# Origin and structure of Devensian depressions at Letton, Herefordshire

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**Abstract:** Circular to oval enclosed depressions in soft sediments of Pleistocene age are normally interpreted as being either glacial or periglacial in origin. Where these features are developed in glacial sediments, a glacial (and specifically 'kettle hole') genesis is considered most likely. Some have been re-interpreted as periglacial in origin and are thought to be the remains of cryogenic mounds (former pingos or palsas/lithalsas). A group of enclosed depressions in the Letton area of Herefordshire within the Last Glacial Maximum ice limit have been investigated by electrical resistivity tomography and ground probing radar. Their morphology and internal structure, and their existence in glacio-lacustrine sediments of Late Devensian age suggests that they are kettle holes resulting from ice block discharge into shallow lakes. The lack of any ramparts and the fact that they do not overlap also indicate that they are not the remains of cryogenic mounds.

There are numerous groups of circular to oval enclosed depressions situated in soft sediments of Pleistocene age in northwest Europe. In formerly glaciated terrain these have often been interpreted as kettle holes, a form of proglacial feature resulting from the burial of ice blocks and their subsequent melt-out, which causes localised ground subsidence (Maizels, 1977). Since these features are relatively common and merely confirm the role of glaciation in the landscape, they have not generally been investigated in detail. Nevertheless, some Last Glacial age kettle holes in Britain are notable for the organic materials that were preserved within them, such as woolly mammoth (*Mammuthus primigenius* (Blumenbach), Allen *et al*, 2009).

In the 1960s, interest in enclosed depressions increased following the publication of investigations of such features in Belgium and Wales (Pissart, 1956, 1963). The features were interpreted not as kettle holes, but as the remains of former pingos - mounds or small hills that develop in permafrost through the growth of a core of ice (Mackay, 1998). Pissart referred to them as 'relict pingos', and their distribution appeared to provide a means of reconstructing the former distribution of permafrost (Washburn, 1983).

Distinguishing kettle hole depressions from relict pingos became essential. It was determined that a key diagnostic criterion for relict pingos was the existence of a raised rim or rampart around the depressions (Watson, 1971; Watson and Watson, 1974; Sparks *et al*, 1972). At that time, kettle holes were not generally believed to display this attribute (*cf.* Maizels, 1992). The ramparts were believed to have formed by material gradually slipping off the sides of the mound and/or from a displacement of material from the interior of the mound during the growth of the ice core (Mackay, 1988). Modern arctic pingos of the hydraulic type were originally seen as the modern analogue (Gurney, 1998), although more recently a palsa (Gurney, 2001) or lithalsa (Pissart, 2002) analogue has been invoked. At some sites the rampart around the features was incomplete or even completely absent (Gurney, 2000). The rampart may have originally existed but had been lost through subsequent land use (ploughing, drainage operations etc). Such rampart-less features require information on the sub-surface to enable correct interpretation.

Although research has tended to focus on either glacial or periglacial origins, it must be remembered that there are many other explanations for such

***Figure 1**. Feature #30; this depression has been dug out so that it now forms a perennial pond; it does however indicate the typical size and shape of the depressions at Letton; see Figure 2 for its exact location.*

enclosed depressions. These include dissolution (to form dolines), nivation, subsidence, mineral workings (e.g. collapsed flint mines, marl pits etc) and bomb craters. Detailed discussions of the possible origins for the enclosed depressions of Norfolk are given by Prince (1961, 1964) and West (1987).

Until recently the investigations of these features primarily involved mapping and the excavation of trenches through the features. A more sophisticated and less invasive approach could now include the use of geophysical techniques to determine the sub-surface structure of the depressions in combination with mapping. To date only a few sites in west Wales have been subject to such an approach, at Cledlyn (Harris, 2001) and at Llanio Fawr (Ross *et al*, 2007). The investigations at the latter site favoured a glaciofluvial origin.

## The Letton site

This site lies about 15 km northwest of Hereford. It has low relative relief and is situated to the north and just above the level of the floodplain of the River Wye. Upstream of Hereford, the Wye is underlain by the Raglan Mudstone Formation of the Devonian Lower Old Red Sandstone (Brandon, 1989). Herefordshire may have been glaciated in several of the Pleistocene cold stages, but only two left evidence, namely the Anglian cold stage and the Late Devensian (Brandon, 1989). Within the relatively well-defined end moraines, Late Devensian glacial deposits are characterised by sizeable areas of irregular relief containing hummocks and kettle holes (Luckman, 1970) along with glaciofluvial and glaciolacustrine sediments (Richards, 2005). The study site is over 7 km inside the Devensian limit and the surficial sediments are believed to be glaciolacustrine in origin, according to the mapping provided by the 'BritIce' project (Clark *et al*, 2004), although these may be underlain by glacial till.

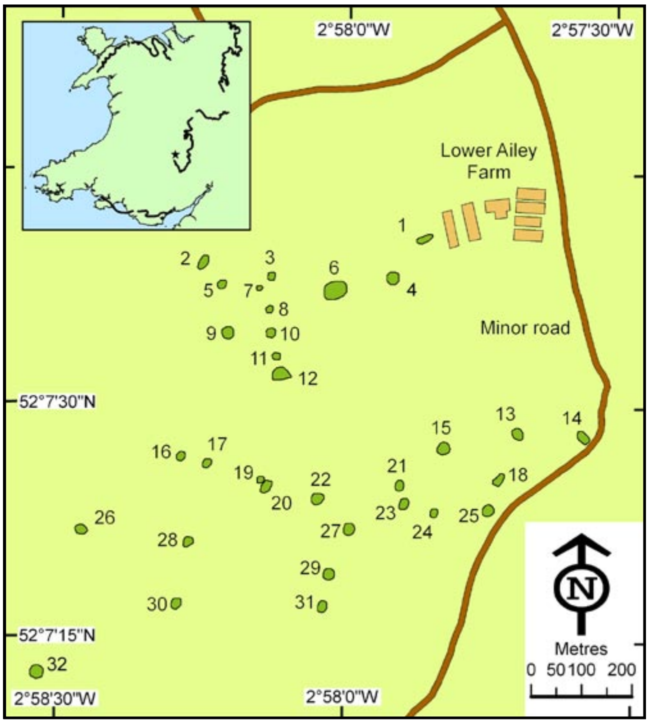


***Figure 2****. Distribution of enclosed depressions at Letton; the inset map indicates the site location (black star) and the Devensian ice limits (bold black line); the depression investigated using geophysics was Feature #21.*

In order to determine the origin of the depressions (Fig. 1), detailed geomorphological mapping and geophysical investigations were undertaken. The mapping was based upon field survey using a base of 1:10,000. The resultant mapping (Fig. 2) was digitised and incorporated into a Geographical Information System (GIS, using ESRIs ArcGIS).

Thirty-two depressions were mapped, and these were circular to oval in plan, although some of their shapes have been modified by the creation of a hedge-line or through some other agricultural development. The depressions range from 10 to 55 m across and are from 0.2 to 0.8 m deep. Some of them are occupied by perennial ponds (Fig. 1) where they have been artificially deepened to provide a source of water for livestock; others have a pool of water only during wet periods.

The ground surrounding and between the depressions is generally of low gradient and is without any specific micro-topography; specifically it cannot be described as 'hummocky'. The spatial pattern of the depressions is not unlike that of kettles holes elsewhere in the Welsh borders (Worsley, 2005). None of the depressions mapped has a convincing rampart and none appears to be 'mutually interfering' (i.e. overlapping), which are both characteristics of relict cryogenic mounds (Gurney & Worsley, 1996).

## Internal structure of Feature #21

In order to determine the distribution and structure of the sediments at depth, two geophysical methods were used to investigate the 2D structure of one of the depressions (Feature #21 on Figure 2). This depression is about 30 m across, and 0.65 - 0.75 m deep. Electrical resistance tomography (ERT) profiles were acquired on two lines (Figs. 3 & 4) at right angles to each other, using a Campus Geopulse multi-channel switching unit and making measurements using a Wenner-Schlumberger array. The two arrays had 25 and 32 electrodes, on a spacing of 3 m. Ground probing radar (GPR) was also employed with GSSI equipment over the same profiles using both 400 MHz and 100 MHz bistatic antennae. The two profiles were oriented northwest to southeast and at right angles to that, and crossed each other in the centre of the depression.

The ERT profiles of Feature #21 confirm the lack of an obvious rampart at the surface or at depth. The sub-surface materials appear to have a three-layered structure (Fig. 4). The surface layer is about 4 m thick, with a resistivity in the range 45-75 Ωm. This overlies a low resistivity layer (25-40 Ωm), whose thickness is

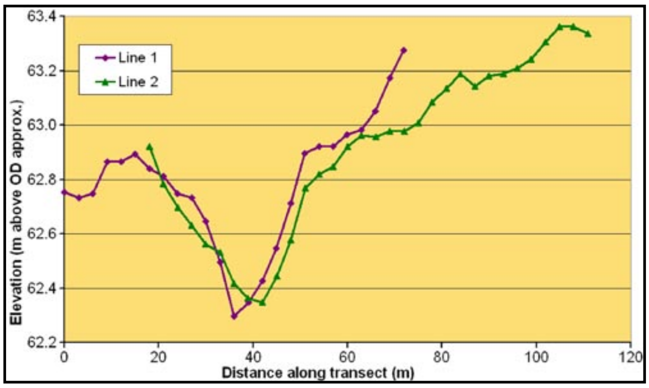


***Figure 3**. Topographic profiles across the depression; the two lines intersect at right angles at the 39 m point.*

not well constrained, but is tentatively interpreted as about 6 m. It overlies material of higher resistance (40-50 Ωm).

Augering down to about 1 m in the depression indicated that the upper layer beneath the topsoil is made of brown silts, locally containing small nodules of iron oxide. Comparison with a recent borehole located about 200 m to the south, suggests that the middle layer is composed of blue-grey clay to silt, with the upper layer being of oxidised clay and silt. Both these layers are inferred to be lake deposits (glacio-lacustrine) from the Late Devensian. The increased and laterally variable resistivity of the upper layer reflects the partial de-saturation and consequent oxidation, of the lacustrine silt/clay. The increase in resistance at depth may reflect the influence of Devonian bedrock, or older Pleistocene deposits (probably glacial till) beneath the lacustrine sequence. The lateral variation in resistance in the upper layer does not show any obvious relationship to the position of the surface depression.

The GPR profiles obtained with the 400 MHz antenna show that the ground absorbs the radar wave and generally has little internal contrast, so that reflections are weak to absent. The 100 MHz antenna shows some additional reflections down to about 75 ns (about 2 m deep) and 50 ns associated with the depression. The deepest reflector is overlain by layers that thicken to the centre of the depression; this has been interpreted as a deformed near-surface layer overlain by accumulated sediment. Data from the GPR suggest that the depression has been formed, and was perhaps enhanced by, local subsidence of the ground, thereby deforming a near-surface soil layer. The accumulation of up to 2 m of sediment within this depression, implies enhancement of the feature over a significant period of time.

## Origins of the depressions

The geophysical imaging provides evidence for understanding the origin of depression #21, and by inference for the other depressions as well. Taken with the results of the nearby borehole, the ERT and GPR results are consistent with a thick sequence (the ERT implying at least 10 m) of fine-grained sediments being present. The ERT further suggests that partial to total de-saturation and oxidation of these sediments has taken place to about 4 m depth (which may represent the water table depth at this site, with its potential link to the River Wye to the south). The GPR profiles are consistent with the perpetuation of the investigated depression by a positive feed-back mechanism. The sediment of the infill provides an additional sediment load which has caused continued slow subsidence of the underlying material, presumably accommodated at depth by compaction of the soft, saturated, lacustrine, silty clays.

The lack of ramparts at the surface or at depth, combined with the fact that none of the depressions displays any so-called 'mutual interference' (*cf.* Gurney, 2000 and Pissart, 2002), suggests that a hypothesis of periglacial and specifically cryogenic mound development is untenable. The presence of the depressions in soft glacio-lacustrine sediments points strongly toward a glacial origin. Other areas with numerous depressions in Herefordshire are associated with hummocky moraines and are clearly glacial in origin. All the evidence leads us to conclude that these depressions are almost certainly glacial in origin and represent the remains of kettles holes.

The glacio-lacustrine origin of the sediments within which the depressions are formed indicates that ice blocks were discharged into a lake or lakes (Theakstone, 1989). The blocks then became grounded in the shallow water, and remnants of them become buried in the lake sediments. Following drainage of the lake, the buried blocks of glacier ice thawed slowly over time, creating the depressions within the surficial sediments. This environment of deposition led to a landscape with kettle holes but no intervening micro-relief, which is in contrast to other sites with kettle holes in Herefordshire (e.g. on the Kington-Orleton moraine). The assumption that 'kettled' topography is always formed by the passive decay of blocks of glacier ice derived from the *in situ* decay of ice at a stagnant margin may not always apply. Observations following

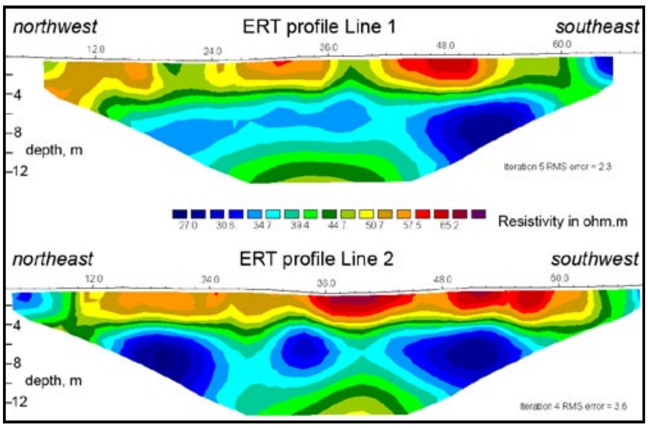


***Figure 4**. Electrical resistance tomography (ERT) profiles across the depression that is Feature #21.*

the 1996 jökulhlaup in southern Iceland has suggested that such outburst floods provide for the release and burial of ice blocks by a mechanism that is far from passive (Fay, 2002).

The thirty-two enclosed depressions at Letton are concluded to be glacial in origin and are likely related to the thaw of ice blocks buried in glacio-lacustrine sediments during the Late Glacial period (*cf.* Ross et al, 2007). Unlike other kettle holes within the glacial sediments of Herefordshire, they are not associated with 'hummocky moraine' (Luckman, 1970).

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