

Fault Reactivation Induced by Mining in the East Midlands

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Abstract: Mining-induced fault reactivation has been observed at several localities throughout the East Midlands, between 1930 and 2000. The generation of new fault scarps has caused widespread damage to structures and land. These scarps are distinct, reach over a metre high and extend for several hundreds of metres at outcrop. In areas of moderate relief, such as on the Permo-Triassic escarpments, natural process of cambering and valley bulging may be exacerbated by mining subsidence. Recent field observations suggest that some faults may undergo renewed phases of reactivation, several years after mining has been abandoned, probably due to minewater rebound, although this is difficult to prove at some sites. Some of the engineering problems and environmental geohazards associated with fault reactivation are outlined with reference to case examples.

Ground movements due to mining subsidence can be normally predicted with a reasonable degree of accuracy and precision (Whittaker and Reddish, 1989). Faults within regions undergoing subsidence are susceptible to reactivation, and their renewed displacements disrupt the predicted profiles of ground movement. At several localities in the East Midlands, fault reactivation has results in the formation of distinct, and often extensive, fault scarps up to 1.5m high across the ground surface. Mining subsidence, with and without fault reactivation, has caused widespread damage to land, property and structures. Furthermore, some faults may provide natural pathways for groundwater discharges and minegas emission.

In recent years inadequate attention has been paid to the effects of geological processes in the design and construction of many buildings and structures (McCann *et al.*, 1999; Culshaw *et al.*, 2000). This has resulted in spiralling costs of claims based on

"unforeseen ground conditions". Fault reactivation is just one of many causes of adverse ground conditions in Britain, although it is poorly understood by many engineers and non-technical specialists. This paper highlights some of the problems caused by fault reactivation in the East Midlands that may be significant for many geologists, engineers, builders, surveyors, planners, insurers and conveyance lawyers.

Fault Reactivation in the East Midlands

Fault scarps caused by mining subsidence are often described by subsidence engineers, as steps in the subsidence profile or 'break-lines' along the ground surface (Fig. 1). In the East Midlands, these have damaged civil-engineered structures, residential houses, industrial premises, roads, motorways and railways. Movement along faults has also effected underground utilities such as gas and water mains,

Figure 1. Reactivation of a fault generated a 0.3m high fault scarp and caused severe damage to a 5m high brick wall at Eastwood Hall. The date of reactivation is not known, but was probably in the 1960s. This section of wall has been demolished, but evidence of further fault reactivation was visible on an opposing wall in May 2000.



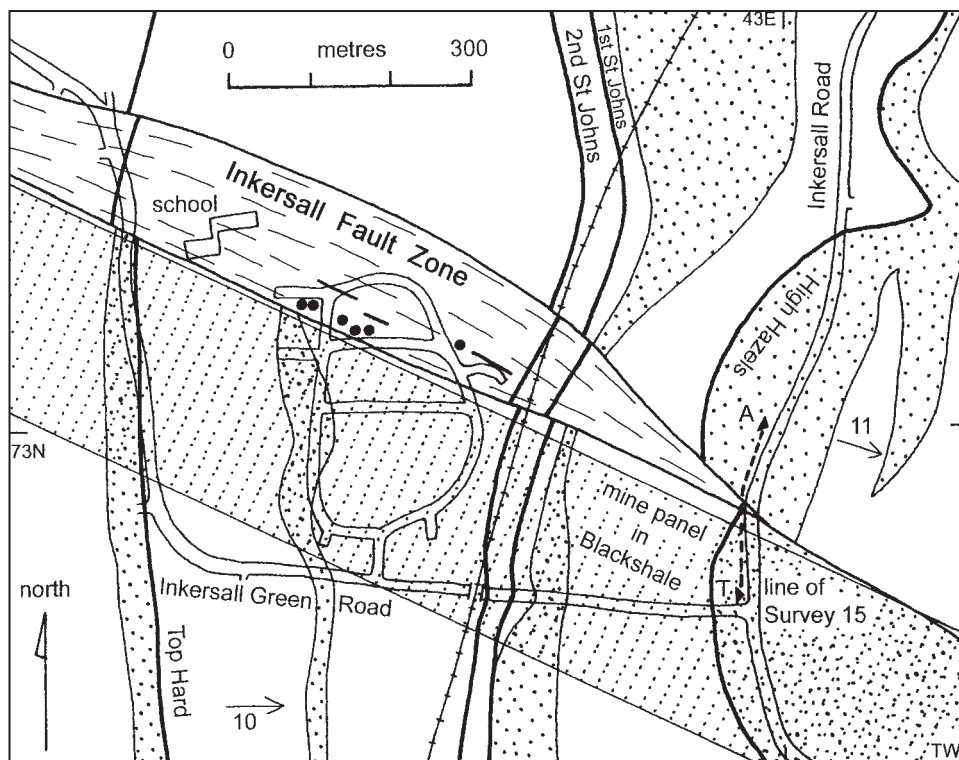


Figure 2. Geological map of the Inkersall Fault at Inkersall Green. Coal seams are named, sandstone outcrops are stippled, and the rest of the outcrop is mainly mudstone of the Coal Measures. The outer limits of the fault zone are as recorded on the BGS map; the short fault lines marked within the zone have been reactivated to create scarps. Solid circles indicate the sites of buildings that have been demolished.

sewers, drains and communication cables. Agricultural land has been disturbed due to the localised alteration of the gradient and flooding. Only recently have the factors that control the mechanisms of mining-induced fault reactivation been identified, following commissioned research into the influence of faulting on mining subsidence (Donnelly, 1994). As a part of this research, several case histories of mining-induced fault reactivation were investigated in the East Midlands (at some sites noted below, specific details and locations have been omitted, due to their current sensitivity and confidentiality).

Inkersall Fault, Chesterfield

This fault crops out in the Middle Coal Measures, near to the villages of Staveley and Inkersall, 6km east of Chesterfield. The fault zone is bounded by two sub-parallel fractures separated by a distance of a few hundred metres (Fig. 2). It is a steep normal fault with an apparent sinistral component of slip, dipping at 74°NE, with a throw of 30-50m. At least six coal seams have been extracted close to, and on both sides of, the Inkersall Fault.

The earliest records of fault reactivation were during the working of the Deep Hard seam in the 1950s, at depths of around 28m below Inkersall. Further phases of reactivation occurred in 1985, during the working of the Piper seam, at about 300m depth, from Markham colliery. This created surface movements that caused severe damage to property in the Inkersall Green housing estate, and generated fault scarps (Fig. 3) that were locally over 1.5m high. Eight houses (Fig. 2) were severely



Figure 3. Reactivation of the Inkersall Fault in the 1980s, caused widespread damage at the northern end of the Inkersall Green housing estate; this small graben feature formed across a road over a subsidiary fault within the Inkersall fault zone.

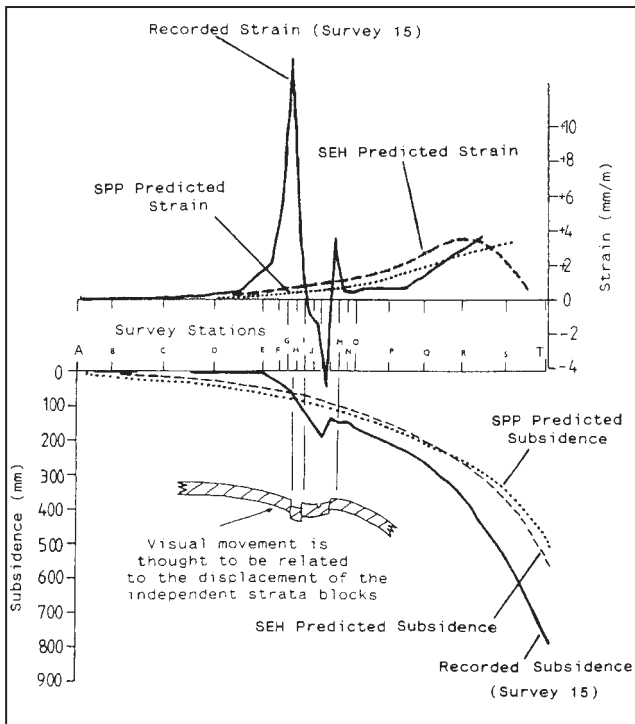


Figure 4. Profiles of subsidence and ground strain measured along survey line #15 across the Inkersall Fault (see Figure 2), showing reactivation in 1988; the broken lines indicate predicted profiles that took no account of the fault movement (after Phillips and Hellewell, 1994).

damaged by fault movements and were subsequently demolished; since the mining has ceased under Inkersall, new houses have been placed on some of these sites. The school was also severely affected and there was extensive damage to roads, walls, pavements, and utilities. Yet more houses on the fault zone were badly damaged or tilted and remained unoccupied for several years. Houses outside the fault zone suffered only the modest damage, as was normal for mining subsidence on unfaulted ground.

Further reactivation of the fault was monitored from August 1987 to December 1988, during the working of the Blackshale seam at a depth of 405m (Phillips and Hellewell, 1994). Observational data suggested that the strong sandstones fractured at outcrop, causing widespread damage due to the cantilevering effect of the individual blocks (Fig. 4). This explained reverse stepping, that is associated with cantilever movements of sandstone beds at outcrop. Residents described loud bangs and rumblings from deep underground; some assumed that these were blasting in the mine, but they originated from collapses in the mine and from disturbances in the faulted sandstones.

In 1991, following reports of further movements along the fault and renewed structural damage to the school and houses in Inkersall Green (Fig. 5), two monitoring lines were established. These were set across the fault along Inkersall Road and Inkersall Green Road and were surveyed regularly from

January 1992 to July 1993 (Donnelly, 1994). The new data confirmed the gradual demise of fault reactivation.

Sheepbridge Lane Fault, Mansfield

This fault is a major geological structure bounding the southern limb of the Hardsoft-Mansfield Anticline, aligned roughly NW-SE. The fault crops out in Triassic sandstones, which overlie the Coal Measures and are comparatively undisturbed, dipping gently to the east. Where the fault crosses Roebuck Drive a fault scarp, in the form of a gentle flexure, developed across the road surface during the working of the Deep Soft seam in 1984. The scarp was about 100m north of the inferred outcrop position on BGS maps. The structural damage was slight to moderate on the subsidence classification scheme (NCB, 1975), and was restricted to the road surface, pavement, kerbstones and a few houses.

At least five coal seams had been previously extracted in the footwall region of this fault since the early 1930s. Some of the workings, including those in the Top Hard seam, extracted coal right up to the fault, but there were no reports of fault reactivation until 1984. This does not necessarily imply that reactivation did not occur before this date, as maybe it was not recognised. In 1991, following observations of fault movement and reports of slight structural damage, two precise levelling lines were established along Roebuck Drive and Nottingham Road (A60) during the working of the Deep Hard seam at a depth of around 460m (Donnelly, 1994).



Figure 5. A scarp within the Inkersall fault zone during the early 1990s phase of reactivation, in the back garden of a house at Inkersall Green.

These were surveyed on a regular basis until August 1993, but did not record movement along the fault. Anticipating that reactivation may occur, specifically designed, narrow longwall panels were used to extract the coal; this reduced the effects of subsidence and fault reactivation.

Springswood Street, Temple Normanton

On 29th April 1966, a distinct scarp developed across Springswood Street and caused severe and extensive damage to several terraced houses. Local newspaper reports described the scarp and claimed that it appeared during the working of the Clay Cross Soft seam, 250m below the village, from workings at Williamthorpe Colliery (now closed). One newspaper report stated that *“local gas mains fractured and four houses were demolished piece by piece since they were too dangerous to be bulldozed”*. The scarp coincided with the outcrop position of the High Hazles seam and may have been generated by translational bedding plane shear and not by the reactivation of a fault. Shear movements along bedding planes are not uncommon during mining subsidence and have been documented elsewhere in Britain and in the Ukraine (Donnelly and Reddish, 1993).

Vale Road, Mansfield Woodhouse

In 1976, a fault scarp 1m high developed across Vale Road (Fig. 6), causing severe damage to the road, pavements, walls and neighbouring houses. Photographic evidence of repairs to the road surfaces implies that several phases of reactivation may have occurred. This is not uncommon, as faults are capable of multiple phases of reactivation, during mining of three or more seams, separated by periods

of relative stability. Although fault reactivation may continue for weeks or years after ‘normal’ mining subsidence has ceased, movements along faults do also eventually cease.

Shirburne Avenue, Mansfield

In 1992, a house was moderately damaged during mining subsidence after it had been built across a contact between the Magnesian Limestone and the Coal Measures. The structural damage was caused by dilation and translational shear along the lithological contact, during mining subsidence. The position of the contact was proved in 1992 by a seismic survey and an exploratory trench.

Papplewick

The reactivation of a fault generated a scarp that damaged a private house so badly that it was subsequently demolished. The BGS map shows a fault at outcrop in the Lower Magnesian Limestone and Upper Permian Marl at the site. The date of reactivation is not known, but it was probably during working of the Deep Soft seam in 1968, the Blackshale seam in 1971, or both.

Aspley, Nottingham

Reactivation of the 15 Yards Fault was noted by Lee (1965), when the Deep Soft and Deep Hard seams were mined from beneath its western side. Photographs show damage to at least six houses on Newlyn Drive and the ring road, prior to their demolition. There is anecdotal evidence for later reactivation of this fault (Donnelly, 1994), and it is still marked by a low ramp on the ring road.



Figure 6. Reactivation of a fault in 1976, generated a scarp 0.5m high that caused moderate damage to Vale Road, Mansfield.

Gulls at Pleasley Vale, Mansfield

At Pleasley, valley bulging occurs in mudstones on the lower and middle valley slopes causing cambering of the overlying sandstones and limestones that form a strong caprock on the valley margins. This has created the many gulls – caprock ground fissures that lie parallel to the valley sides. Where these have been undermined by deep coal workings, the gulls have dilated in the tension zones induced by subsidence. These fissures are generally filled with rock fallen from their sidewalls or are bridged by superficial deposits, soil and turf. Gulls were exposed in the cuttings of the Pleasley by-pass, but are now less clearly visible in the weathered faces. Where effectively masked by the soil cover on level ground, gulls are particularly hazardous in areas that are undermined.

Belvoir Street, Hucknall

Individual houses in the two long terraces down Belvoir Street were severely damaged when they were undermined in 1955 (Fig. 7). The site is on the outcrop of the Magnesian Limestone, and the damaged houses appear to lie above a few major fissures. The houses on each side along the terraces suffered only minimal movements, as they stood on stable blocks of limestone. The damaged houses had to be completely rebuilt, but subsequent mining of deeper seams caused renewed movement and repeated damage on a lesser scale to the same houses. Mining has now ceased and there has been no recent movement.

The A610 bypass, Ripley

In 1992, a graben about 60m long and 1.5m wide, was accompanied by subsidiary scarps, compression humps and en-echelon fissures across the roundabout on the A610 outside the police headquarters. The date when the scarps first appeared is not known, but their growth has caused visible damage to the road surfaces, roundabout, pavement, grass verges and fields almost continuously until the present day. The main scarp is currently marked by a low east-facing step in the road surface (Fig. 8), whose frequent repairs cause temporary traffic delays. There is no current mining beneath the site, and the continuing deformation of the ground is not fully understood.

Boothorpe Fault, Woodville and Swadlincote

The Boothorpe fault marks the northeastern boundary of the South Derbyshire coalfield. In 1995, the reactivation of the fault produced a west-facing fault scarp 0.2m high and over 50m long. This caused moderate damage to road surfaces, drains, brickwork, windows, doorframes, sills, kerbstones, and footpaths, but the scarp was less conspicuous in grass verges. Houses close to the fault were skewed and tilted, and a garage door



Figure 7. Damage to a terraced house in Belvoir Street, Hucknall, in 1955. The house has since been rebuilt.

directly over the trace of the fault was severely buckled. Gaps in rows of houses along the fault outcrop are thought to represent the sites of previous phases of fault reactivation that resulted in damage and subsequent demolition. En-echelon fissures were observed sub-parallel to the fault scarp, in asphalt and concrete driveways. Evidence for the reactivation of this fault was limited to field observation and geological mapping, and appraisal of mining records are required to verify this interpretation.

Burton Road and Ashby Heights, Woodville

In 1963, 1992 and 1994, reports from local geotechnical consultants, provided information on the reactivation of a fault, which was claimed to be the Boothorpe Fault, where one phase of movement caused the failure of an embankment in the rear of a house on Burton Road. This created a scarp, that was matched with further movements along the fault

in the Ashby Heights area of Norris Hill. Subsequent investigations by the BGS and others confirmed that the scarp did represent mining-induced fault reactivation, though this was not the Boothorpe Fault (which lies 400-500m southwest of the Burton Road site). However, other investigators have disputed whether the failure of the embankment was caused by the reactivation of a fault.

Moira Fault, Overseal

The reactivation of this fault, along the southwestern margin of the South Derbyshire coalfield, was first documented in 1939, on wartime coalfield reconnaissance field maps. The movement was interpreted as being induced by differential subsidence along the Moira Fault, caused by underground coal mining along the eastern side, in the footwall. A fault scarp was also noted on a 1970 BGS field map, along the outcrop of the Moira Fault. Unconfirmed reports of further movements along the fault were given in 1991 and 1995.

Copperas Road, Stanton, Burton

In 1985, several faults experienced mining-induced reactivation in Stanton, over the western tip of the South Derbyshire coalfield. The faults were proved in underground workings in the Main, Eureka and Stanhope seams, but there are no recorded details of the extent and intensity of damage caused by fault reactivation.

Groundwater rebound at Swannington

In 1996, field observations and groundwater monitoring around Swannington, Leicestershire, provided evidence of ground deformation as a consequence of minewater rebound (Smith and

Colls, 1996). Two scarps were observed across a field, 250m from the Church Hill pumping station (now demolished). These were sub-parallel, 0.7m high, trending NW-SE, over a length of 30-40m, in weathered clays of the Coal Measures. An amateur archaeologist, living nearby, reported that the scarps developed over an 18-month period. The upper scarp was more recent, but the lower scarp was more distinct and caused damage to a field drain by shearing. Comparable cases of movement along faults in the absence of mining, have been reported in other British coalfields. Though the processes are not fully understood, it appears that the faults are reactivated by the rising groundwater pressures that follow the cessation of mine drainage (Donnelly, 2000).

Engineering on faulted ground

The majority of faults in the former and current mined regions of the East Midlands are stable. However, under certain circumstances renewed ground movement with or without potentially detrimental side-effects can occur. Faults may enhance the permeability of a rock mass between mined seams and the ground surface, creating pathways for groundwater, minewater and mine gas discharges into the surface environment. The potentially explosive, noxious and asphyxiating gases include methane (firedamp), carbon monoxide (whitedamp), hydrogen sulphide (stinkdamp), 'stythe' (blackdamp – air that is depleted of oxygen and enriched with carbon dioxide) and radon. Rising groundwater along faults may also cause non-mining-related subsidence due to the washing out of clay or silt fines from granular materials. Aggressive waters may cause chemical attack of buried concrete structures and foundation piles. Fault zones that contain weak gouge infilling may create ground with reduced



Figure 8. The latest in a series of fault reactivation phases, from 1991 to 2000, causing moderate to severe damage to the A610 bypass at Ripley.

Figure 9. A fault scarp across a road in a housing estate at Inkersall, near Chesterfield, has reactivated as successive coal seams have been mined from beneath, causing repeated damage to the road and adjacent houses.



bearing capacity that can cause differential settlement to structures.

Following partial or complete abandonment of a coalfield, minewater pumping stations, necessary to keep modern active workings from flooding, are usually shut down. The environmental consequences of mine closure in urban Britain, in addition to the social and economic problems, are primarily related to the recovery of groundwater levels on termination of the pumping and consequent flooding of the abandoned mine workings. Should water levels rise to the ground surface, discharges may cause pollution and contamination of surface watercourses and aquifer water supplies (Dumpleton and Glover, 1989; Younger, 1994). Minewater rebound may increase porewater pressures within faults, thereby reducing normal stress across the fault and consequently reducing shear strength - to a level that reactivation may occur. Under these conditions, faults may be susceptible to reactivation in the absence of current mining (Smith and Colls, 1996; Donnelly, 2000). This is not expected to be widespread across the East Midlands, but may occur at sites on major faults that have a history of reactivation or have been previously undermined.

The hazards of fault reactivation

The purpose of this paper has been to draw attention to some effects of fault reactivation in the East Midlands, as a consequence of underground coal mining. These faults have generated distinct and occasionally extensive scarps across the ground surface, and have caused widespread damage to structures, utilities and land (Fig. 9). The scarps tend to be temporary features of the landscape, and

are soon destroyed by land redevelopment, necessary road repairs, or ploughing of fields. It is necessary to record the precise location and reactivation history of these faults, since they may have a significant bearing on future land use and civil engineering.

Where faults crop out in strong, well-jointed, competent limestone or sandstones, open fissures may be created by dilation of the fault plane. This is most common on sloping ground that also has gulls due to past cambering. Both fissures and gulls are commonly not visible where they are wholly or partly filled by debris and spanned by the soil cover.

Topographic scarps may be generated during mining subsidence in the absence of faults, while sharing the morphological characteristics of a fault scarp. These occur due to translational shear along bedding planes; they occur most frequently at bedding interfaces between strong sandstone or limestone and weak mudstone, and by differential displacements along coal seam contacts with mudstone.

There is often a tendency in mining regions to attribute the appearance of ground surface scarps to fault reactivation, merely due to the known existence of local mining. However, it is significant that topographic scarps may also be generated by natural processes such as cambering, or by other events such as the collapse of buried drains. Each situation requires detailed assessment of the geology and mining history. Reactivated faults are frequently the source of disputes, due to the damage that they may cause, and can result in legal claims for compensation. Unfortunately, due to perceived sensitivity, most of the cases of fault reactivation are

known only to those who have carried out subsidence-related investigations. There is no public record of fault reactivation activity (Donnelly, 1996), and consequently some areas in the old coalfields are undergoing regeneration and redevelopment on ground that has a history of fault movements. Provided that no further phases of reactivation, gas emissions or groundwater discharges occur, this should not present any problems, but total stability can rarely be guaranteed.

Residual movements along faults in the absence of mining have been reported at some locations. These are not all fully understood, and some cases may be due to the deterioration of the road or structure itself. In certain circumstances, for instance during minewater rebound following the cessation of pumping, renewed fault reactivation may be possible, but this can be difficult to prove.

The slight risk of fault reactivation should not blight land or property in the East Midlands, since most faults are now stable. Engineering geologists should familiarise themselves with the potential problems associated with faulted ground, and should identify these for engineers, builders, planners, insurers and conveyance lawyers who are concerned with both urban and greenfield sites where previous mining may have taken place.

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