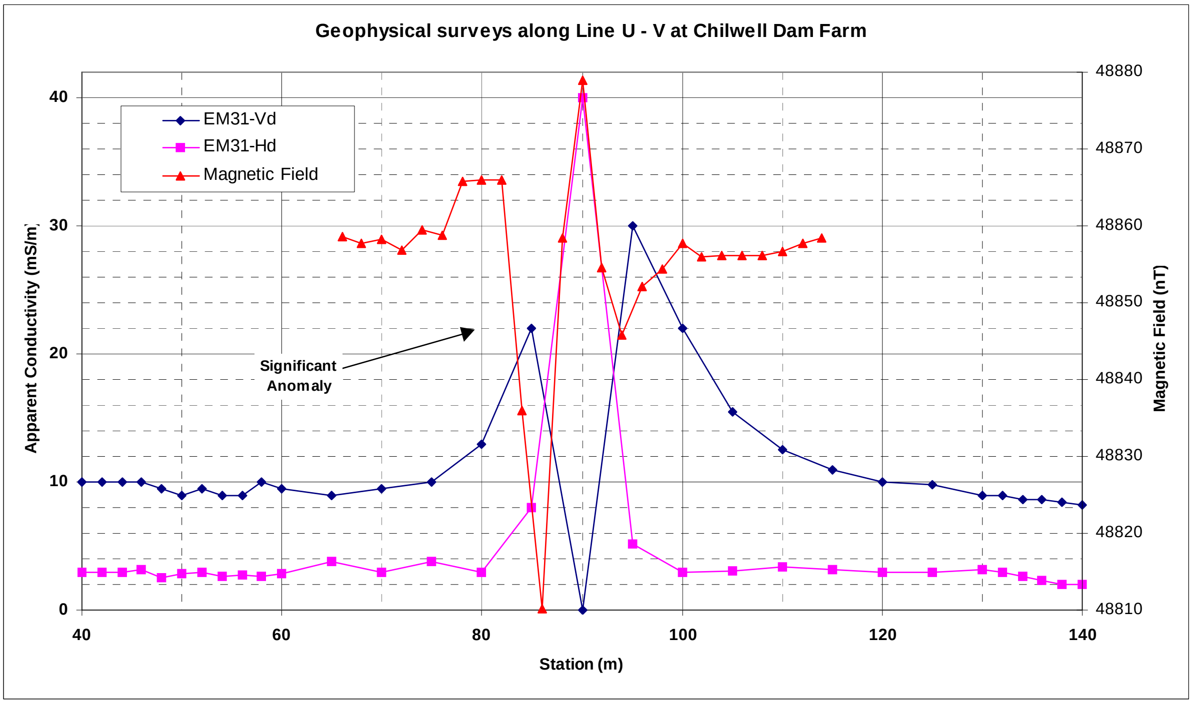
Fig. 11. Interpreted pre-dawn thermal image of Chilwell Dam Farm, flown 12th March 2001.

a. Vegetation change over a mound about 0.5 m in height.

b. Soil mixed with coal measures mudstone, brick and coal at shaft.

Fig. 12. Shaft 15: Ground conditions at time of thermal survey and after soil stripping.

a. Localised change in the grass coincident with thermal and geophysical anomalies.



b. Localised perturbations to electrical conductivity and magnetic field over shaft.

Fig. 13. Shaft 6: Ground conditions at time of thermal survey and geophysical response.