The Origin of Fault Scarps & Fissures on Moorland Plateaux & in the Vicinity of Landslides, in the South Wales Coalfield, UK

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ABSTRACT: Fault scarps and fissures occur on moorland plateaux and in the vicinity of deep-seated landslides in the South Wales Coalfield, UK. These scarps may reach about 4 m in height and 3-4 km in length. The ages of the fault scarps and fissures are difficult to determine. Their relatively fresh and unweathered appearance would seem to suggest they were generated during subsidence as a result of coal mining which has taken place for some 150 years. However, their large magnitude, which make them dramatic features of the landscape, sets them apart from the much lesser features generated during coal mining subsidence in other UK coalfields. Some fault scarps seem to pre-date Ordnance Survey and British Geological Survey maps from the late 1800s-early 1900s. As total extraction (longwall) methods associated with fault reactivation had yet to develop widely at that time it is probable that mining subsidence alone could not have generated such distinct topographic features. The paper reviews the evidence of analogous non-mining fault steps and fissuring, mine abandonment plans and recent fissure treatment works to cast new light on the origin and development of these features. A conceptual model to demonstrate the causative mechanisms and evolution of fissures is also presented. The paper concludes that some fault steps and fissures developed in response to stress relief caused by deglaciation and periglacial activity and have subsequently undergone a later phase of development as a consequence of differential mining subsidence.

1 INTRODUCTION

Parts of the South Wales Coalfield form elevated moorland plateaux, which are dissected by incised glacial valleys. The interfluves between these valleys are disrupted by the extensive development of distinct, often dramatic fault scarps, graben and fissures. Dating of these features is difficult and somewhat speculative. Many of these almost certainly originate from, or have been exacerbated by, mining subsidence associated with past coal mining which has taken place over a period of at least several centuries. However, several other processes also seem to have occurred to generate the fissures and scarps. The aim of this paper is to draw attention to scarps, graben and fissures and to suggest causes for their generation.

2 GEOLOGY

The elevated moorland plateaux in the South Wales Coalfield consist of predominantly strong, well-jointed, often cross-bedded sandstones of the Pennant Sandstone Formation. These in turn, overlie alternating, interbedded sequences of siltstone, shales, mudstones and coal seams of variable thickness and quality belonging to the South Wales Coal Measures Group. These strata dip at low angles, and crop out on the middle and upper slopes of glacially steepened valley sides which have incised the plateaux. The rock mass is broken by discontinuities, which include faults, fissures, bedding planes and at least two sets of high-angle joints that trend north-east to south-west and north-west to south-east. The latter is associated with the principal orientation of faults across the coalfield (Figure 1).

Figure 1. (Left). The 4m high Tableland fault scarp that can be traced for several kilometers. (Right) A typical fissure, approximately 1 to 2 m wide, tens of metres long and of unknown depth (photograph Laurance Donnelly).

Superficial deposits consisting of 'head' cover most of the plateaux surfaces and upper slopes. These comprise thin layers of sandy gravel which has been derived from the underlying bedrock into which they grade in the weathering profile. Some of the head deposits have been transported downslope by solifluction that most probably occurred under periglacial conditions when the valley glaciers retreated some 23,000 years ago (in the late Devensian period) and in a later cold phase approximately 10,800 to 10,000 years ago (the Loch Lomand stadial). Variable thicknesses of peat occur in some areas and probably represent remnants of much more extensive deposits that have subsequently been eroded over the last 5000 years. Annual rainfall is around 1500mm and the hydrogeology of the region is dominated by unconfined aquifers formed by the sandstones. This is accentuated by the joints that allow downward infiltration of precipitation to replenish the aquifer, militating against any permanent streams on the interfluves and escarpments. Mine workings of coal seams that occur at the base of some sandstone units have considerable influence on groundwater flow paths.

3 MINING

The date of the first mining is not known, although it is likely to have taken place for several hundred years. The earliest mine workings from adits and small shafts exploited the coal where it cropped out. Organised room and pillar (or pillar and stall) workings were developed in the nineteenth century and were replaced by total extraction methods, using longwall techniques in the twentieth century. From the middle of the 1980s the industry declined rapidly, leaving few mines operating at the present day.

4 DESCRIPTION & CLASSIFICATION OF FAULT SCARPS & FISSURES

The fault scarps and fissures occur as distinct, dramatic and extensive landscape features that influence significantly the morphology of entire slopes. The reactivated faults appear as relatively unweathered, steep-sided, fault-scarp walls up to 4 m high and up to several kilometres long. They are most pronounced on the escarpments, formed from the strong, 'Pennant' sandstones. Some dissipate towards the centre of the plateaux and virtually all peter out where weaker shales and mudstones crop out on the upper and middle valley sides. They also occur in multiple sets with both uphill and downhill facing sub-scarps. Where the fault scarps have opposing directions of displacements they form graben. Usually these are oriented north-west to south-east parallel to the principal joint trends, slightly oblique to the north to south trending valleys. The graben channel groundwater to certain parts of the spring line, and can reactivate existing landslides and become the focus for the development of new instability.

The fissures may reach several tens of metres long and up to about 10 m wide where superficial deposits have caved. They are both parallel and oblique to the valley crests and are restricted to the plateaux areas and upper valley sides. When they intersect valley crests, blocks may become detached and transgress down-slope for several tens of metres. The following types of scarps and fissures have been recognized:

- Single scarps or fissures oblique or parallel to valley crests or ridge lines. These occur as isolated features, in en-echelon arrays, conjugate sets or as box-work and saw-toothed arrangements.
- Multiple scarps or fissures oblique or parallel to valley crests or ridge lines. These extend from the plateaux across escarpments and along upper valley sides but tend to peter out on the middle valley slopes, although the faults continue across the valleys.
- Clusters of scarps or fissures parallel to and near to, the crest of slopes or in the centre of the plateaux.
- Graben parallel to slope crests, which may be several tens of metres wide and long.
- Graben which cut oblique across interfluves.
- Clusters of obsequent or antislope scarps and fissures.

Fissure walls often display horizontal and/or vertical slickensides and most contain an accumulation of debris on their floors which has fallen from the roof and/or side walls. Further information on South Wales fault scarps and fissures may be found in Donnelly 1994, 2005, 2006, Donnelly et al., 2000a, 2000b, 2002. The fissures are envisaged to develop over time by the processes summarized in Figure 2.

5 PROCESSES CAUSING THE GENERATION OF SCARPS, GRABEN & FISSURES

The processes which cause the generation of fissures and reactivation of faults are not fully understood. They may however have originated by a combination of the following mining and geomorphological processes.

5.1 Mining subsidence

Subsidence is an inevitable consequence of longwall coal mining. It is conventionally modelled as a subsidence trough with compressive ground strains in the centre and tensile (extensional) ground strains around its edges (Anon 1975, Whittaker & Reddish 1989). Ground deformation occurs as a ‘wave’ as the longwall panel advances. The ‘angle-of-draw’, which defines the area-of-influence, is approximately 35^{o} from the vertical over the edge of the panel in UK coal fields. Geological faults are susceptible to reactivation when they are subjected to the strains induced by coal mining subsidence and are capable of several phases of reactivation during multi-seam mining. Fault reactivation changes the geometry of subsidence profiles and can affect the area-of-influence. Fault reactivation, in certain circumstances, may continue for weeks to several years after ‘normal’ subsidence has been completed but eventually ceases. Fault reactivation occurs throughout the coalfields of Britain. Reactivated faults which are unequivocally induced by mining subsidence alone rarely exceed 0.5 to c.1m in height, but usually much less than. The magnitude and extent of the scarps, graben and fissures in South Wales differ markedly from those cases investigated in other UK coalfields as they are much more pronounced and distinct. This may reflect topographic effects on the transmission of subsidence that make conventional modelling inapplicable.

5.2 Support pillars and shallow workings

Many of the fissures on South Wales moorland plateaux can be seen to be associated with inter-colliery pillars.

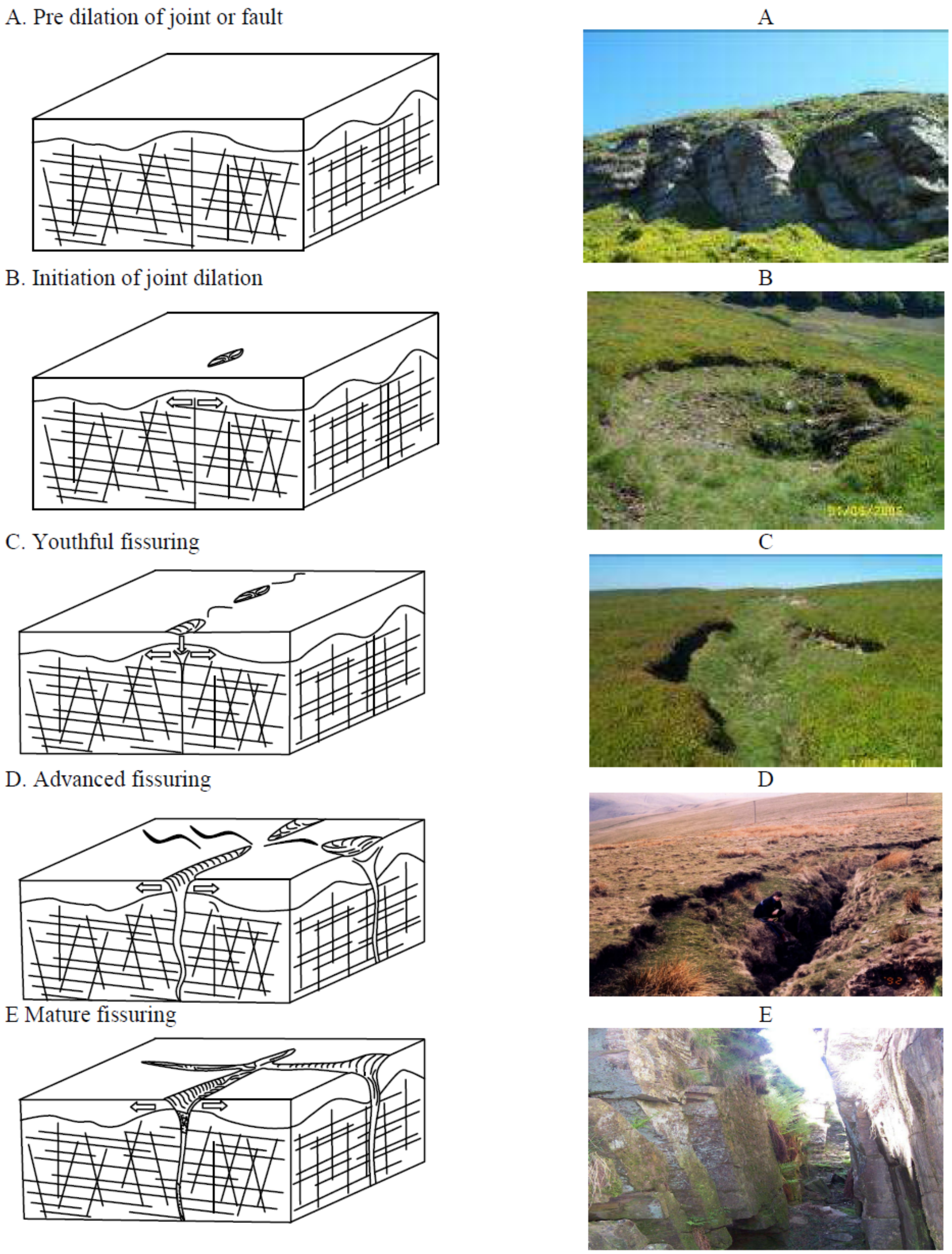

Figure 2. Schematic diagram to illustrate the evolution of fissures. Dilation of fissures in direction of arrows may be strongly influenced by glacial stress relief and/or mining-induced movements as shown in Figure 3. (A) Pre-fissuring, head and weathered sandstone forming a soil cover, above strong, well-jointed, Pennant sandstone. (B) Initial dilation of a high-angled joint causing the development of a circular subsidence depression, 1 to 5 m in diameter. (C) Youthful fissuring, subsidence depressions begin to coalesce caused by increased joint dilation. (D) Advanced fissuring, linear fissures develop, some bridged by superficial deposits that later collapse. (E) Mature fissuring, several fissures may coalesce, some may become filled with debris washed in, or fallen from the fissure walls (based on Donnelly 1994, photographs Laurance Donnelly).

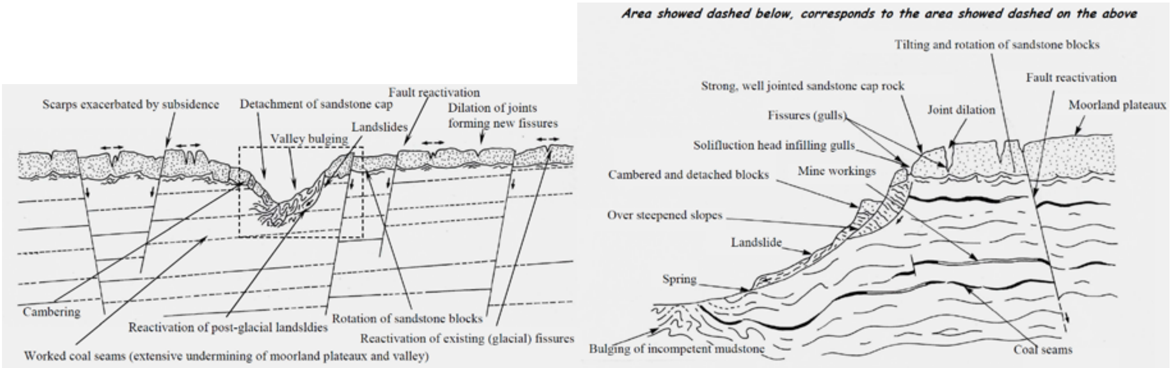

Figure 3. Schematic illustration (not to scale) to represent the coal mining subsidence-induced reactivation of faults and fissures on steep slopes and moorland plateaux, and their influence on the rejuvenation of ancient (probably post-glacial) landslides. It is possible that the faults were originally reactivated during the deglaciation of the valley sides, accompanied by stress relief, cambering and mass wasting. The faults and joints in the strong sandstone caprock, being subsequently exacerbated by mining subsidence, producing graben and up-hill and down-hill facing slope scarps, suggesting that lateral spreading of the moorland plateaux has taken place (after Donnelly 2005).

5.3 Landslides

Retrogression of deep seated landslides cause tension fissures parallel to the rear scarp as a result of stress relief due to the loss of support by a previous landslide event. Many examples of these exist behind the rear scarps that eat into the edge of the moorland plateaux in South Wales (Siddle et al. 2000; Conway et al. 1980).

5.4 Cambering and valley bulging

Cambering and valley bulging are characteristic of valleys incised into near horizontal strata comprising a rigid, jointed cap-rock overlying a thick layer of stiff, fissured clay or clay shale. The processes of cambering and valley bulging generates gaping fissures (known as gulls) on the crest of the slopes and progressively beyond, increasingly causing the disaggregation of the cap rock on the upper valley slopes (Hutchinson 1988). However, the classic features of major cambering are absent in South Wales and features associated with valley bulging have not been reported in any of the coafield valleys.

5.5 Stress relief of valley sides

Recently de-glaciated parts of Sweden, Finland, Norway, Russia, British Colombia and Scotland provide evidence for fault reactivation caused by the process of deglaciation. It has also been suggested that similar processes may have operated in the Pennines under conditions of periglacial weathering and erosion (Donnelly et al. 2002, Donnelly 2008). In the South Wales valleys periglacial weathering was limited to a relatively short period after the late Devensian glaciation when glaciers were retreating, and also during the Loch Lomand stadial. At these times the valley sides would have remained relatively stable, supported by glacier and ground ice. On retreat of the valley glaciers, glacial stress relief of the valley slopes would have been accompanied by periglacial weathering, weakening and erosion of the mudstone and shale sequences underlying the sandstone cap rocks. Rapid river erosion and down-cutting would have further contributed to stress relief of the adjacent slopes. These processes would have further reduced support of the overlying sandstones, causing dilation of joints and fissures and promoting failure of the sandstone strata at the plateaux margins. In addition to stress relief, the melting of ground ice is likely to have resulted in increased pore pressures within the argillaceous beds underlying the capping sandstone strata. leading to plastic deformation and 'squeezing' of the shales/mudstones beneath the capping sandstone. Under these conditions, some cambering of the edge of the sandstone escarpment would have been further exacerbated. It would seem reasonable that the extensional movements of the jointed sandstone strata are reflected in the formation of graben, and fissures, probably due to reactivation along existing fault planes and prominent joints.

5.6 Lateral spreading & gravitational rebound

Lateral spreading has been defined as, 'the lateral extension of a cohesive rock or soil mass over a deforming mass of softer underlying material in which the controlling basal shear surface is not defined' (Dikau et al. 1996). During lateral spreading the central part of the cap rock undergoes subsidence and is associated with compressive ground strains, although this may result in the dilation of joints oriented perpendicular to the principal compressive stresses, or the opening of joints at depth. The gravitational adjustment of the plateaux in response to movements below caused the lateral spreading of the cap-rock and the generation of graben by the reactivation of fault and joint networks. The lateral spreading of the plateaux is controlled by the geological structures within the rock mass and the distribution of the principal rock mass discontinuities. These deeper seated ground movements cause subsidence of the individual blocks and the generation of scarps and fissures on the ground surface. Spreading would break up the Pennant Sandstone Formation caprock into successive blocks or units and generate fault scarps (formed by the shear displacement along pre-existing tectonic faults), topographic scarps (formed by the shear displacement along joints), ridges, graben, fissures, depressions, cambered and displaced blocks. These features extend for several hundreds of metres and may occur up to several hundreds of metres from the crest of the plateaux. This may develop many tens to hundreds of metres beyond the valley crests.

6 DATING FAULT SCARPS & FISSURES

Dating the time when fault scarps and fissures were initially generated or reactivated is difficult. There are very few cross cutting relationships such as walls or other man-made structures or superficial deposits. Lichen and vegetation colonisation rates, pollen, or radiometric dating of silica exposed on fault scarps have proven to be not possible or suitable in most situations for dating purposes. However, the relative date of some fault scarps and fissures may be estimated by the analysis of the following:

- Geological maps published by the British Geological Survey, supplemented by supporting field slips and field notebooks, and topographic maps published by the Ordnance Survey
- Mine abandonment plans
- Field observations

6.1 Geological and topographic maps

Some Ordnance Survey and British Geological Survey maps (including published versions and unpublished field slips) record the presence of landslides, fault scarps and fissures. Although these records do not give a precise date for their initiation, they can confirm their existence at a given point in time. For instance, the Tableland fault scarp, which passes behind the backscarp of the Darren Goch landslide, pre-dates the Ordnance Survey map of 1876 and is indicated with the annotation '*major fault scarp'*. The geological maps of 1896 and 1900 record the Darren Goch landslide and the inferred outcrop of the faults, but the scarps are not noted. The 1949 geological survey records the increase in size of the landslide and, along a 600 m section of the Tableland fault, the annotation, '*subsidence crack*' is given. To the east of the landslide a note on the geological field slip states, '*well-marked subsidence step 10 feet high*' along the outcrop of the fault.

Another notable example is the Darren Ddu landslide, which is located on the western flank of the Ebbw Fach Valley. Here numerous extensive fissures, scarps and graben pass in close proximity to the backscarp of the landslide. The field slip of the 1894 geological map notes the presence of the landslide and a '*rift 1 foot wide, great depth in sandstone'* sited on the present strike of a graben fault scarp. The field slip notes also indicate '*no sections*' along the slope crest implying no exposures were seen in outcops or extensive open fissures during the field survey. The later 1925 field slip of the same area records the presence of coal seams and the landslide but not the presence of any '*rifts*' scarps, graben or fissures, all of which exist today as conspicuous morphological features. However, it is known that the 1925 survey was undertaken solely for the purposes of coal seam identification and not for detailed re-mapping of other lithologies or morphological features (Donnelly et al. 2000a).

The examples given above highlight the caution and careful research required in interpreting old maps and associated field notes. The absence of indicated fault scarps and fissures on turn-of-the century geological maps can not be taken as clear evidence that they did not exist. This can be in part explained by the fact that around this time the emphasis was on the national need to identify and classify economic deposits (particularly coal seams), with fault scarps and fissures being of only minor interest.

6.2 Mine abandonment plans

It was probably not until the middle part of the 1900s when total extraction methods took place in the footwall and/or hanging wall regions of the faults or in un-faulted ground beneath the plateaux. Therefore, were partial extraction methods of mining and any associated subsidence sufficient enough to generate the scarps/fissures (recorded as up to 10 feet, or c. 3 m, high on some maps) in the latter part of the 1800s? This is currently difficult to prove and requires further research and investigation.

6.3 Field Observations

During fissure treatment works in 2007, a fissure associated with a graben fault scarp on the sandstone plateau above the Darren Ddu landslide was found to contain peat to a depth of approximately 1 m. The bottom of the fissure contained gravely peat, which graded upwards into soft amorphous to fibrous peat, with some fine sand layers. This peat soil profile was interpreted as being formed insitu. If so the dilation of the fissure must pre-date the formation of the peat. As peat is no longer forming, it must have been preserved in the fissure from the time when peat formed a more extensive thin veneer over the plateaux and prior to its removal by weathering and erosion. The sand layers in the upper peat profile potentially represent sand deposits which have subsequently been blow-in, washed-in or fallen into the fissure. The precise date for peat formation in South Wales is difficult to determine but in the Black Mountains this has been estimated to have been between 7500 and 4000 years BP (Charman 2002). In the UK the removal of peat by erosion and anthropogenic processes possibly took place between a few thousand and a few hundred years ago. The observation of peat filled fissure may therefore suggest that it is several thousands of years old, which predates mining (Figure 4).

Figure 4. Peat filled fissure showing also the vertical displacement of the orange-purple-brown iron pan (an oxidized horizon) which often tends to develop at the bottom of a peat profile (photograph Howard Siddle)

7 CONCLUSIONS

Fault scarps, graben and fissures occur as pronounced, distinct and often extensive morphological features of the South Wales Moorland plateaux. It is difficult to determine the age when these features were initiated and reactivated. There remains the possibility that some of these originated several thousands of years before present by processes associated with the deglaciation of the valleys under periglacial conditions. This may have caused the reactivation of faults and the dilation of high-angled joints in the 'Pennant' sandstones, facilitated by the weakening of the underlying mudstones and shales which form the sides of the valleys underlying the stronger sandstone cap rock. Reactivation of the faults and renewed dilation of the fissures is likely to have occurred as a result of strains induced by coal mining subsidence associated mostly with longwall coal mining extraction methods. It is not currently possible to determine which faults, graben or fissures were caused by geomorphological process associated with valley deglaciation and those exacerbated or accelerated by mining subsidence.

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