May 2014

GALMOY MINE

Investigation of the Possible Causes of the Sinkhole in the vicinity of the Galmoy Mine Workings and Recommended Remediation

Submitted to:
Galmoy Mines Ltd
Galmoy
Co. Kilkenny

REPORT

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EXECUTIVE SUMMARY

Background

Golder Associates (Golder) was contacted by Galmoy Mines (Galmoy) on Saturday 15 February 2014 regarding the development of a 'sinkhole' (dropout doline) on lands in the vicinity of the CW Orebody at Galmoy. The sinkhole appeared sometime between the evening of 14 February and the morning of 15 February 2014. No further subsidence has occurred since that date and there is no evidence of any cracking or ground movement in the surrounding area. On inspection it was found that the sinkhole was located above the footprint of a, sub-vertical, NNW-SSE trending structural feature (the Main Fissure) that had been encountered during mining of the CW Orebody. Golder was tasked with reviewing the mechanisms that caused the sinkhole to occur and evaluate the risk of further sinkhole development.

Underground mining (and dewatering) at Galmoy began in mid-1995 and continued until early 2012 and dewatering until 2013. Groundwater rebound was rapid and the water-table had fully recovered to above pre-mining conditions by March 2014.

The first orebody to be mined at Galmoy, the CW Orebody, is a flat, tabular, undulating shaped orebody dipping gently at 10° to the west. Ore was extracted using Room and Pillar mining by conventional 'blast, load, haul and dump' to a central underground crusher. Open excavation support was provided by standardized rock-bolt patterns and shot-crete depending on ground conditions. Where fissures or poor ground was encountered, a combination of rock-bolts, reinforced shotcrete and metal straps (depending on ground conditions) were installed with drainage pipes for water collection and management. The mined out stopes in the CW Orebody were extensively backfilled with cemented pastefill.

Dimensions of the Sinkhole

The sinkhole is elliptical in plan with its long axis in alignment with the Main Fissure. Its dimensions are; long axis 13 m, short axis 8 m, depth ca 7 m with an approximate volume of 550 m^3. The sinkhole is deep-sided with no bedrock visible in its walls or base, both of which are composed of sandy glacial till.

The sinkhole is at an elevation of ca. 139 m AOD, approximately 80 m above the mine workings. Bedrock is estimated to occur at ca 132.5 m AOD, with the water table at ca 123 m AOD.

Geology

In common with large areas of the Irish Midlands the Galmoy area is underlain almost entirely by a sequence of Lower Carboniferous limestones. The stratigraphic sequence at Galmoy (from oldest to youngest) consists of the Lower Ballysteen Limestone Formation (ABL), the Waulsortian Limestone Formation and Supra-Waulsortian limestones. Some of these limestones are very impure, mainly argillaceous, and hence do not support the development of karst landforms and drainage. However, there is widespread agreement that over most of the Midlands the limestones were subject to extensive, but episodic, karstification during the Tertiary Period, 65.5 – 2.6 million years ago (Drew & Jones, 2000; Coxon & McCarron, 2009).

During the early Tertiary a karstic drainage system developed in the Galmoy area, with water movement concentrated along predominantly NNW-SSE and N-S trending strike slip fissures/fractures/faults and in particular along what has subsequently become known as "The Main Fissure". This sub-vertical, NNW-SSE trending feature pinches and swells dramatically over very short distances both along the dip and strike, with weathered areas up to 8 m wide being recorded laterally (from underground mapping). In contrast to the NNW-SSE and N-S trending features the E-W trending faults such as those in the G Fault Zone tend to be tight and there has been minimal water movement along them and hence an absence of karst.

By the mid-Tertiary karstification had reached a depth of at least 40m in the Galmoy area and there were solution dolines (sinkholes) in which organic clays accumulated (Coxon & McCarron, 2009). However evidence from underground mapping indicates that karstification had developed to ca 90 m depth in the case of the CW Orebody. During the Quaternary the climate oscillated between cold (glacial) and warm (interglacial) stages. The extent of glacial erosion and the number of times that ice advanced over the Midlands is still a subject of debate but there is agreement that the last widespread ice sheet had begun to melt by 14,500 years ago and that the Midlands were ice-free by the start of the Holocene, about 12,000 years ago. By this time the voids in the limestone that had formed in the Tertiary had become clogged with sediment and there was no longer any active groundwater circulation. The term ‘palaeokarst’ is used to describe such “buried, inert and fossilised karst” (Jones, 2000).

Across the Midlands the limestone surface was buried beneath varying depths of superficial deposits, primarily of glacial and fluvio-glacial origin. At Galmoy the superficial deposits primarily consist of 5 - 6 m of sandy glacial sediments (commonly called Boulder Clay) with a well-developed clay matrix. In common with much of the limestones in the Irish Midlands groundwater flow is through immature fissures some of which have been enlarged by Holocene dissolution to form channels and conduits (Drew, 2008).

Mineral exploration boreholes, including those in the Galmoy area provide important evidence for palaeokarst in Ireland and at Galmoy underground mapping of the CW Orebody identified palaeokarst at the orebody horizon in an area beneath the footprint of the sinkhole. An area immediately to the west of the Main Fissure was found to be choked with clays and dolomite sands when it was mined into. Material was not extracted from this area as it carried no grade.

Conceptual Groundwater Model

The Galmoy mining district occurs within a tightly-bounded block of Waulsortian dolomitised limestone (the “Galmoy Block”). All of the orebodies occur close to the southern end of the Galmoy Block, in close proximity to the G Zone Fault Zone. During dewatering, the boundaries of the block acted to localise the area of drawdown, which is very well defined around the mine area. The Galmoy Block is approximately 8 to 10 km² in extent.

Groundwater recharge to the Galmoy Block is mostly derived from infiltration of precipitation and local runoff. Most of the block has a natural recharge of between 200 and 350 mm/yr, consistent with other estimates in the area, such as nearby Lisheen Mine where water balance estimates provide a “dewatering” recharge rate to the Waulsortian of about 275 mm/yr. This primarily occurs between October and March when rainfall exceeds evapotranspiration. However, it should be noted that both the annual rainfall amounts, and the seasonal pattern of rainfall, have been variable over recent years.

Geophysics

To assist in the understanding of the mechanisms of the sinkhole formation and investigate the potential for repeat events, a geophysical investigation involving Ground Penetrating Radar (GPR) and Electrical Resistivity Imaging (ERI) was undertaken. The investigation focused on identifying the presence of voids within the base of the overburden above the bedrock and the extent of fractured/fissured (weathered) dolomitised limestone under the landowners’ field in the vicinity of the Main Fissure and under the adjacent road.

A total of 540 GRP profiles using a 100 Mhz frequency transmitter was used to collect data in the field surrounding the sinkhole. In addition a total of 9 ERI lines were surveyed, with depths of investigation ranged from 50 to 80 m below ground level. Available borehole information was correlated with the geophysical data to provide confidence in the overall ground model in the vicinity of Main Fissure.

The GPR surveys did not identify any reflectors in the overburden indicative of open cavities/voids. However, it did identify a number of reflectors that demonstrate the highly varied nature of the overburden and bedrock interface. For example, in the vicinity of the Main Fissure, profiles display thickening of the overburden, indicating the presence of a bedrock depression along its strike. The variable nature of the subsurface is to be expected in well glaciated, heavily weathered, fractured, dolomitised limestone bedrock which exhibits palaeokarst features.

The ERI pseudosections show similar resistivity patterns which correlates well with information provided by existing mineral exploration boreholes by confirming the highly variable nature of the ground conditions underlying the field in the vicinity of the Main Fissure. In contrast, the pseudosection for the line along the road exhibits more massive, less weathered/fractured rock underlying the public road. This indicates that in general, the rockmass underlying the field in the vicinity of the Main Fissure is naturally more weathered/fractured than that underlying the road.

In summary, no reflectors were detected from the geophysical surveys conducted that indicate the presence of a void(s) in the superficial material that could result in a sinkhole similar to the event on the 14/15th February 2014.

Ground Model in vicinity of Sinkhole

The overburden in the vicinity of the sinkhole is approximately 6 – 7 m in thickness and is typically comprised of topsoil (ca. 0.2 m), over sub-soil (ca. 0.6 m in thickness), over ca 2.5 – 3 m of sandy glacial till, over a more clay rich, cohesive glacial till (ca.2.5 – 3 m).

From borehole and underground mapping information the bedrock underlying the sinkhole is comprised of dolomitised Waulsortian limestone, which is approximately 90 m in thickness. The initial top 20 to 30 m tends to have more intensely weathered fractures and joints. Below this weathered zone the rock tends to become more competent, with less weathered and tighter fractures and joints. Within 10 to 20 m of the orebody hangingwall, areas of highly weathered ground can occur. These areas of deep seated weathering which developed during Tertiary times are associated with sub-vertical features and sub-horizontal argillaceous bands and can also occur within the orebody itself.

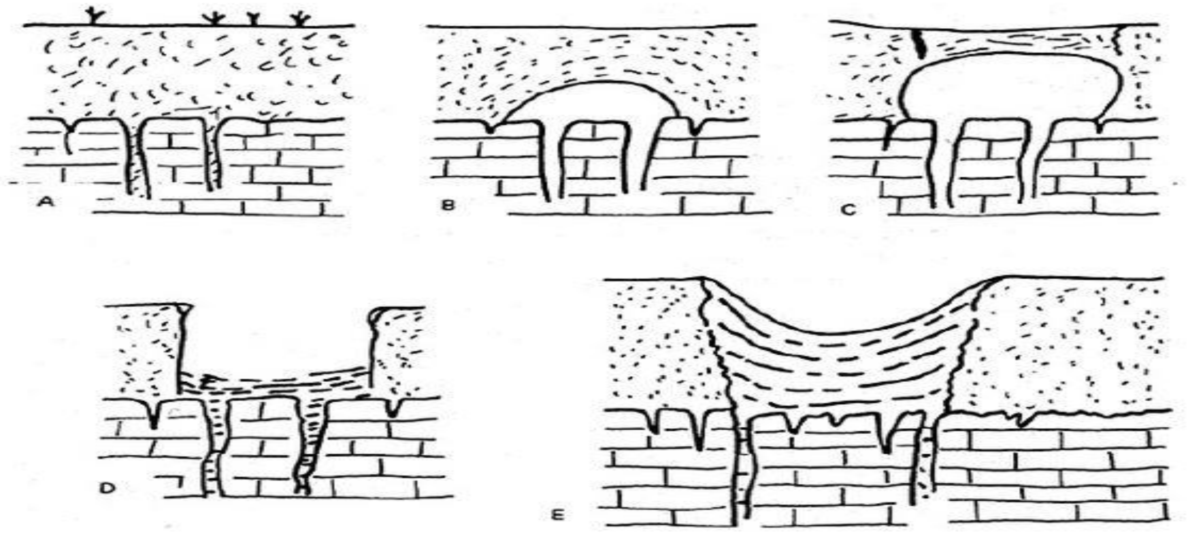
Palaeokarst sediment filled features and water ingress to the underground workings are predominantly associated with the NNW-SSE sub-vertical structures (i.e., the Main Fissure which underlies the sinkhole) and N-S trending sub-vertical structures.

Potential Mechanism of Sinkhole Formation

Closed depressions, commonly referred to as sinkholes or as dolines, are the commonest landform in karst areas. There are six broad types of sinkhole and in all cases focussed vertical groundwater movement and bedrock dissolution are essential precursors to their formation. In solution sinkholes there is dissolutional lowering of the bedrock surface with drainage focussed on a central fissure or fissures. Environmental change may lead to solution sinkholes being filled with sediment and buried sinkholes are common in Ireland.

Formation of collapse sinkholes requires focussed dissolution of bedrock at depth leading to the growth of a void in the roof which ultimately fails. Cap-rock sinkholes are a special type in which the collapse propagates upwards through non-limestone cover rocks.

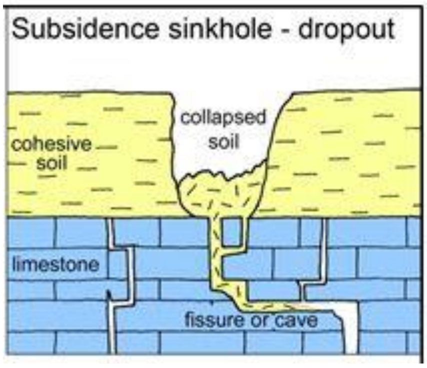
There are two types of subsidence sinkhole, dropout and suffosion, which have a common origin. A fissure in the bedrock is enlarged by dissolution until it reaches a size sufficient for turbulent flow and the transport of sediment. Where the superficial deposits overlying the bedrock are non-cohesive they gradually slump into the enlarged fissure forming a broadly conical suffosion sinkhole. Where the superficial deposits are cohesive the basal sediment is washed into the bedrock fissure forming a void that grows upwards from the bedrock-overburden interface and forms an arch. The arch grows until a threshold is reached where it is no longer able to support the overburden. The arch then suddenly gives way forming a dropout sinkhole with near-vertical sides.



The Formation of a Cover Collapse Doline. A) Solutional openings in the bedrock wash material downward. B) A small arch forms in the subsoil where the material is being washed away. C) The void grows in size as more material is being downwashed until it reaches a critical point and starts to rupture. D) The arch suddenly collapses as it can no longer support its own weight. E) Overtime the vertical sides will degrade and the hole will become less deep.

In the diagram below the key characteristics of a dropout sinkhole (from Waltham et al., 2005) are compared with the evidence at Galmoy demonstrating that the sinkhole is of this type.

Characteristics of a dropout sinkhole

Diagrammatic representation (after Waltham et al, 2010)	Key Characteristics (after Waltham et al, 2010)	Evidence at Galmoy
	***Formation process:*** Soil collapse into void over bedrock fissure. ***Host rock types:*** Cohesive soil overlying limestone, dolomite, gypsum. ***Formation speed:*** In minutes, into soil void evolved over months or years. Typical max size: Up to 50 m across and 10 m deep. ***Engineering hazard:*** The main threat of instant failure in soil-covered karst. Other names in use: subsidence sinkhole, cover collapse sinkhole, dropout doline.	Sinkhole appears to be within soil column; in the vicinity of heavily weathered bedrock; no intact bedrock visible in the base. Some evidence in borehole logs of fractures in-filled with poorly consolidated, sandy material. Host is a cohesive glacial till, overlying limestone. Hole was reported to have formed overnight. Approximately 7 m deep and 13 m long. Present in an area of glacial till covered palaeokarst.

It is considered that the sinkhole formed due to a combination of the following factors:

- The presence of a palaeokarstic void system, the Main Fissure, which had been filled with sediment;

- Lowering of the local water-table by dewatering and intersection of the Main Fissure in the mine which together allowed the ancient flow-path down the fissure to be re-activated. Groundwater flowed down the fissure towards the mine, taking with it some of the fissure sediment fill and opening void space within the fissure. The process was enhanced by concentration of drainage at the location of the Main Fissure due to a depression in the rockhead (the solid rock surface under the overburden) along the Main Fissure and an up gradient catchment associated with the Main Fissure;

- The development of open voids within the glacial till due to washout of material through fractures (i.e. palaeokarst features) in the bedrock above the Main Fissure; and

- Recent exceptional rainfall and infiltration, coupled with the spreading of soiled water on the field shortly before the sinkhole appeared (ca. within 24hrs) increased the weight of the overburden and acted as the trigger for collapse into the void which formed the sinkhole.

The timing for the development and formation of the Main Fissure sinkhole may be considered in four stages:

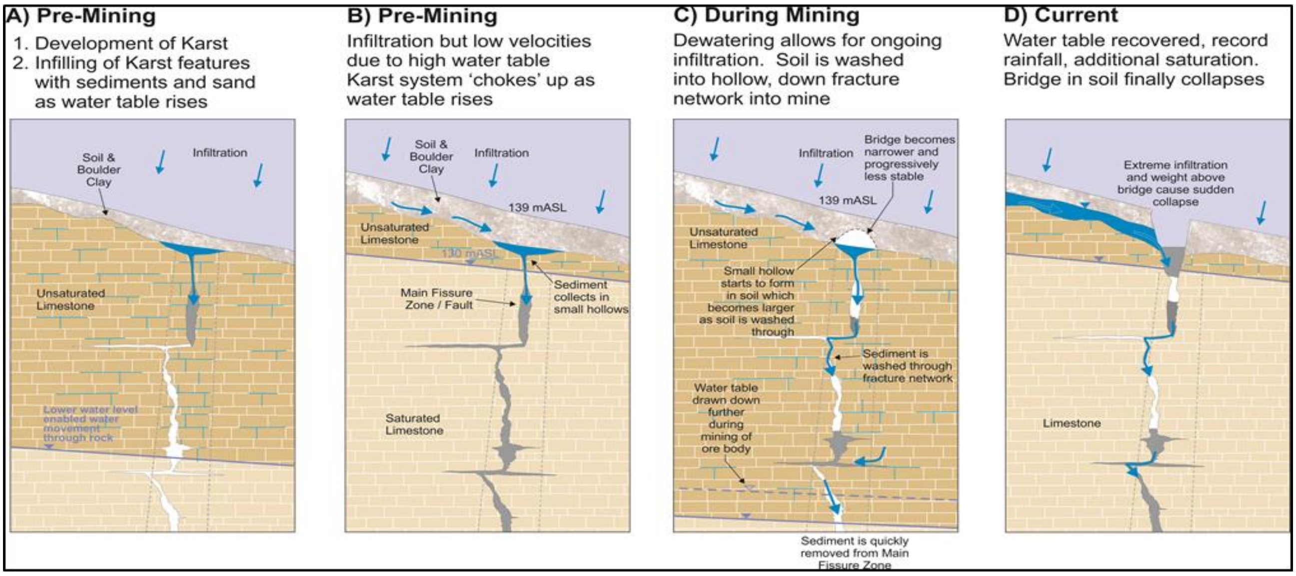
- **A) Development of palaeokarst (65.5 million to 12,000 years ago)**: Evidence from mid-Tertiary organic clays in buried sinkholes indicates that there was an active karst at this time and it is considered likely that groundwater was circulating through the Main Fissure. There may have been subsequent periods of active karstification but by 12,000 years ago all the voids in the limestone that had formed in the Tertiary had become clogged with sediment and there was no longer any active groundwater circulation through them;

- **(B) Pre-mining (12,000 to 20 years ago)**: During the Holocene there was slow groundwater flow at shallow depth through immature fissures some of which are likely to have been slightly enlarged by dissolution to form channels and conduits. The water-table would have been similar to that which it has recovered to following cessation of dewatering with very low hydraulic gradients and consequent low groundwater velocities which would have been insufficient to entrain and transport sediment. Hence, no void could have formed in the overburden at this stage;

- **(C) During Mining**: During the mining stage dewatering had the effect of lowering of the water-table and increasing the water velocity giving rise to a greater washout potential. The higher velocity water flows in the Main Fissure accelerated the removal of sediment and water through this route and it is likely that voids formed in the Main Fissure allowing sediment to be moved down from the overburden and development of a void at the base of the overburden; and

- **(D) Current**: Upon cessation of mine related dewatering the water-table began to return to its original pre-mining stage level. Importantly, as water was no longer being removed from the mine active circulation of groundwater ceased and the rainfall recharge gradually filled up all of the voids with a consequent steady rise in the water-table. Observations of turbid water in some wells for a short period suggests that there may have been a final phase of sediment mobilisation as the water-table approached pre-mining levels and groundwater started to flow through pre mining paths. It is likely that the void within the overburden had grown to a size whereby the arch was close to the instability threshold. The period of heavy rain, possibly assisted by application of water to the field, increased the weight of the overburden to such an extent that the unstable arch collapsed suddenly, giving rise to a 'dropout sinkhole'.

Schematic summary of the Main Fissure sinkhole development



Risk of Further Sinkhole Development (Risk Assessment)

A qualitative risk assessment was conducted to identify and rate areas that are potentially at risk of surface subsidence from sinkhole development, pillar failure or crown failure. This approach enables a targeted strategy for further action toward areas identified as having significant risk, for example categories of land usage in the vicinity of the mine workings.

Numerical values for hazard likelihood and land usage consequence are assigned on the basis of a calibration scale that results in lands with no recognised hazards scoring a low value which corresponds to a "Very Low" risk rating.

The results show all risks as Low to Very Low Risk This is a result of the consequence of very limited interaction between the three most likely hazards identified (geological features, water and mine workings) occurring at any given location in the vicinity of the mine, with the likelihood that the consequence is mostly limited to agricultural land. The highest risks areas are associated with the CW Orebody and are shown below.

Summary of Risk Assessment Results

Summary	Land Usage	Geological Structures	Mine Workings	Risk Rating	Control	Residual Risk
1b	Agricultural Land	Main Fissure	Open Workings	LOW	Geophysics over Main Fissure	VERY LOW
7	Minor Road (CW Orebody)	Major Fissure	Collapsed Mine workings	MEDIUM	Geophysics over Main Fissure	LOW

The risk assessment approach considered all land uses at risk from sinkhole development (and surface subsidence) and found that:

- It is highly unlikely that a repeat sinkhole event will occur, similar to that of February 2014;
- The water-table is at, if not near, pre-mining levels, reducing the risk of further changing hydrogeological conditions. Consequently any palaeokarst feature should not be exposed to further water flows in the future. Therefore, the risk of further erosion of sediments in any palaeokarst features is considered to be significantly reduced;

- In the immediate vicinity of the Main Fissure there was an above background risk of there being another void in the superficial material that could develop into a sinkhole. The void would have formed whilst the mine was dewatered, due to the bedrock surface depression, associated with Main Fissure, into which water could flow washing out the material to form the void. Due to this risk the GPR survey was conducted as a control measure to look for any such voids. The survey did not identify any voids in the superficial material and therefore the residual risk was reduced to Low to Very Low; and

- Local water extraction activities could pose an increased risk to sinkhole development as they may allow a flow path to develop that could washout sediments.

Due to the nature of the underlying bedrock (i.e. limestone with palaeokarst) it is recognised that there remains a background risk (Very Low to Low Risk) of future sinkhole development in the vicinity of the mine, as there does elsewhere in the Irish Midlands where limestones (and karst) occur.

Sinkhole Remediation

A simple bridging mechanism, over the throats between the limestone pinnacles, is proposed for the remedy of the sinkhole; the lower section comprises a permeable rip rap and ballast plug encapsulated in a geotextile. The upper section of repair entails compacted layers of rock fill/glacial till and a final capping layer of appropriate subsoil and topsoil to rehabilitate the agricultural surface.

A permeable plug is recommended to conserve the drainage pathway and to help alleviate the formation of further sinkholes in the vicinity. The repair of the sinkhole is recommended to commence without excessive delay to alleviate the risk of collapse of the sides of the sinkhole.

Conclusion

The sinkhole that occurred at Galmoy can clearly be classified as being a dropout sinkhole. As it is located above the Main Fissure the failure mechanism was most likely a result of:

- Water infiltration into the Main Fissure due to the bedrock depression above it and lowering of the water-table by mine dewatering;

- Washout of the sediments within the Main Fissure as a result of water with sufficient velocity to carry sediments flowing down the fissure following the mine dewatering;

- Formation of a void at the base of the overburden material as the sediments were washed through the Main Fissure; and

- The recent heavy rainfall that triggered the collapse of the arch in the overburden above the void.

There was concentrated flow towards and through the Main Fissure (which is located beneath the sinkhole) several million years ago and subsequently it was completely infilled with sediment. As part of the current study, it has been demonstrated that the Main Fissure which is located beneath the sinkhole, has developed enhanced weathering of the bedrock. Historically this led to an increase in karst formation locally and created a subsurface geomorphology which concentrated flow towards and through the Main Fissure in the vicinity of the sinkhole prior to the system being choked. The Main Fissure is a unique feature within the Galmoy deposit and so comparable conditions are unlikely to occur elsewhere in the vicinity of the mine. This provides a unique set of circumstances that coincide at this particular location and which are not (to our knowledge) repeated elsewhere in the vicinity of the mine at Galmoy.

It is considered that the potential of future sinkhole development at Galmoy will remain at historical background levels, provided the water-table remains close to its pre-mining level, thus preventing flow rates developing that could entrain sediments.

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APPENDICES

1.0 INTRODUCTION

Golder Associates Ireland Ltd (Golder) was contacted by Galmoy Mines Ltd (Galmoy) on Saturday 15 February 2014 regarding the development of a 'sinkhole' (dropout doline) on lands above the CW Orebody at Galmoy. It was understood that the sinkhole appeared sometime between the evening of 14 February and the morning of 15 February 2014. On inspection it was found that the sinkhole was located above the footprint of a large, sub-vertical, NNW-SSE trending structural feature (the Main Fissure) that had been encountered during mining of the CW Orebody.

Golder was tasked with the following scope of works:

- Collate available geological information (including lithology, structure, alteration and karstification-palaeokarst) in the vicinity of the sinkhole from both drilling and underground mapping;
- Carryout geophysical surveys (GPP and ERI) to identify possible shallow features in the vicinity of sinkhole and follow-up with an investigation of possible deeper features and connectivity with the Main Fissure;
- Develop a ground model for the area in the vicinity of the sinkhole, with special emphasis on variation in ground conditions;
- Explore the likely mechanisms and causes of the sinkhole, including a chronology of events from pre-mining through dewatering and finally mine re-watering;
- Provide a risk assessment on the likelihood of repetition of sinkhole development in relation to key surface infrastructure, residences and farmland; and
- Provide a design and method statement for the remediation (filling) of the sinkhole.

As part of the investigation into the cause of the sinkhole, Schlumberger Water Services (SWS) was retained by Galmoy to provide the hydrogeological background to the mine, discuss possible mechanisms of sinkhole development and comment on the potential for these mechanisms to induce future sinkholes in the vicinity of the mine workings. SWS's work has been extensively referenced in collating this report and can be found in its entirety in Appendix A, (*Analysis of Groundwater Conditions Relating to the Recent Sinkhole Occurrence*).

1.1 Background

The CW Orebody is a flat, tabular, undulating shaped orebody dipping gently at 10^o to the west. Ore was extracted using Room and Pillar mining by conventional 'blast, load, haul and dump' to a central underground crusher. Open excavation support was provided by standardized rock-bolt patterns and shotcrete depending on ground conditions. Where fissures or poor ground was encountered, a combination of rock-bolts, reinforced shotcrete and metal straps (depending on ground conditions) were installed with drainage pipes for water collection and management. The mined out CW Orebody stopes were extensively backfilled with cemented tailings.

Underground mine development (and dewatering) commenced in mid-1995. Mine production ceased in 2012, with the pumps (CW Orebody) being finally turned off in March 2013.

1.2 Sinkhole Description

The sinkhole developed overnight between 14 and 15 February 2014. No further subsidence has occurred since that date and there is no evidence of any cracking or ground movement in the surrounding area.

The sinkhole is elliptical in plan with its long axis in alignment with the Main Fissure. Its dimensions are; long axis 13 m, short axis 8 m, depth ca 7 m with an approximate volume of 550 m^3. The sinkhole is deep-sided with no bedrock visible in its walls or base, both of which are composed of sandy glacial till.

The sinkhole is at an elevation of ca. 139 m AOD, approximately 80 m above the mine workings. Bedrock is estimated to occur at ca 132.5 m AOD, with the water table at ca 123 m AOD.

1.3 Topography

The orebodies at Galmoy occur beneath small hills where the overburden is generally very thin. Away from the hills the overburden is typically thicker and primarily consists of a sandy till. The topography of the field in which the sinkhole has occurred forms a gently dipping swale towards its centre, dipping away to the north where the topography flattens out in the adjoining field.

2.0 GEOLOGY AT GALMOY

2.1 Overburden

The overburden at Galmoy primarily consists of 5 - 6 m of a sandy Glacial till (or Boulder Clay) with a well-developed clay matrix. However, highly variable thicknesses of overburden can occur due to the undulating nature of the bedrock surface, which was developed by glacial processes over a highly fractured, dolomitised and karstified limestone.

The field where the sinkhole has developed is situated on the slope of a hill, this coupled with the underlying free draining sandy Glacial Till drains water down-slope towards the north.

Figure 2.2, Appendix A of the SWS report shows the type and extent of the overburden at Galmoy.

2.2 Lithology

The Galmoy area is underlain almost entirely by a sequence of Lower Carboniferous limestones (Figure 1) that in general young and dip to the southeast with a northeasterly regional strike (termed the Rathdowney Trend).

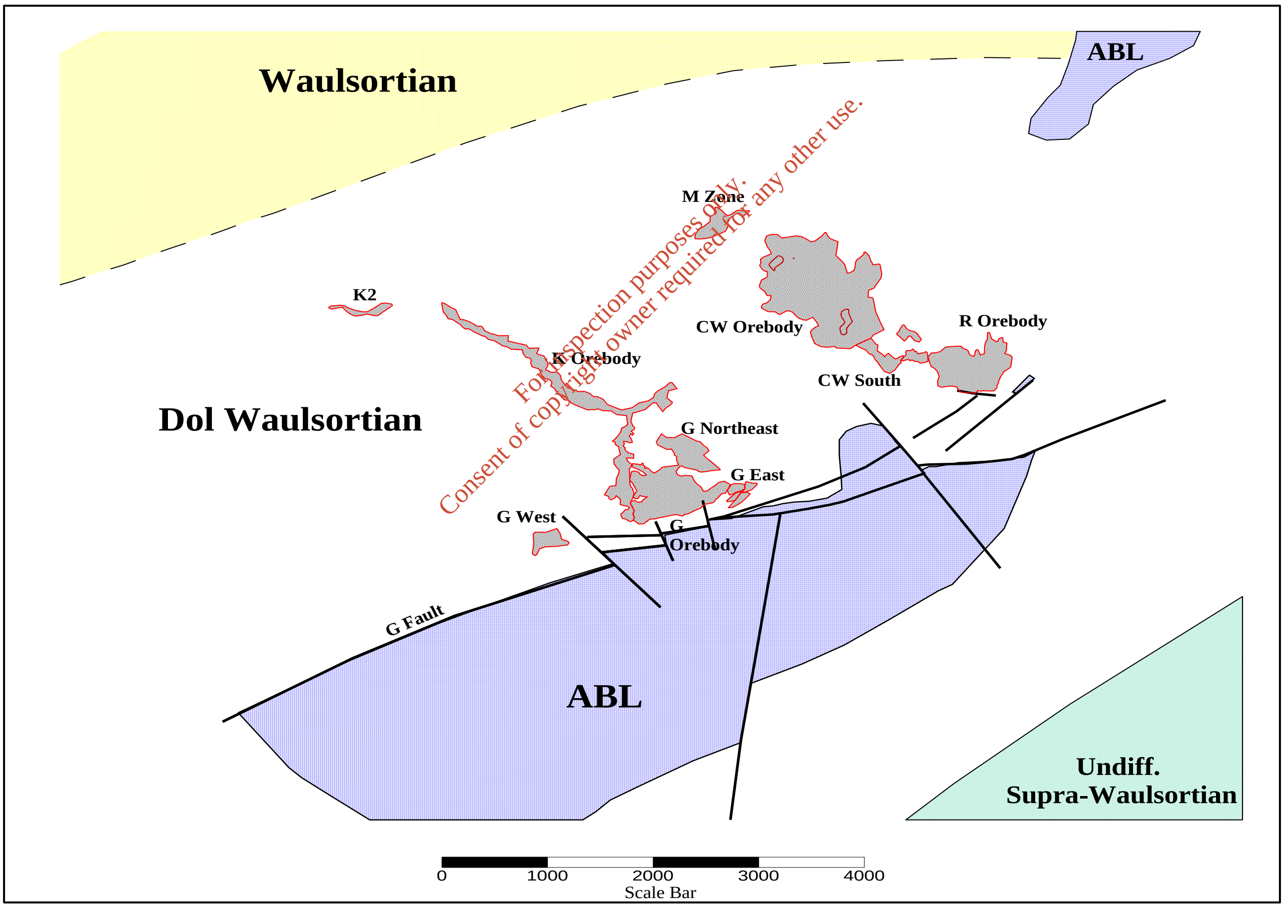


Figure 1: Geology of the Galmoy area and location of orebodies

The sequence (from oldest to youngest) consists of the Ballysteen Limestone Formation, the Waulsortian Limestone Formation and the Supra-Waulsortian limestones of the Crosspatrick, Aghmacart, Ballyadams and Clogrenan Formations.

The Upper Ballysteen Formation (Argillaceous Bioclastic Limestone or ABL), consisting of interbedded micrites and dark bioclastic calcareous mudstones and forms the footwall of the mineralization at Galmoy.

The contact between the ABL and the overlying Waulsortian Limestone Formation is generally sharp, and is usually marked with a 50 – 300 mm distinctive green to green-grey ‘mudstone’ band. From underground mapping it was found that the contact between the two formations acted as a movement plane within the CW Orebody. The movement in the overlying Waulsortian was predominately taken up by the formation of well-developed small scale sub-vertical faults and strongly developed joints (generally trending NNW-SSE), with movement in the ABL been taken up both along sub-horizontal argillaceous bedding planes and sub-vertical joints. It is along the sub-vertical structures in the Waulsortian that subsequent karst development has taken place.

Approximately half of the sub cropping Waulsortian in the area of the mine appears to be dolomitized. The contact between predominantly undolomitized and predominantly dolomitized Waulsortian Limestone runs parallel to strike midway through the crop of the Waulsortian, approximately 1 km north of the CW Orebody. Northwest of the boundary line undolomitized Waulsortian consists of pale to light grey micritic limestone with prominent bryozoan fronds and stromatactis. Southeast of this boundary line, the dolomitized Waulsortian at the surface is usually a buff dolomite accompanied by veining and brecciation. The matrix to this breccia is coarsely crystalline dolomite. The Galmoy deposits lie at the base of the Waulsortian where drilling shows that in most holes the entire section is dolomitized. The dolomite ‘front’ must therefore cross-cut the stratigraphy.

Above the Waulsortian and to the southeast lies the laterally variable Crosspatrick Formation (Supra Waulsortian), which in the Galmoy licence block mainly consists of pale grey crinoidal calcarenites with interbedded cherts or chert nodules. The stratigraphy of the Gamoy area is summarised in Figure 2 below.

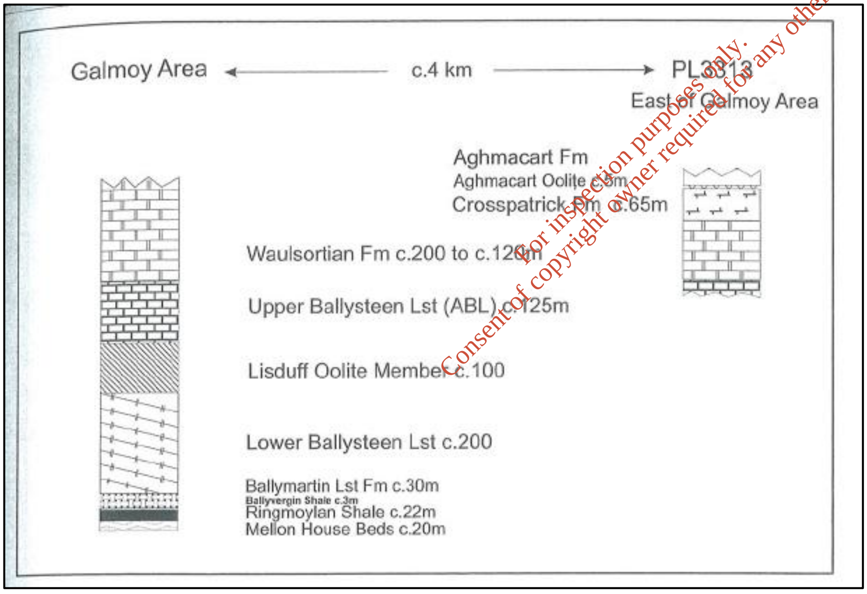


Figure 2: Stratigraphic Column showing sequence of geological formations at Galmoy (the Waulsortian Formation hosts the mineralization), (Lowther et al, 2000)

Within the Galmoy deposit area the Waulsortian is typically brecciated, with two distinct breccias being recognized.

- A rock matrix breccia found at the base of the Waulsortian; and
- A crystalline dolomite breccia which occurs throughout the remainder of the section.

From underground mapping and borehole information it appears that early incipient brecciation (which occurred during diagenesis) underwent various stages of dolomitization, leading to an increase in porosity of the rockmass as a whole and thereby facilitating fluid flow.

The rock matrix breccia may have developed in a sub-facies of the Waulsortian. Dolomitized micrites clasts within the rock matrix breccia tend to be darker grey and generally do not exhibit the fabric textures such as stromatactis, which are obvious in the overlying crystalline dolomite breccia. The matrix to the rock matrix breccia is dark and fine-grained and in certain instances appears to be stratiform and partly derived from *in situ* bands or laminae. The remainder of the Waulsortian, though dolomitized and brecciated (crystalline dolomite breccia), appears to be the normal, and characterized with distinctive facies which are widespread throughout much of central Ireland.

The ore mineralization at Galmoy is principally hosted within dolomitised rock matrix breccias towards the base of the Waulsortian Limestone Formation and occurs as tabular lenses of semi-massive to massive sulphides, generally bounded by the underlying ABL. The sulphide mineralization is predominantly zinc rich in the CW Orebody, zinc-lead rich in the K Orebody and zinc-lead-iron rich in the G Orebody.

2.3 Structures

The area in the vicinity of the mine is cut buy numerous fissures/fractures/faults. Three main sets are recognized in the CW Orebody: NNW trending (Main Fissure and F1), N-S trending (F2) and NE trending (F3) structures (Figure 3).

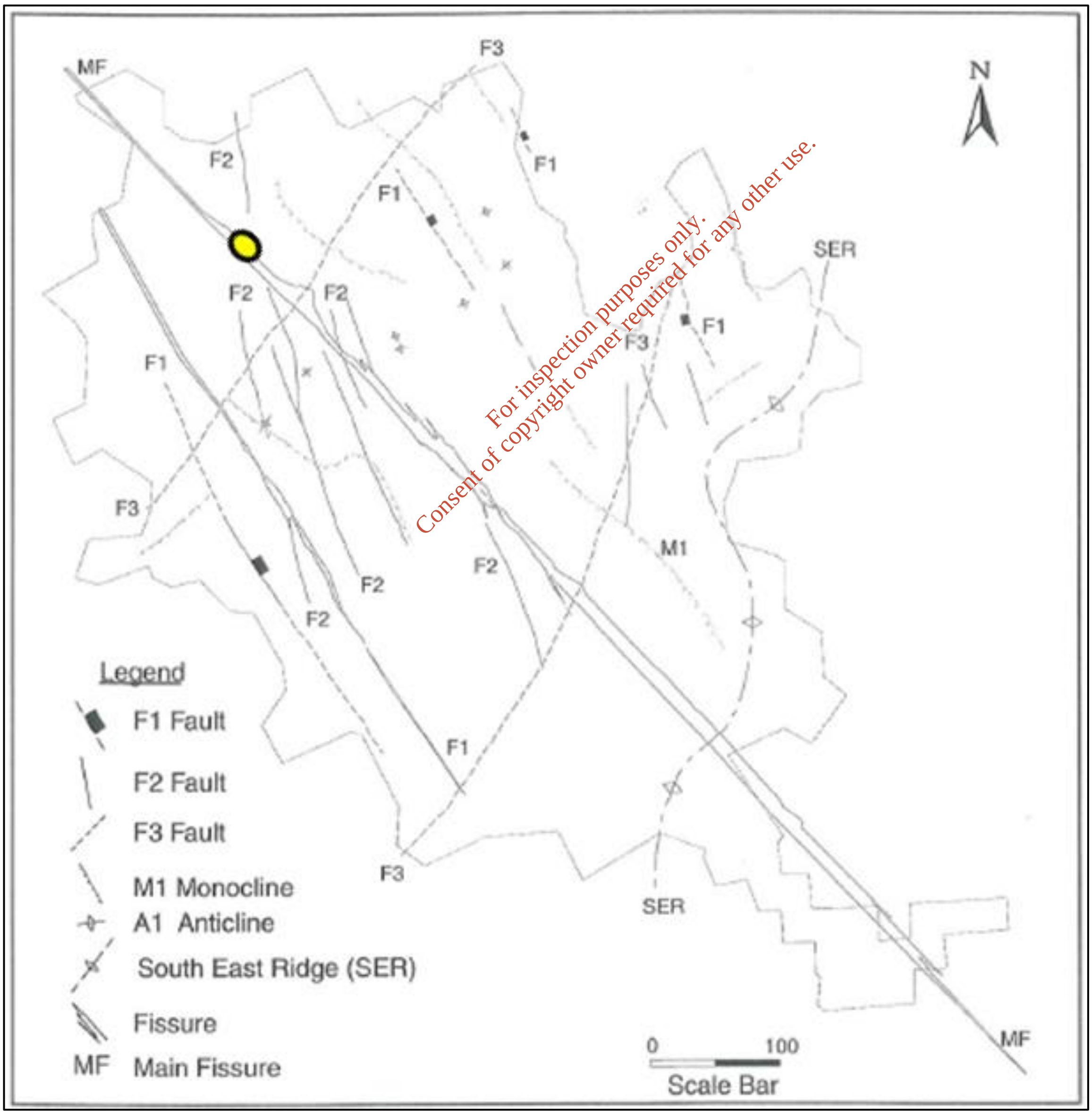


Figure 3: Main structural features of the CW Orebody (location of sinkhole in yellow), (Lowther et al, 2000)

The F1 faults trend parallel to the Main Fissure, which give the impression (when mapped underground) of displacing the orebody horizon by up to 3 m vertically at a number of locations. These structures are strike-slip faults and their apparent vertical displacements are explained by the undulating nature of the footwall. Associated with these structures is a set of sub-parallel faults which trend almost N-S (F2 faults). F3 faults (NE trending) tend to be steeply dipping and predominately strike slip in nature. These structures displace the ore horizon by up to 4 m vertically in a number of areas where an undulating footwall contact is found.

The structures that appear to control the location of the mineralization in the CW Orebody is the steeply dipping (about 83° to the NE) NNW trending fault zone, known as the Main Fissure, with displacement down to the east of between 2 to 3 m and an undulating NE-SW trending anticlinal structure (the southeast ridge, SER) which plunges to the SW (Figure 3). The Main Fissure is interpreted as marking the position of a pathway for mineralizing fluids from below. This feature pinches and swells dramatically over very short distances both along the dip and strike, with weathered areas up to 8 m wide being recorded laterally (from underground mapping). The Main Fissure has subsequently been the focus of intense karst weathering and is filled with a mixture of strongly fractured rock, sand and highly altered, clayey material.

The main structural feature associated with the Galmoy orebodies is the G Fault Zone, a generally E-W trending normal fault system which has a maximum displacement in excess of 200 m, down thrown to the north. The fault dips at approximately 55^{o} to the north and is approximately 50 m wide at surface. The G Fault is one of a series of E-W trending, SW stepping, *en echelon* faults, interpreted as being formed by trans-tensional movement on a major NE trending basement structure during N-S extension. The CW Orebody lies some 400 m to the north of the G Fault (Figure 4).

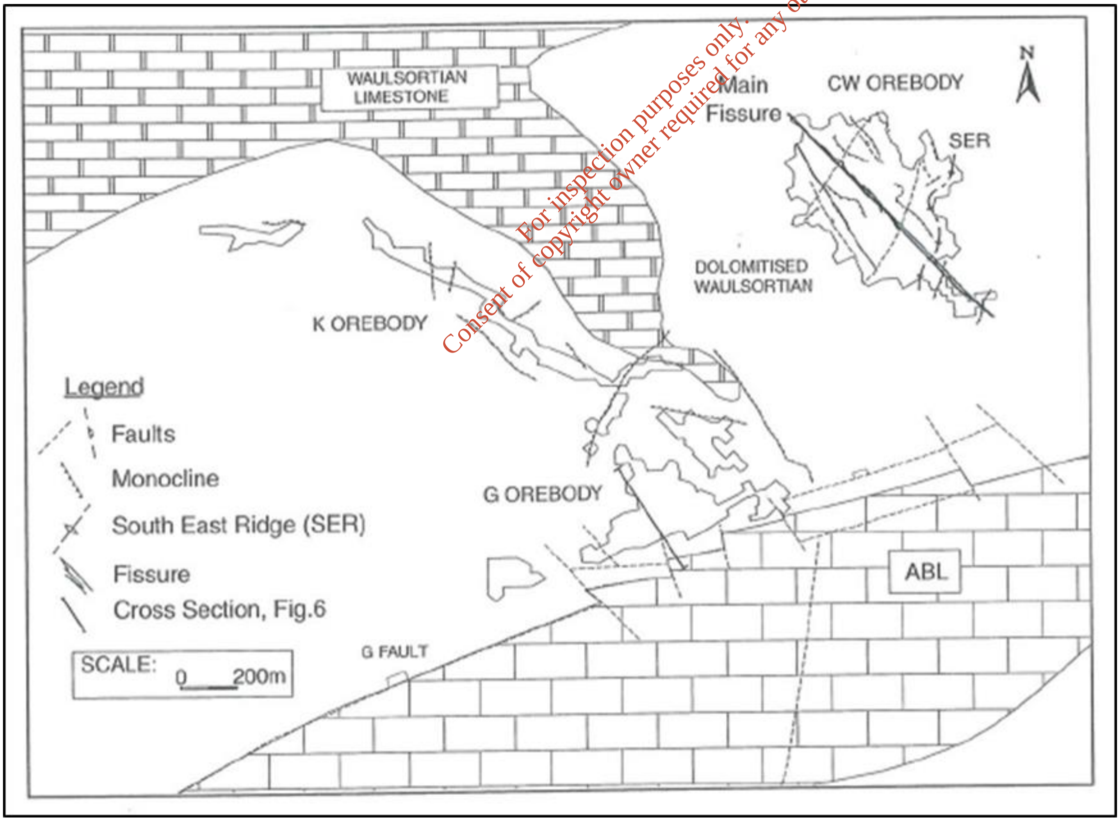


Figure 4: Main structures, Galmoy orebodies, (Lowther et al, 2000)

The predominantly NNW (i.e. the Main Fissure) and NS trending strike slip fissures/fractures/faults associated with the orebodies at Galmoy tend to be the main conduits for water movement in the vicinity of the mine. Whereas the E-W trending faults tending to be tight and have minimal water movement associated with them (e.g. the G Fault and R Orebody boundary faults).

2.4 Alteration

Within the CW Orebody three types of alteration (Table 1) were recognised from underground mapping and borehole information. This alteration manifested itself in the form of oxidation/weathering in the orebody hangingwall and also in places in the orebody itself due to a lower water-table in Tertiary times (Figure 5). Additional alteration was also recognised in the footwall of the CW Orebody, where leaching of the ABL (by hydrothermal fluids) is suggested to have taken place.

Table 1: Alteration types associated with the CW Orebody

Alteration Type	Description
Hanging wall Oxidation	Ranging from partially to heavily oxidised decomposed dolomite, with associates sand and clay.
Orebody Oxidation	Ranging from partially to heavily oxidised decomposed ore, with associated sand and clay. The concentration of iron has a major influence on the extent of oxidation.
Footwall Alteration	Soft, bleached, clayey material associated with footwall waste only.

From underground mapping a well-developed, NE-SW trending, sub-vertical structure (F3) was identified as possibly acting as a control on the lateral extent of both hangingwall and orebody alteration / oxidation during Tertiary times (Figure 3).

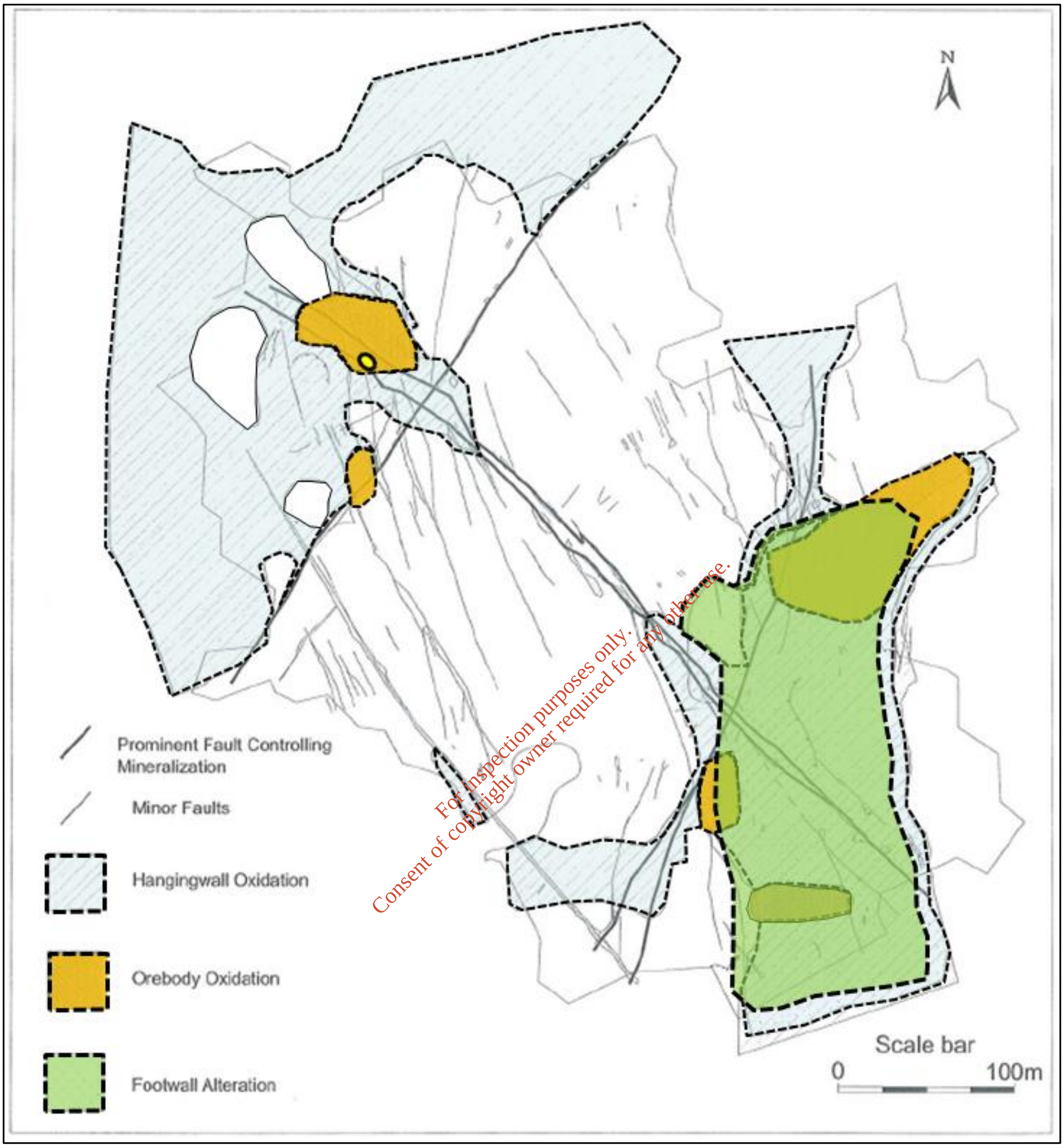
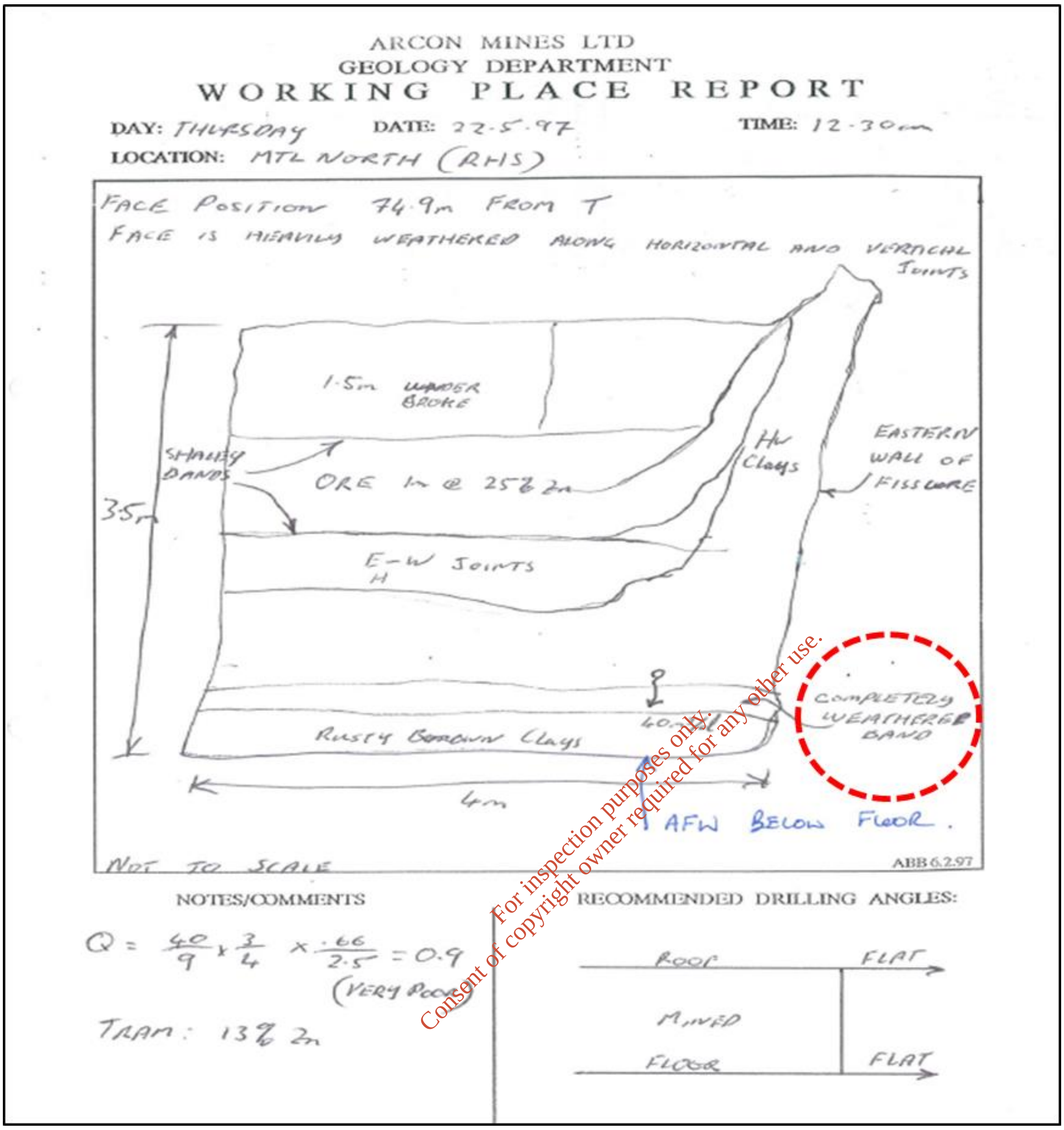


Figure 5: Areas of alteration associated with the CW Orebody (location of sinkhole in yellow), (Lowther et al, 2000)

Also, from underground mapping the nature and extent of oxidation and associated ground conditions can be seen where areas of mineralization has been completely altered / weathered and where poor/unstable ground conditions have been encountered when a sub-vertical fissure intersects the excavation (note water-make and low Q value of 0.9 for the face in Figure 6 – a development drive in close proximity to the Main Fissure).



ARCON MINES LTD
GEOLOGY DEPARTMENT
WORKING PLACE REPORT

DAY: THURSDAY DATE: 22-5-97 TIME: 12-30am
LOCATION: MTL NORTH (RHS)

FACE POSITION 74·9m FROM T
FACE IS HEAVILY WEATHERED ALONG HORIZONTAL AND VERTICAL JOINTS

NOTES/COMMENTS

$Q = \frac{40}{9} \times \frac{3}{4} \times \frac{.66}{2.5} = 0.9$
(VERY POOR)

TRAM: 13% Zn

RECOMMENDED DRILLING ANGLES:

Figure 6: Face mapping sheet for MTL North (a development drive in close proximity to the Main Fissure)

2.5 Karst and Palaeokarst

Karst is terrain with distinctive hydrology and landforms that arise from a combination of high rock solubility and well developed secondary (fracture) porosity (Ford & Williams, 1989). Globally carbonates (limestones and dolostones) are the commonest karst rocks and carbonate dissolution is dominantly driven by carbonic acid derived by hydration of carbon dioxide. Where sulphide minerals are locally present, as at Galmoy, sulphuric acid may contribute to carbonate dissolution although the process is more complex than commonly assumed (Bottrell et al., 2000). Organic acids may also make a small contribution.

In some areas there may be active karst development at depth that has no surface expression, for example where carbonate rocks are overlain by non-carbonate rocks. However, where the carbonate rocks outcrop at the surface a characteristic set of surface landforms develop including limestone pavement (present only in areas of recent glacial erosion such as the Burren of County Clare) and enclosed depressions (commonly called sinkholes or dolines) which are considered to be the diagnostic karst landform. Caves are commonly present in karst areas but they are not a diagnostic feature for karst, simply the extreme end of a spectrum of dissolutionally enlarged channels that allow focussed, commonly rapid, groundwater flow through carbonate bedrock.

The term ‘sinkhole’ is mainly used to describe an internally draining enclosed depression within karstic terrain. ‘Doline’ is an alternative term to describe karstic enclosed depressions that is used more commonly by geomorphologists. The term sinkhole is sometimes used to describe the point where a surface stream sinks into the karst but these are better referred to as sinks, stream sinks or swallow holes. The terms ‘sinkhole’ or ‘sink hole’ have also been applied to ground failures due to migrating roof collapse over mine workings but these are correctly termed ‘crown holes’.

There are six broad types of sinkhole (Figure 7) and in all cases focussed vertical groundwater movement and bedrock dissolution are essential precursors to their formation.

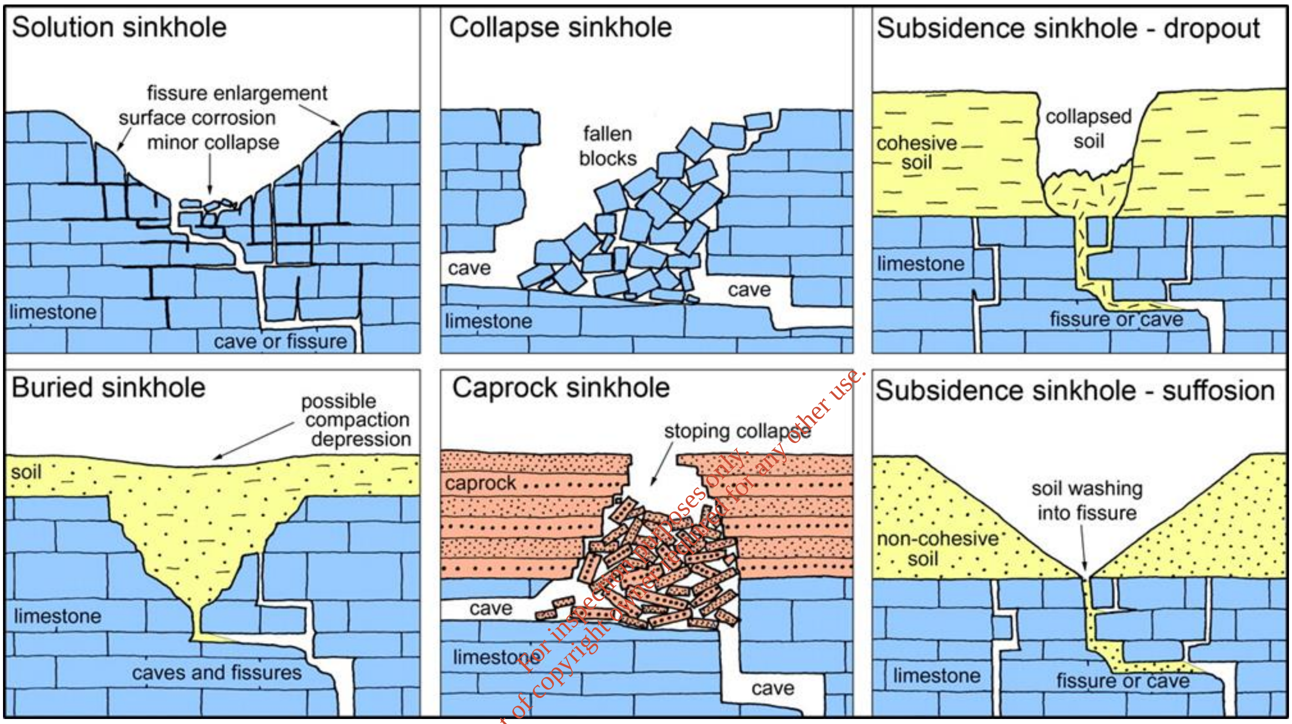


Figure 7: Classification and terminology of sinkholes (after BGS, 2011).

In solution sinkholes there is dissolutional lowering of the bedrock surface with drainage focussed on a central fissure or fissures. Formation of collapse sinkholes requires focussed dissolution of bedrock at depth leading to the growth of a void the roof of which ultimately fails. Cap-rock sinkholes are a special type in which the collapse propagates upwards through non-limestone cover rocks.

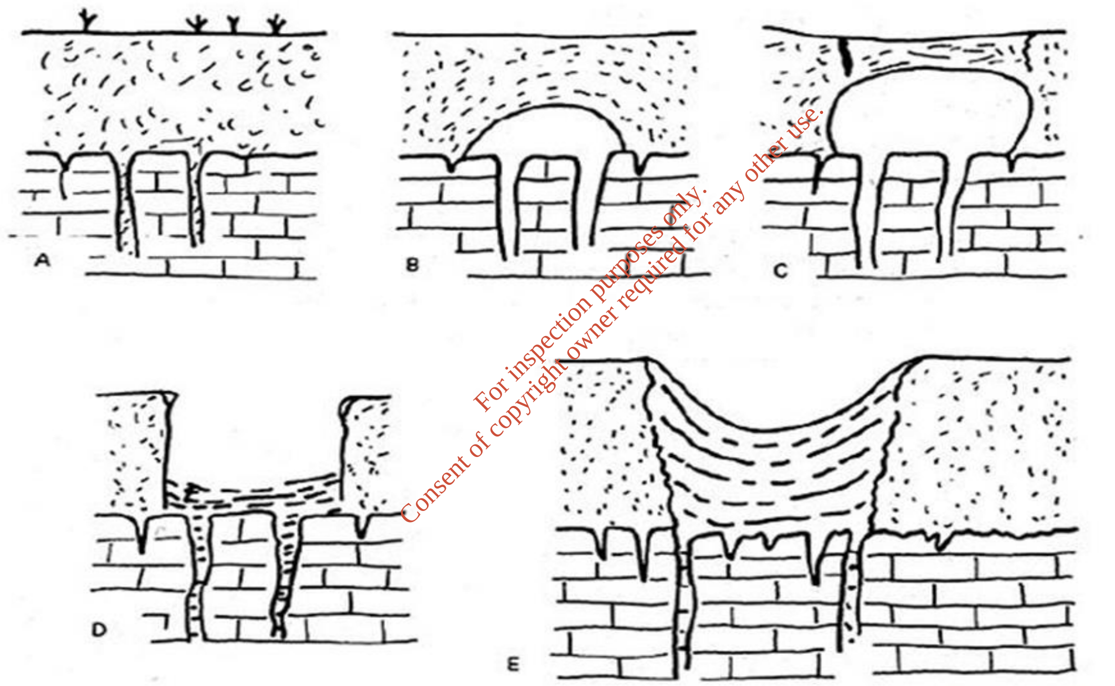
There are two types of subsidence sinkhole, dropout sinkholes and suffosion sinkholes, which have a common origin. A fissure in the bedrock is enlarged by dissolution until it reaches a size sufficient for turbulent flow and the transport of sediment. Where the superficial deposits overlying the bedrock are non-cohesive they gradually slump into the enlarged fissure forming a broadly conical suffosion sinkhole. Where the superficial deposits are cohesive the basal sediment is washed into the bedrock fissure forming a void that grows upwards from the bedrock-overburden interface and forms an arch. The arch grows until a threshold is reached where it is no longer able to support the overburden. The arch then suddenly gives way forming a dropout sinkhole with near-vertical sides.

Environmental change may lead to solution sinkholes being filled with sediment and buried sinkholes are common in Ireland although they have little or no surface expression and most have been discovered during mineral exploration and construction works. The term palaeokarst is used to describe areas where there was active karstification in the past but the old surface landforms have been buried and the underground drainage has been filled by sediment rendering it inert. There are two distinct processes involved in the development of a dropout sinkhole, firstly the development of a void in the superficial material above the bedrock and secondly the failure of the material arching above it, for which there is often a triggering mechanism, such as heavy and prolonged rainfall that increases the weight of the overburden above it.

Active void formation in the limestone only occurs in active karst regions, however palaeokarst features that have been filled with sediments may get washed out to form a void, alternatively such a void can form in the overlying soil material, as it is washed down into the limestone fissures.

Dropout or subsidence dolines/sinkholes form when soil or heavily weathered bedrock is removed by downwards drainage into fissures formed by dissolution of the underlying rock. The process by which this occurs is known as 'piping' (Figure 8). Piping occurs when soil (e.g. Till) material is washed downwards into fissures in bedrock, creating a cavity which then grows upwards into the form of an arch. Once the arch has grown sufficiently and is no longer able to support the overburden, the arch then suddenly gives way (Ford and Williams, 1989).

In order for a dropout sinkhole to form it is not necessary for a large hollow to be present in the bedrock, it is merely necessary for an efficient pathway to be present for the removal of the 'washed-down' sediment. This washing out or suffosion of soil typically occurs as a result of the coincidence of a high permeability (to soil and water transport) pathway combined with (in the local area) the lowering of the natural water-table, thus creating a more rapid flow of rainfall recharge once it enters the bedrock which in turn increases the potential for sediment transport.



The Formation of a Cover Collapse Doline. A) Solutional openings in the bedrock wash material downward, B) A small arch forms in the subsoil where the material is being washed away, C) The void grows in size as more material is being downwashed until it reaches a critical point and starts to rupture, D) The arch suddenly collapses as it can no longer support its own weight, E) Overtime the vertical sides will degrade and the hole will become less deep.

Figure 8: Piping process giving rise to the formation of a dropout or cover-collapse doline (from: http://www.gsi.ie/newsletters/sinkholes+in+ireland.htm).

Void formation is dependent on the velocity of the water flowing down the fissure being sufficiently high to transport sediment. Some dropout sinkholes are entirely natural but groundwater velocities are commonly too low to transport sediment in suspension and many dropout sinkholes are induced or accelerated by human disturbance of natural drainage patterns that result in an increase in the flow of water through the soil / unconsolidated deposits into the karst bedrock. Waltham et al. (2005) state that withdrawal of water (for example by abstraction or by de-watering of a surface quarry or a mine) and consequent drawdown of the water-table is the most frequent cause of dropout sinkhole formation. This is thought to have been the case at Galmoy.

It is noted by many researchers that most sinkholes form on lineaments, i.e. fault/fracture structures, (e.g. Littlefield et al, 1984) consistent with the occurrence of a sinkhole on the Main Fissure at Galmoy

2.6 Karst and Palaeokarst in Ireland

About 40% of the island of Ireland is underlain by carbonate rocks most of which have been karstified to some extent (Drew et al., 1996). In the upland areas such as the Burren of County Clare the karst is very obvious with extensive areas of limestone pavement, enclosed depressions and many caves but in the lowland areas there are few obvious karst landforms and few cave systems. Despite this the presence of many springs and of turloughs (enclosed depressions in karst that are intermittently inundated on an annual basis, mainly from groundwater, and have a substrate and/or ecological communities characteristic of wetlands) provides evidence of karstic flow systems in lowland limestones.

There is also an increasing body of evidence showing that the Irish lowland limestone areas were subject to more active but episodic karst processes during the Tertiary period, 65.5 to 2.6 million years ago (Drew & Jones, 2000; Coxon & McCarron, 2009). The karst was eroded and at least in part filled with sediment during the later Tertiary and during the Quaternary further sediments were deposited, particularly during and immediately after ice sheets advanced over the karst. Hence, the Irish lowland limestones are blanketed with superficial deposits which may reach tens of metres in thickness and beneath at least some of which there is an inert palaeokarst. This means that: "present-day groundwater flow systems are developed in immature fissure or conduit systems of Holocene age [that is, developed in the past 12,000 years], or in reactivated ancient conduits from which sediment has been eroded, or in a mixture of both" (Drew, 2008, p63).

2.7 Karst and Palaeokarst in the Galmoy Area

During the early Tertiary a karstic drainage system developed in the Galmoy area, with water movement concentrated along predominantly NNW-SSE and N-S trending strike slip fissures/fractures/faults and in particular along what has subsequently become known as "The Main Fissure". This sub-vertical, NNW-SSE trending feature pinches and swells dramatically over very short distances both along the dip and strike, with weathered areas up to 8 m wide being recorded laterally (from underground mapping). In contrast to the NNW-SSE and N-S trending features the E-W trending faults such as those in the G Fault Zone tend to be tight and there has been minimal water movement along them and hence an absence of karst.

By the mid-Tertiary karstification had reached a depth of at least 40 m in the Galmoy area and there were solution dolines (sinkholes) in which organic clays accumulated (Coxon & McCarron, 2009). However evidence from underground mapping indicates that karstification had developed to ca 90 m depth in the case of the CW Orebody. During the Quaternary the climate oscillated between cold (glacial) and warm (interglacial) stages. The extent of glacial erosion and the number of times that ice advanced over the Midlands is still a subject of debate but there is agreement that the last widespread ice sheet had begun to melt by 14,500 years ago and that the Midlands were ice-free by the start of the Holocene, about 12,000 years ago. By this time the voids in the limestone that had formed in the Tertiary had become clogged with sediment and there was no longer any active groundwater circulation.

Across the Midlands the limestone surface was buried beneath varying depths of superficial deposits, primarily of glacial and fluvio-glacial origin. At Galmoy the superficial deposits primarily consist of 5-6 m of sandy glacial sediments (commonly called Boulder Clay) with a well-developed clay matrix. In common with much of the limestones in the Irish Midlands groundwater flow is through immature fissures some of which have been enlarged by Holocene dissolution to form channels and conduits.

As part of the ground investigations associated with the development of the mine a number of surface depressions were identified and investigated in relation to the presence of (palaeo-) karst features in the Galmoy area. From combining geophysics and probing it was found that the majority of these surface features were not related to karstification of the bedrock. However, convincing evidence of the direct connection of a bedrock developed karst feature with the surface was recorded when a borehole intersected organic material and peat (Golder 1992).

As part of investigations (pre-mining) in 1992, a geophysical survey was completed which identified a number of anomalous areas within the underlying bedrock as part of the ground investigations associated the construction of the Tailings Management Facility (TMF). The anomalies were subsequently drilled and found to be either highly weathered-fractured ground or clay / sand / debris filled palaeokarst features. These features were subsequently grouted as water used in the drilling process had 'washed-out' the materials encountered in the palaeokarst features. The footprint area of the TMF was flooded (with water pumped from below the TMF footprint) as part of the investigations prior to construction of the TMF, in an attempt to identify areas of possible infiltration into underlying palaeokarst features. The outcome of the investigations was that no infiltration rates above what would be expected for the underlying glacial till were recorded, i.e. there was no reactivation of palaeokarst features underlying the TMF – as the palaeokarst system in the Galmoy area is **'choked'**.

The sinkholes and dolines identified and investigated as part of the 1992 study are not currently active and can be interpreted to be inactive since at least the time of the last ice age (Midlandian) some 15,000 years ago. Therefore, the karstification of the underlying carbonate rocks in the Galmoy area can be interpreted as being palaeokarst, i.e. **belonging to a system in which the conditions which promote karstification are no longer present.**

Underground mapping of the CW Orebody identified the development of localised karstification in the vicinity of the sinkhole at the orebody horizon where an area immediately to the west of the Main Fissure was found to be choked with clays and dolomite sands when it was mined into (Figure 9). As this material carried no grade it was not extracted.

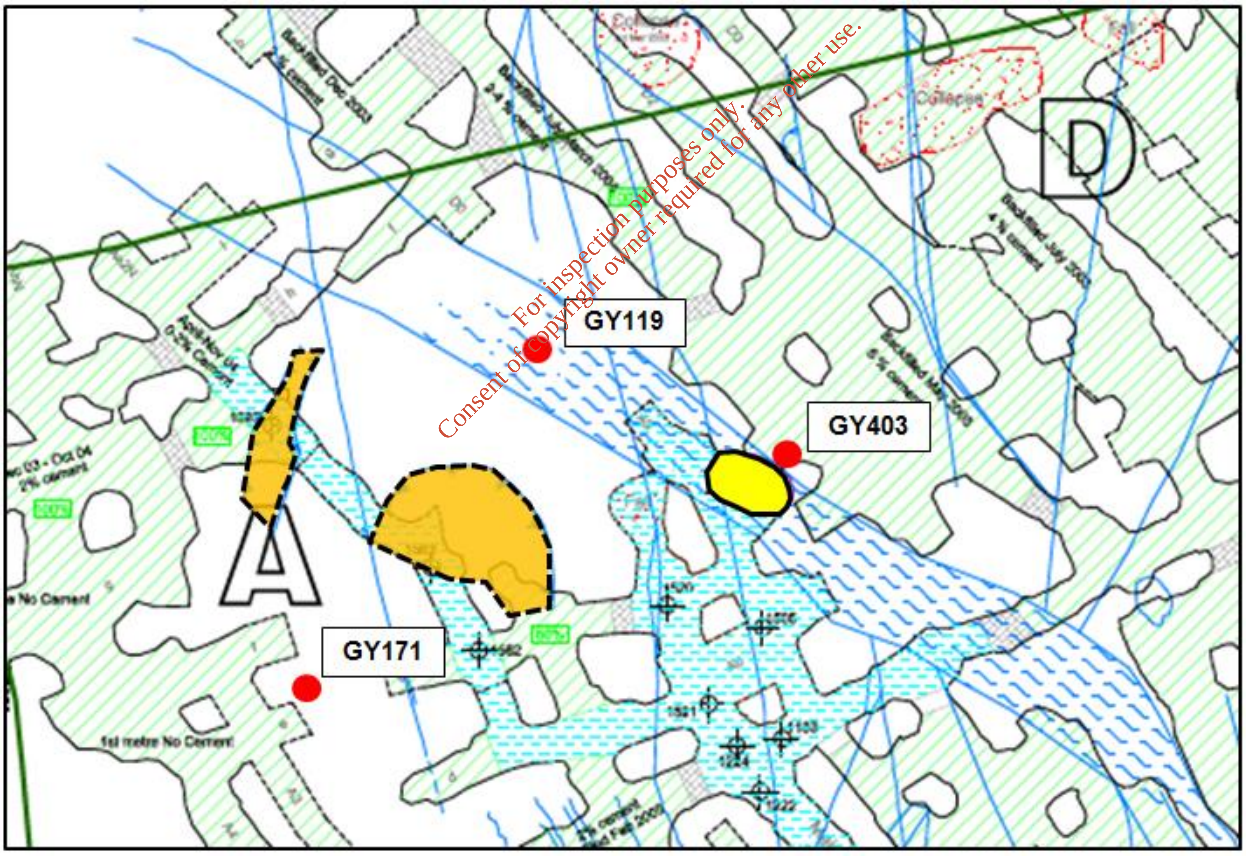
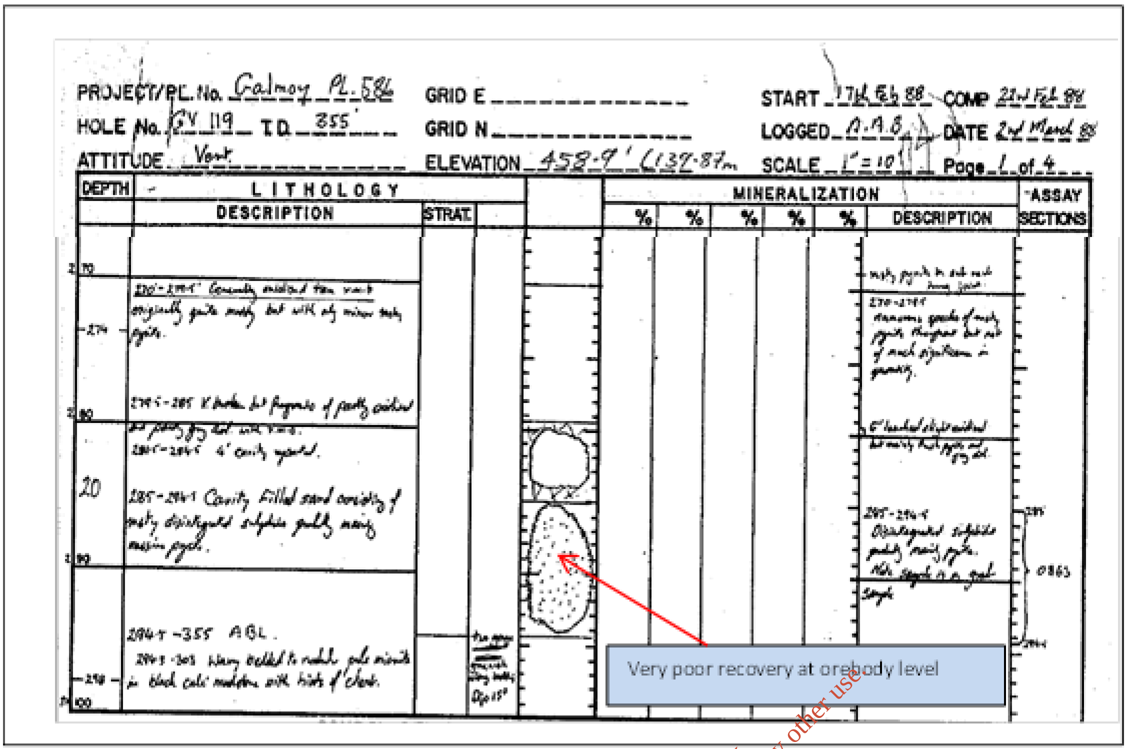


Figure 9: Areas of underground karstification and extent of Main Fissure from underground mapping (orange). Also, note locations of GY119, GY171 and GY403 and sinkhole (yellow). Backfilled areas in green open excavation in light blue.

Further evidence for karstification can be found in boreholes GY119 (which plots on the Main Fissure when projected to surface) and GY171 where there was very poor recovery of material from the orebody horizon (Figure 10).

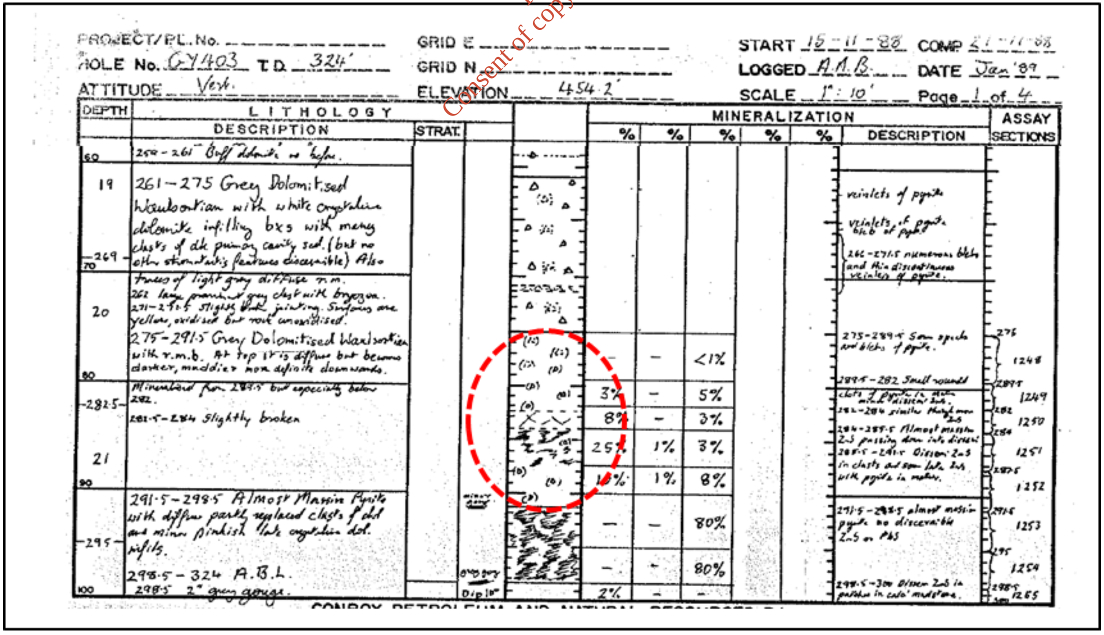


PROJECT/PL. No. Galmoy PL. 586 GRID E START 17th Feb 88 COMP 22nd Feb 88
HOLE No. GY 119 T.D. 355' GRID N LOGGED A.A.B. DATE 2nd March 88
ATTITUDE Vert. ELEVATION 458·9' (139·87m SCALE 1" = 10' Page 1 of 4

Very poor recovery at orebody level

Figure 10: Borehole log for GY119 (drilled on the underground mapped extent of the Main Fissure) showing a zone of very poor recovery at orebody level (note scale on log is in feet)

However, borehole GY403 drilled adjacent to the Main Fissure (see Figure 9 for location) encountered 100% recovery at orebody level (Figure 11), indicating the variable nature of karstification in the vicinity of the Main Fissure at the orebody horizon (i.e. karstification '*pinches and swells*').



PROJECT/PL. No. GRID E START 15-11-88 COMP 21-11-88
HOLE No. GY403 T.D. 324' GRID N LOGGED A.A.B. DATE Jan '89
ATTITUDE Vert. ELEVATION 454·2' SCALE 1" : 10' Page 1 of 4

Figure 11: Borehole log for GY403 (drilled adjacent to the Main Fissure) showing a zone of 100% recovery at orebody level (red dashed line) (note scale on log is in feet)

Again illustrating the variable nature of the rock mass, a NW-SE trending fissure zone was intersected to the west of the orebody (Figure 12 and Figure 13). This structure was intersected in the No1. Access Decline during mine development and is associated with a palaeokarst feature at the orebody elevation similar to that intersected to the west of the Main Fissure in Figure 9).

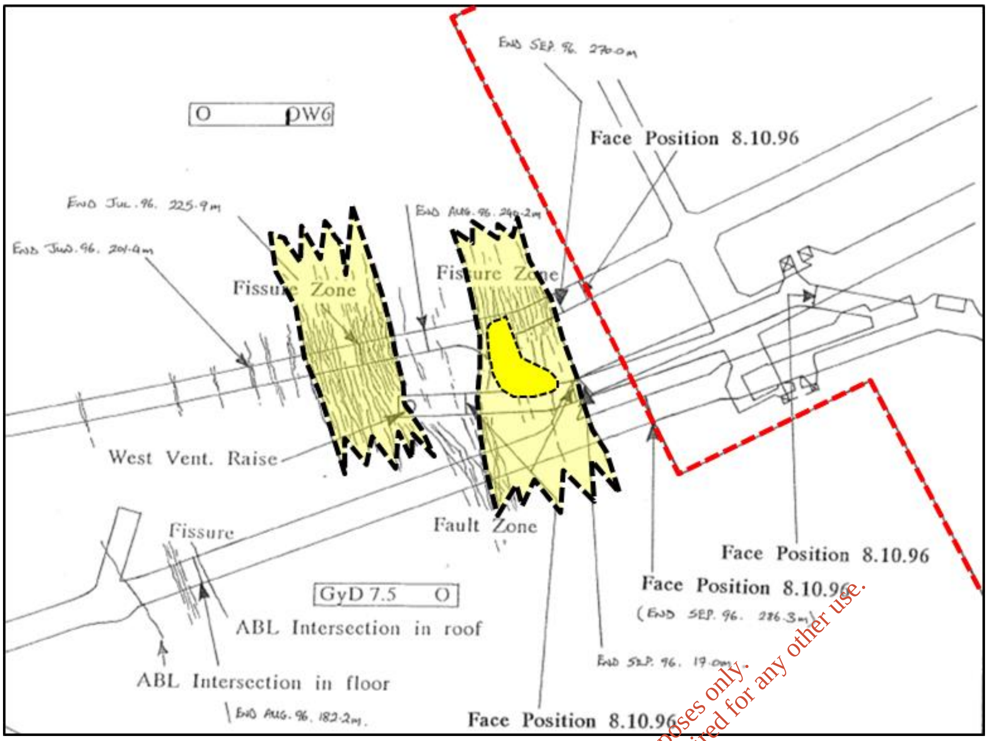


Figure 12: Plan showing location of NW-SE trending fissure zone along western edge of CW Orebody (red dashed line). Palaeokarst feature in yellow

The palaeokarst feature when mined into was found to be choked with clays and dolomite sands.

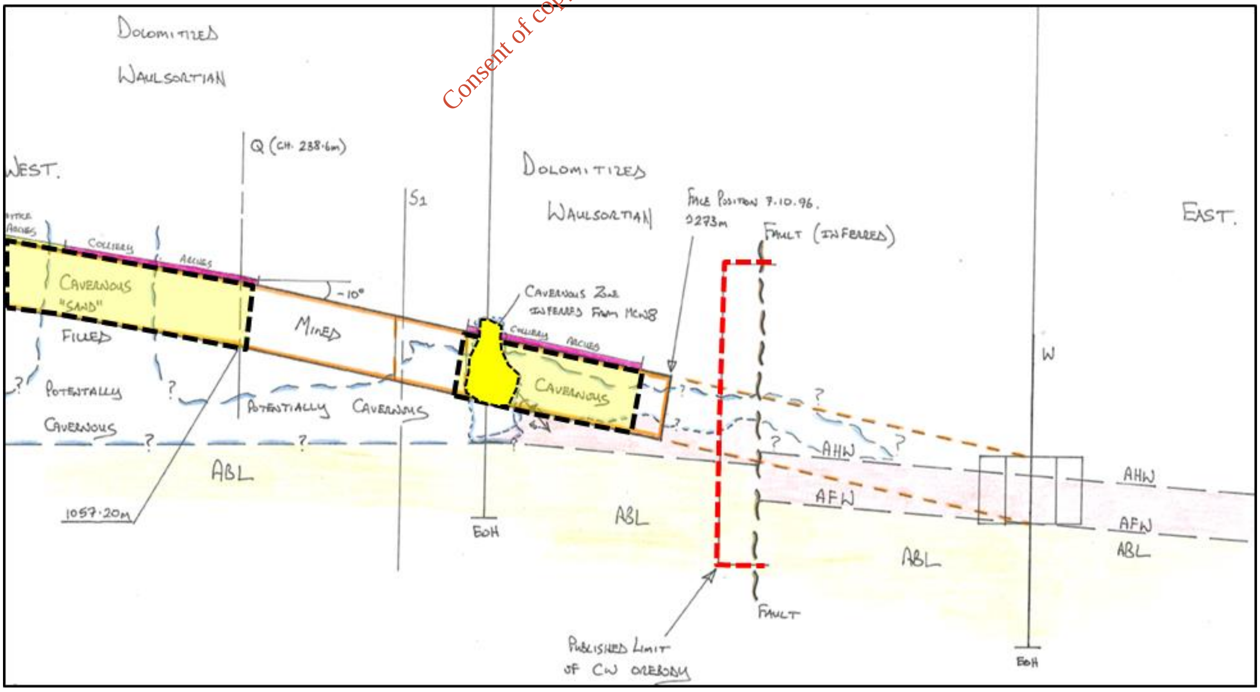


Figure 13: Cross-section No. 1 Access Decline looking north, showing intersected ground conditions on 7th October 1996. Areas in yellow denote extent of intersected fissure zones as shown in Figure 12

On being mined through this feature was successfully supported with steel arches, metal straps, rock bolts and shotcrete. Areas above the steel arches were filled with foam-crete (and expandable grout like material). Drainage pipes for the collection and long-term management of water were installed with the support measures.

3.0 GEOPHYSICS

Following the appearance of the sinkhole on Saturday 15 February 2014 a geophysical investigation involving Ground Penetrating Radar (GPR) and Electrical Resistivity Imaging (ERI) was initiated on Wednesday 19 February 2014. The aim of the geophysical investigation was:

- To check for the presence of possible voids within the base of the overburden under the road and also under the landowners' field in the vicinity of the Main Fissure (as mapped from underground);
- To check for the presence of possible voids within underlying bedrock under the road and also under the landowners' field in the vicinity of the Main Fissure;
- To check the extent of fractured/fissured (weathered) dolomitised limestone under the road and also under the landowners' field in the vicinity of the Main Fissure; and
- To correlate available borehole information with the geophysical data and so provide confidence in the overall geological / ground model in the vicinity of Main Fissure.

3.1 Methodology

3.1.1 GPR (Ground penetrating radar)

The GPR technique is a highly versatile geophysical tool allowing a wide range of different sub-surface features to be identified and mapped with the potential to achieve high horizontal and vertical resolution. The basic principles of GPR combine those of EM measurements with the acquisition methodologies of seismic reflection.

A GPR survey involves using a pulsed electromagnetic field (radio wave) transmitted via a tuned frequency antenna that can penetrate soils, rock, concrete, and other common natural and man-made materials. Variations in the electrical properties of sub-surface materials cause EM radiation to propagate at different velocities. Interfaces in the sub-surface, representing boundaries between materials with contrasting electrical properties, reflect a fraction of the transmitted radiation back towards the surface, whilst the remainder passes through the interface to deeper levels. The reflected radiation (reflection event) is then recorded at a receiver antenna situated close to; or coincident with, the transmitter. Typical interfaces may include the interface between soil and concrete, between soil types, at the water-table, or at discrete objects such as pipes, buried storage tanks, voids and miscellaneous debris (Figure 14).

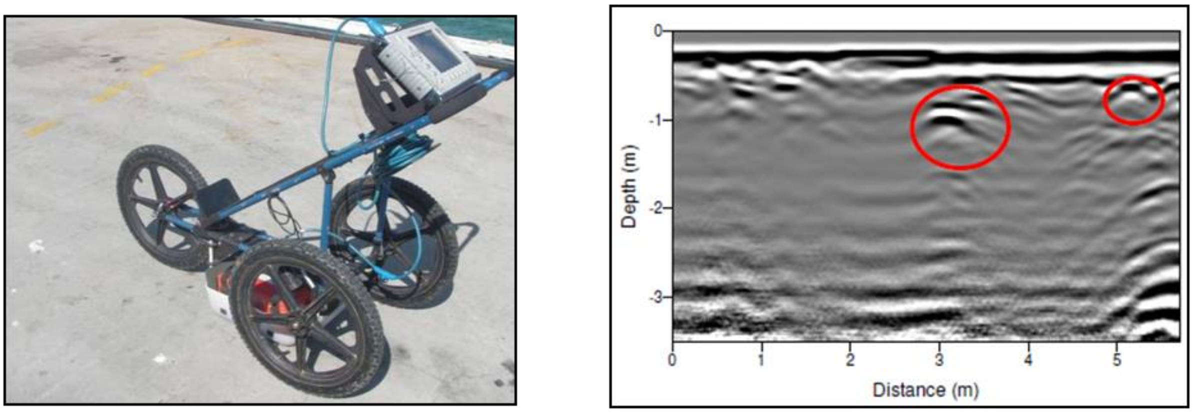


Figure 14: General arrangement for GPR survey instrument and typical output showing anomalies circled in red

The depth of penetration achievable using GPR is also affected by the ground characteristics and obeys a frequency dependent relationship. As the frequency of the EM radiation increases, so the degree of absorption increases and hence the signal attenuates more rapidly such that the depth of penetration is reduced. However, as frequency of the EM radiation increases, the resolution of the technique improves, resulting in a more detailed image of the sub-surface and more accurate depth resolution. The selection of the correct transmitter frequency therefore represents a compromise between maximum resolution and achieving the desired depth of penetration.

GPR is generally unaffected by above ground features, however, the presence of near surface conductive materials (such as clays or conductive groundwater) greatly increases the attenuation of the transmitted signal and so significantly reduces the depth of penetration.

3.1.2 ERI (Electrical Resistivity Imaging)

ERI Surveys typically highlight changes in material type using conductivity measurements. Surveys provide information on rock type and are particularly useful for determining overburden properties. An electrical current is passed between grounded electrodes and the response recorded is used to measure subsurface variation in resistivity. Ground resistivity is related to various geological parameters including mineral and fluid content, porosity and rock water saturation. By moving the electrode arrays laterally as well as changing electrode spacings, a cross-section of ground apparent resistivity with depth can be constructed, enabling sub-surface electrical properties to be modelled and imaged (Figure 15).

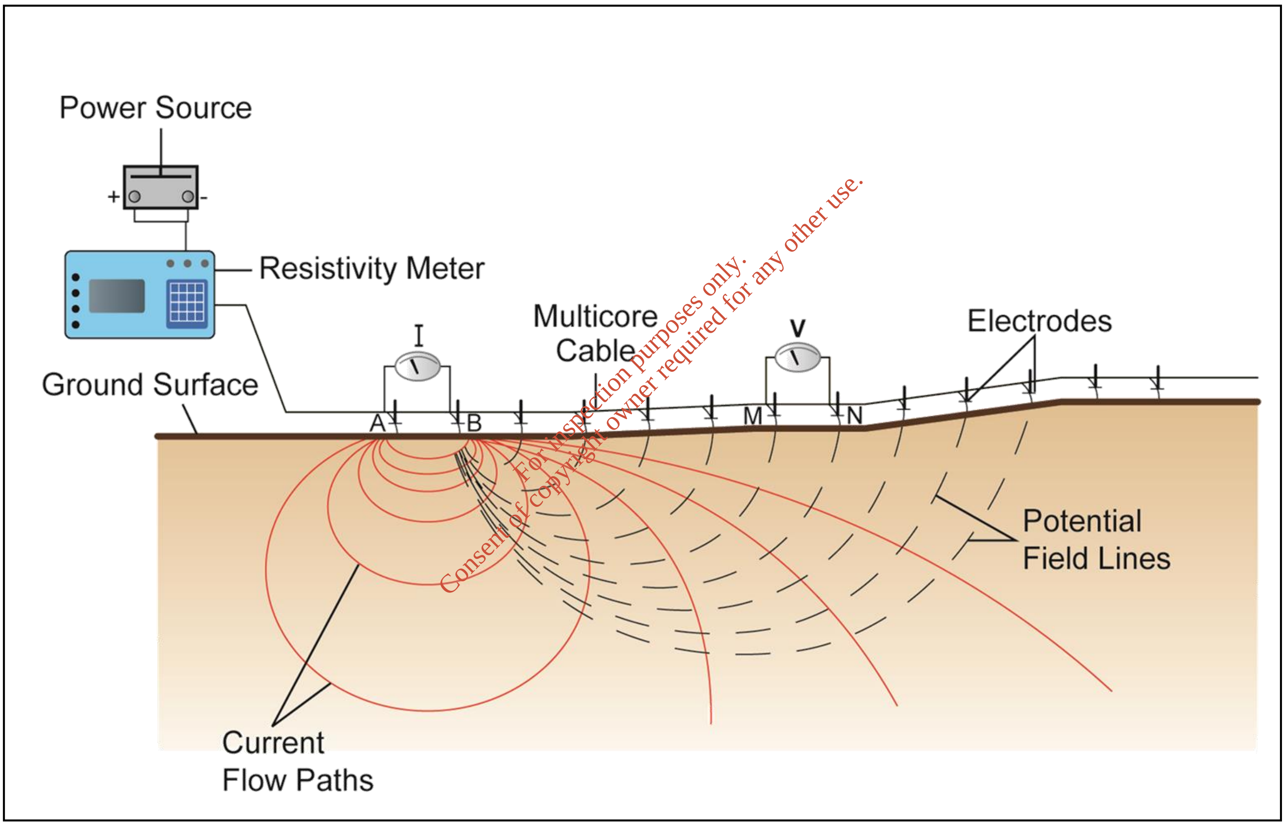


Figure 15: Schematic diagram showing the arrangement for an ERI survey

Initially an electrode spacing of 5 m was used to provide information at depth. Subsequently, an electrode spacing of 3 m was used to provide more detail of variation of material type in the near surface (within ca. 30 m). Data was collected using a multi-electrode imaging system (an ABEM® Terrameter SAS 4000-Lund Imaging System) which allows large amounts of data to be collected quickly and efficiently.

Topographical information obtained allowed accurate topographic data for each line to be attained and to be used in the processing of the resistivity data.

The data from the resistivity survey was processed using the software package RES2DINV (V. 3.5). This package allows for the editing of noise from the data, the application of a variety of filters and parameters and the inclusion of topographic information. The results of the inversion indicated that the inverted images produced using a horizontal filter provided the best fit with the observed data, as determined by the Root Mean Square (RMS) errors for the individual inversions. The final results were plotted as 2D resistivity pseudosections.

The data was interpreted taking into account a number of criteria, including: resistivity pattern, comparison between survey lines and underlying geology. Reference to similar conditions and environments elsewhere enabled a realistic ground model of the area surveyed to be developed.

3.2 Work Carried Out

3.2.1 GPR

A total of 540 GRP profiles using a 100 Mhz frequency transmitter was used to collect data in the grass field surrounding the sinkhole and the field to the north. Data was collected perpendicular to the strike of the Main Fissure along parallel profiles 2 m part (Figure 16). Two profiles were also collected along the public road (815m in length) adjacent to the grass field. A further four profiles at 2 m intervals were also collected parallel to the road. Depending on ground conditions, depth of penetration was typically 6 to 8 m below ground level (bgl). The higher than average depth penetration for the GPR is related to the sandy nature of the glacial till underlying the field (indicating a relatively free-draining medium).

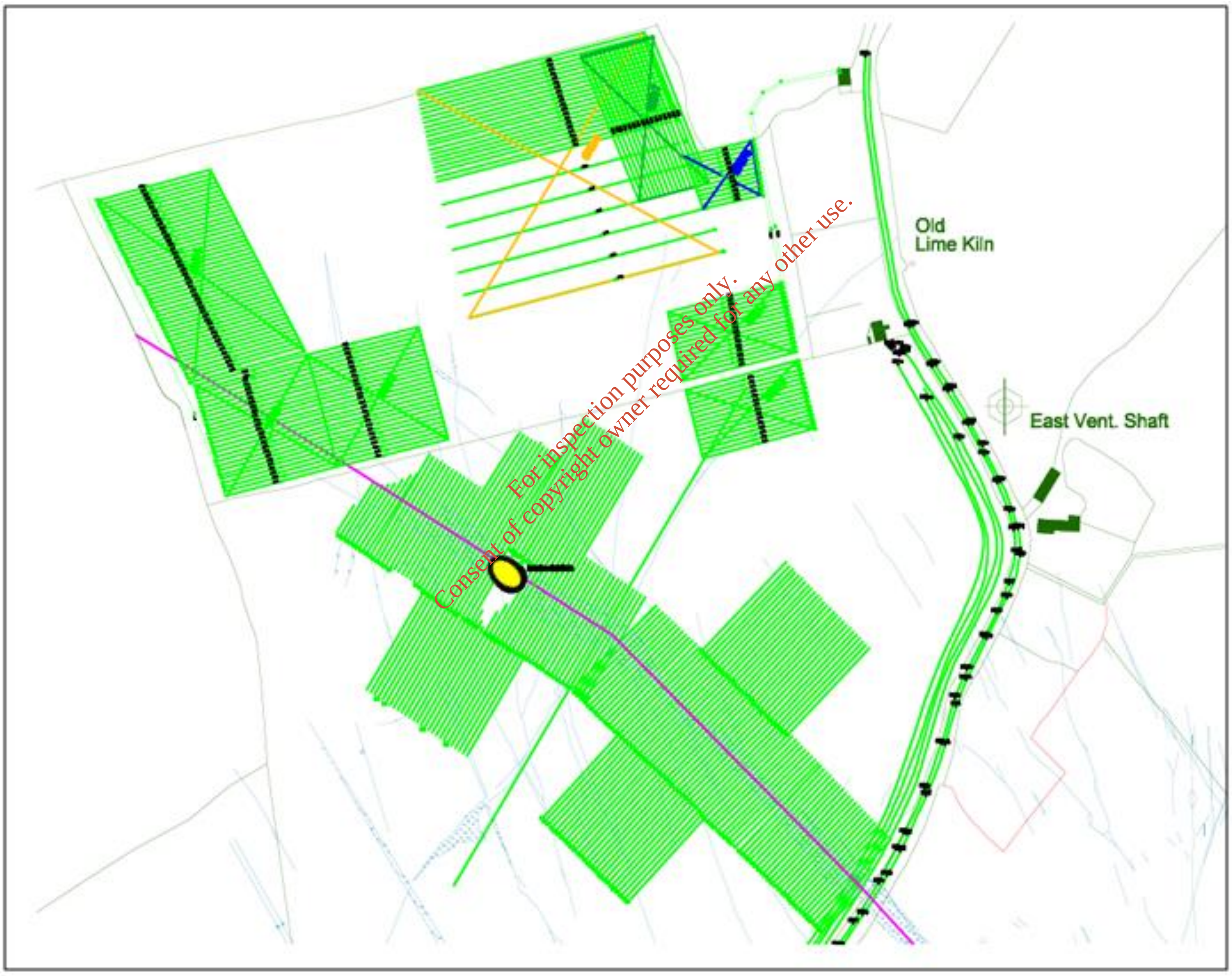


Figure 16: Showing layout of GPR profiles (green), landholding (red), centre-line of Main Fissure (magenta) and sinkhole (yellow)

All GPR profiles were processed to enhance their reflected signal and then visually screened for reflections that might indicate the presence of anomalies.

No reflectors were detected that would indicate the presence of a void in the superficial material that could result in a sinkhole similar to the event on 14 / 15 February.

However, two other types of reflectors (i.e. reflections indicative of infilled cavities) were observed; (i) single point reflectors with a hyperbolic diffraction pattern usually associated with relatively narrow (sub metre) diameter single point air or sand filled cavities, and (ii) wider linear reflectors which could be associated with larger diameter cavities but which can also arise from a sudden stratigraphical change such as the transition to a sand or a gravel lens within the overburden/glacial till.

The features identified were divided into two groups; probable (blue) and possible (red) (Figure 17). A detailed explanation of the findings of the GPR survey is given in Appendix B.

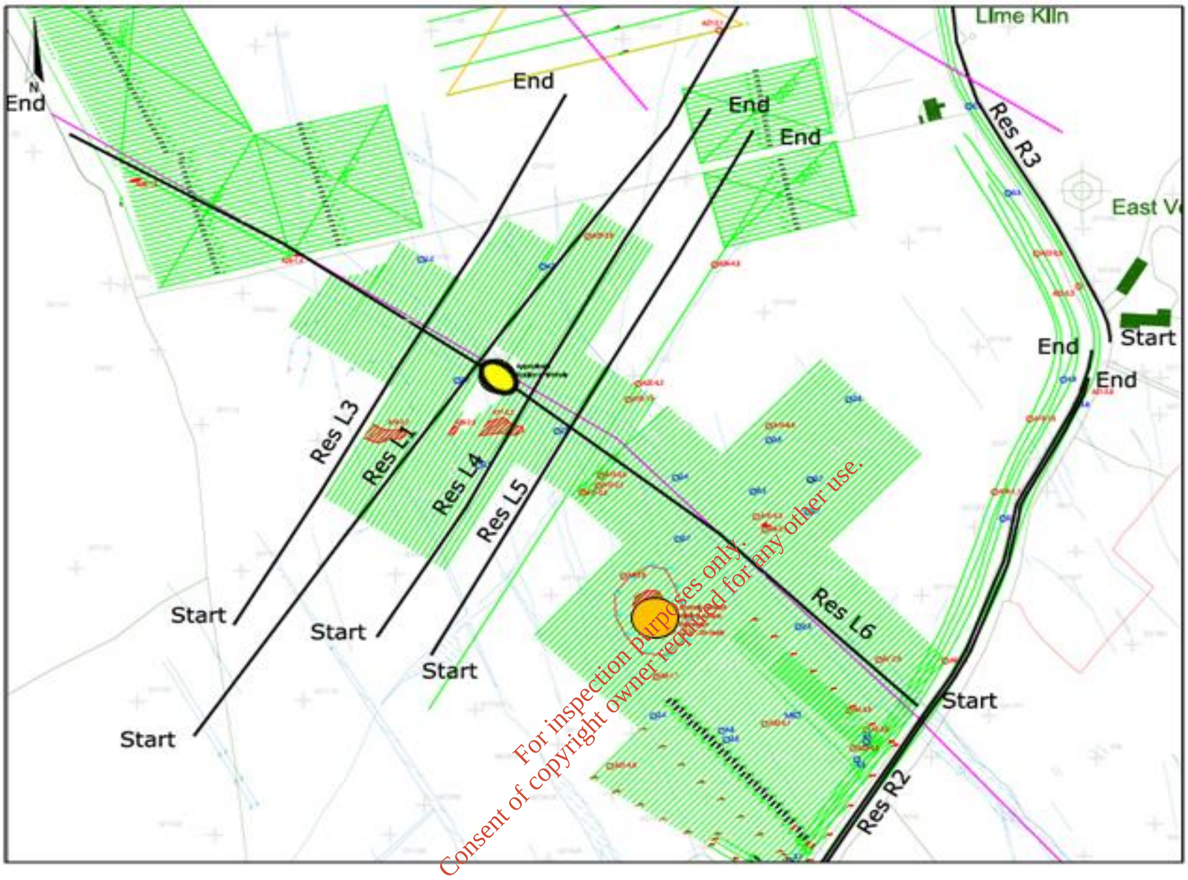


Figure 17: Plan showing location of identified GPR features possible (red) and probable (blue), with sinkhole (yellow) and surface depression (orange)south-east of sinkhole

A surface depression to the south-east of the sinkhole was identified at the time of the GPR survey (it occurs on the original OSI 6” sheet from ca. 1850). This feature was surveyed with the GPR and shows reflections consistent with previous subsidence and infilling (interpreted as an old suffosion sinkhole adjacent to the Main Fissure) (Figure 18).

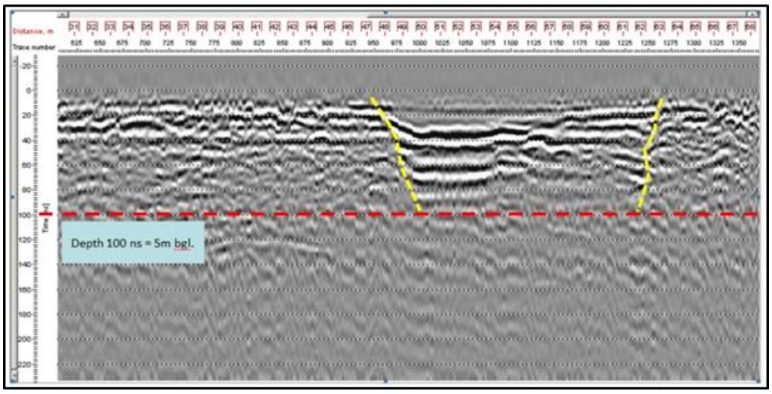
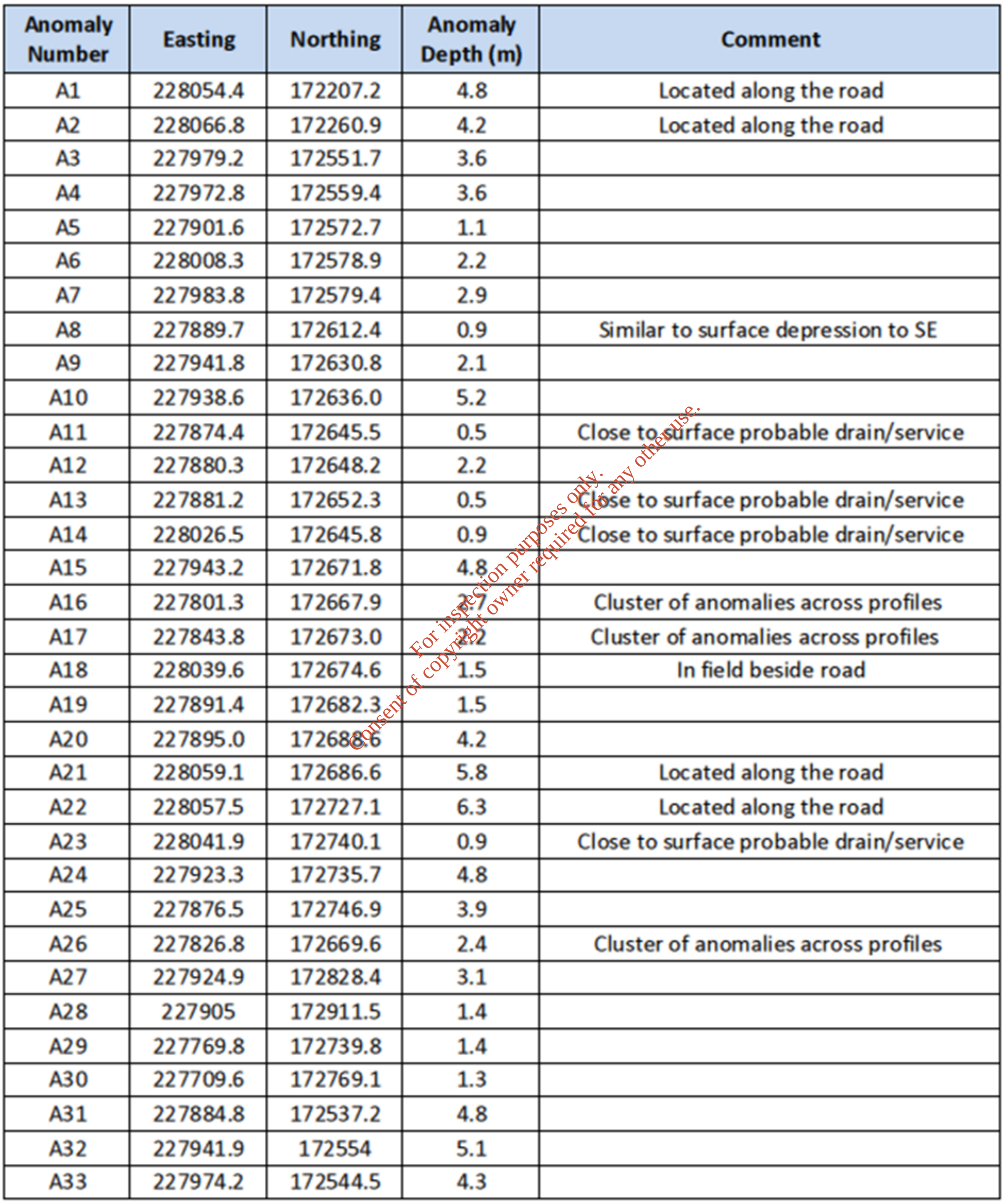


Figure 18: GPR profile across surface depression showing evidence of previous subsidence that has subsequently been naturally filled by material washing into it (see Figure 17 for location).

The list of the ‘probable’ reflectors from the GPR investigations is provided in Table 2. However, where the Main Fissure crosses the road there are no reflectors indicative of possible cavities from the GPR profiles collected.

Table 2: Main GPR Reflectors (probable – blue on Figure 17)



Anomaly Number	Easting	Northing	Anomaly Depth (m)	Comment
A1	228054.4	172207.2	4.8	Located along the road
A2	228066.8	172260.9	4.2	Located along the road
A3	227979.2	172551.7	3.6	
A4	227972.8	172559.4	3.6	
A5	227901.6	172572.7	1.1	
A6	228008.3	172578.9	2.2	
A7	227983.8	172579.4	2.9	
A8	227889.7	172612.4	0.9	Similar to surface depression to SE
A9	227941.8	172630.8	2.1	
A10	227938.6	172636.0	5.2	
A11	227874.4	172645.5	0.5	Close to surface probable drain/service
A12	227880.3	172648.2	2.2	
A13	227881.2	172652.3	0.5	Close to surface probable drain/service
A14	228026.5	172645.8	0.9	Close to surface probable drain/service
A15	227943.2	172671.8	4.8	
A16	227801.3	172667.9	2.7	Cluster of anomalies across profiles
A17	227843.8	172673.0	2.2	Cluster of anomalies across profiles
A18	228039.6	172674.6	1.5	In field beside road
A19	227891.4	172682.3	1.5	
A20	227895.0	172688.6	4.2	
A21	228059.1	172686.6	5.8	Located along the road
A22	228057.5	172727.1	6.3	Located along the road
A23	228041.9	172740.1	0.9	Close to surface probable drain/service
A24	227923.3	172735.7	4.8	
A25	227876.5	172746.9	3.9	
A26	227826.8	172669.6	2.4	Cluster of anomalies across profiles
A27	227924.9	172828.4	3.1	
A28	227905	172911.5	1.4	
A29	227769.8	172739.8	1.4	
A30	227709.6	172769.1	1.3	
A31	227884.8	172537.2	4.8	
A32	227941.9	172554	5.1	
A33	227974.2	172544.5	4.3	

Profiles trending SW-NE at 90^{o} to the Main Fissure (Figure 19) show thickening of the overburden in the vicinity of the Main Fissure. Deep point reflectors, indicative of cavities within the heavily weathered bedrock are especially evident along the north-eastern part of the profile in Figure 19). These may be reflecting karstification of the upper part of the bedrock.

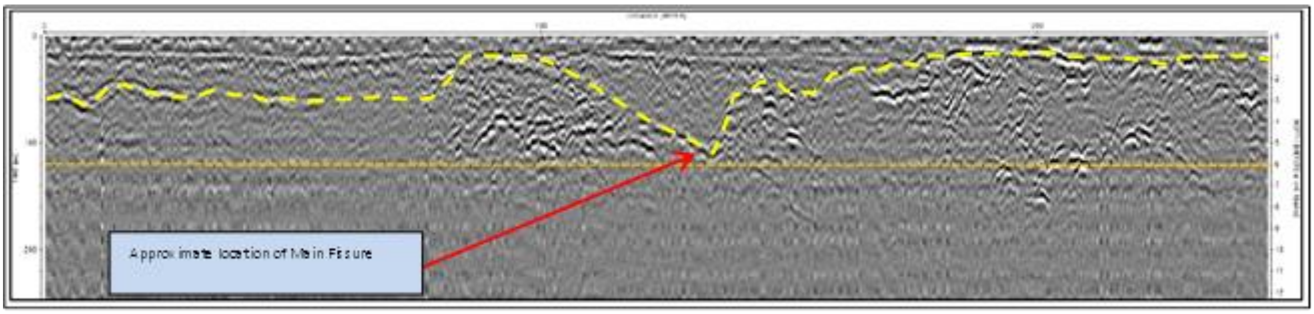


Figure 19: GPR profile running SW-NE (looking north-west) at 90^{o} to the Main Fissure (red arrow), showing increase in overburden thickness in the vicinity of the Main Fissure (dashed yellow line). Also evident are point reflections on either side of the Main Fissure

3.2.2 ERI

A total of nine ERI lines were surveyed, with four lines (Res L1, Res L3, Res L4 and Res L5) being surveyed across the Main Fissure in the vicinity of the sinkhole, one along the length of the Main Fissure (Res L6), and four along the public road (Res L2, Res R1, Res R2 and Res R3) (Figure 20).

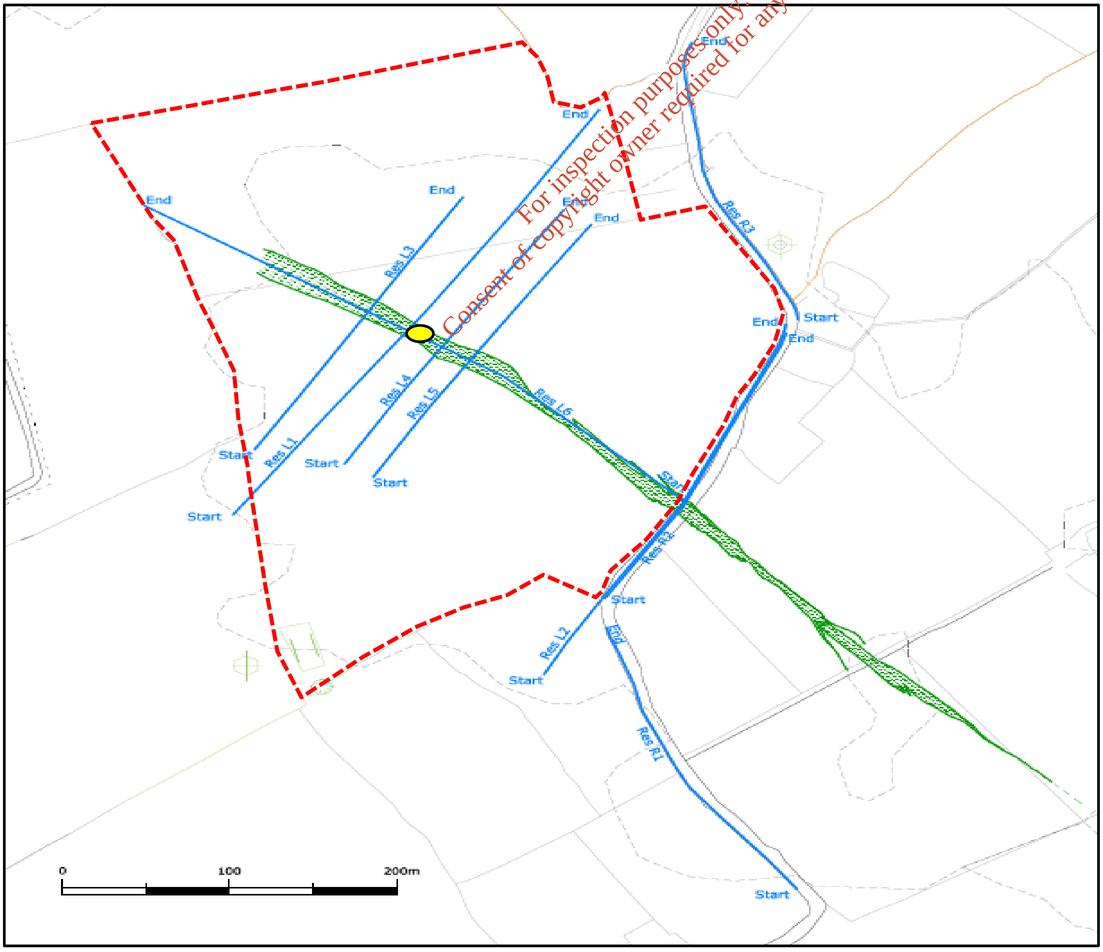


Figure 20: Showing layout of ERI lines (blue, landholding (red), Main Fissure (green) and sinkhole (yellow)

The pseudosections for the lines surveyed (Figure 22 to *Figure 27*) correlate well with the information from the mineral exploration boreholes, with resistivity values of typically <200 ohm metres indicating the presence of overburden material and, values of between 200 and 600 ohm metres indicating a heavily weathered/fractured dolomitised limestone bedrock typically between 20 to 30 m bgl. Below ca. 20 to 30 m bgl resistivity values indicate the presence of less weathered/fractured bedrock to locally within 10 to 20 m of the orebody horizon where bedrock can become more weathered and fractured.

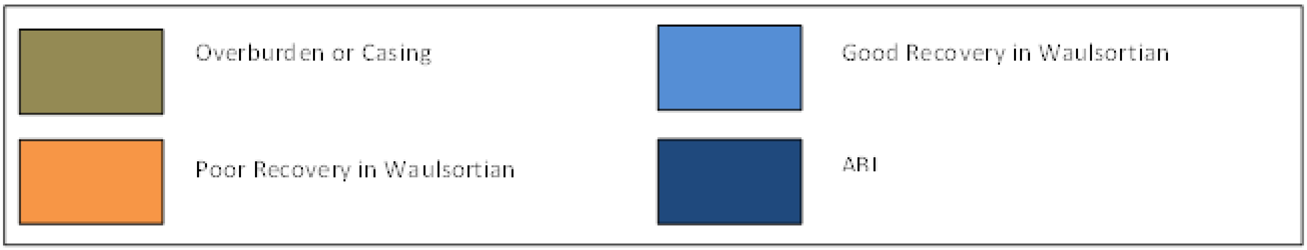


Figure 21: Legend for mineral exploration boreholes shown in Figures 22 to 27)

Below ca. 25 m depth and under the road (Lines R1 – R3) resistivity values tend to be >1000 ohm metres indicating the presence of a more massive less weathered/fractured dolomitised limestone. Line Res L2 (Figure 23) along the road exhibits resistivity values > 1000 ohm metres for the most part except around chainage 160 m, where lower resistivity values correlate well with the position of the Main Fissure as it's mapped underground.

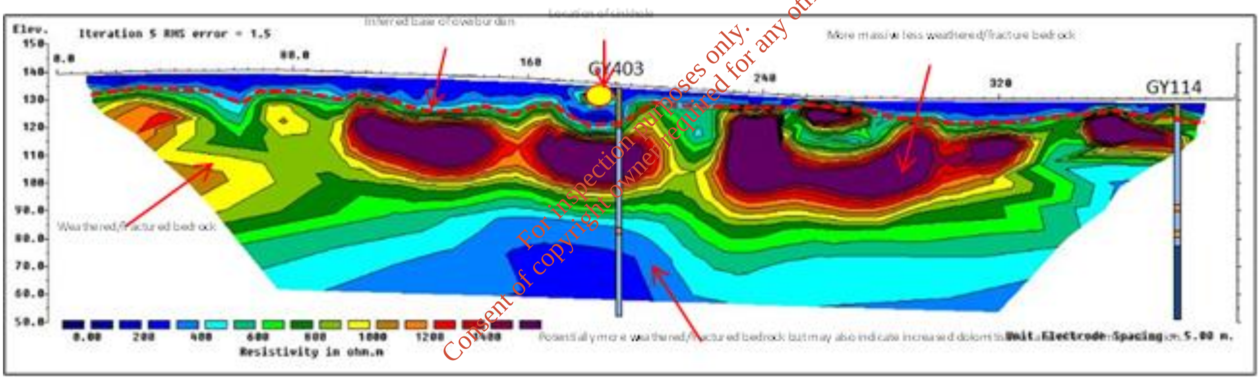


Figure 22: ERI line: Res L1 looking north-west

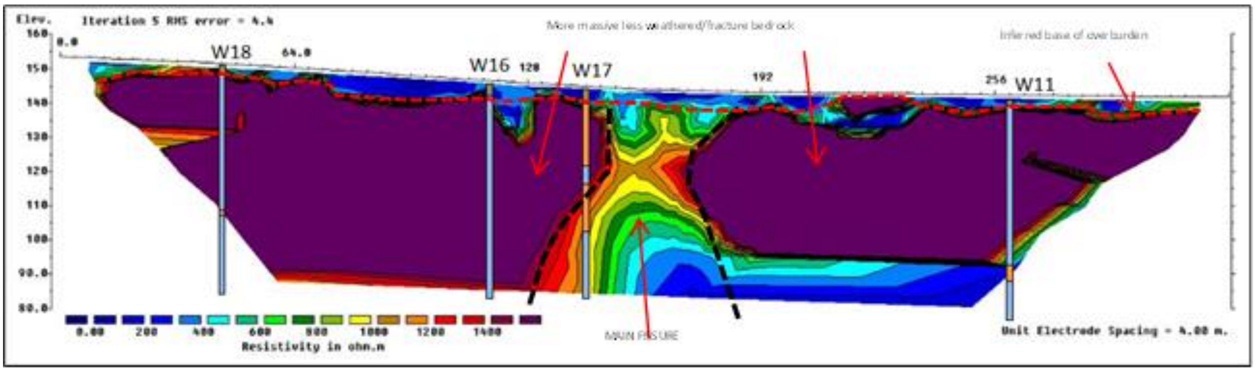


Figure 23: ERI line: Res L2 looking north-west

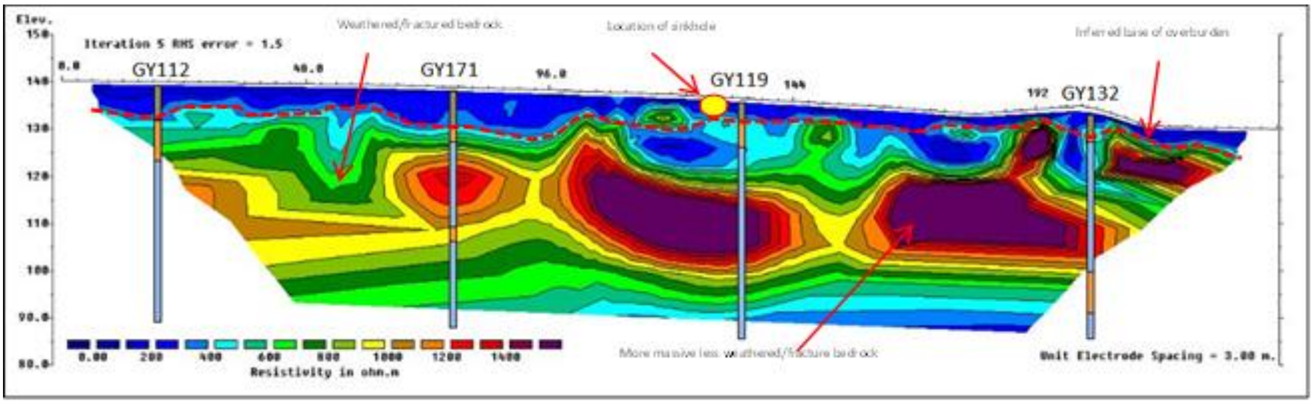


Figure 24: ERI line: Res L3 looking north-west

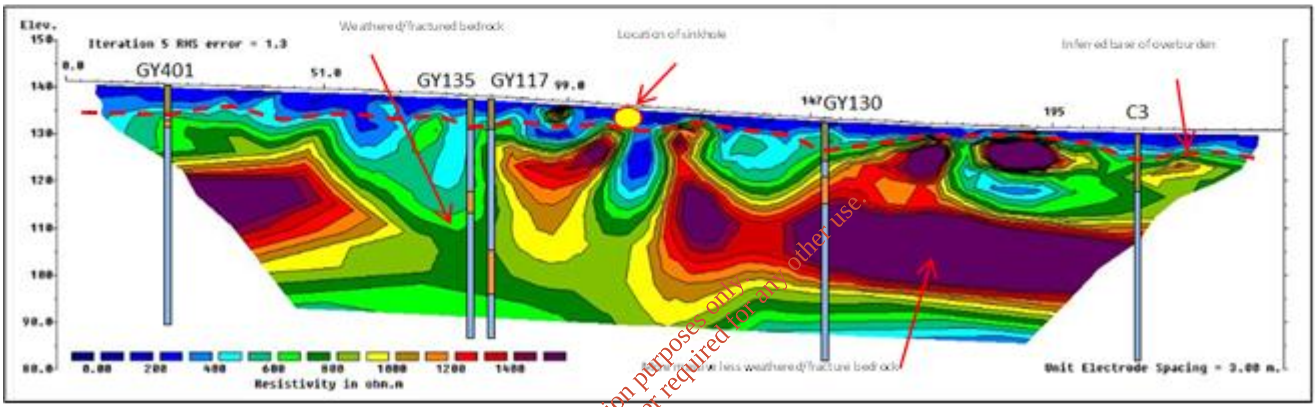


Figure 25: ERI line: Res L4 looking north-west

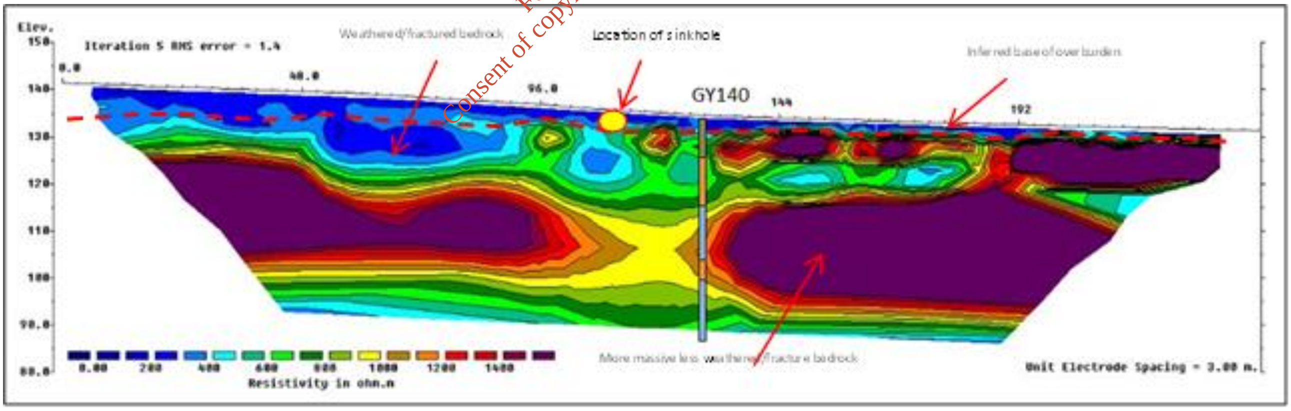


Figure 26: ERI line: Res L5 looking north-west

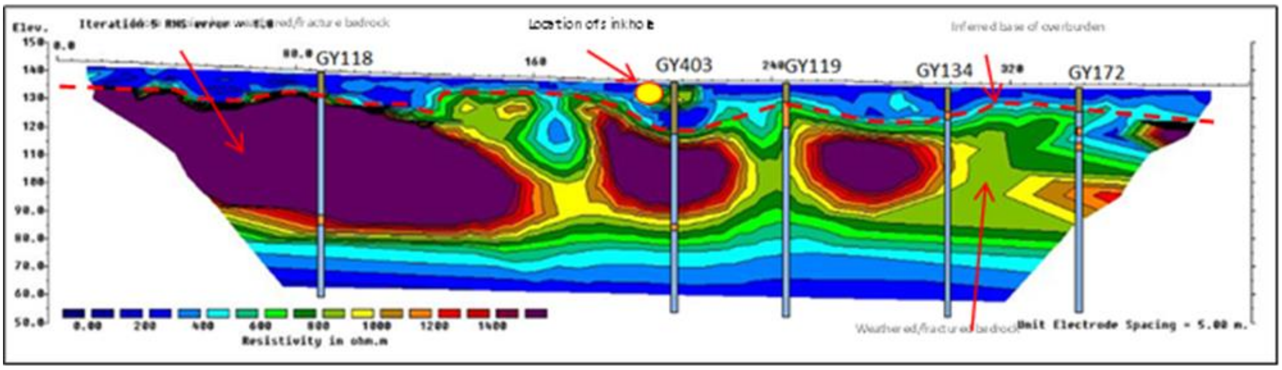


Figure 27: ERI line: Res L6 looking south-west

3.3 Summary

In summary, the GPR surveys have not identified any obvious reflectors in the overburden indicative of possible open cavities/voids. However it has identified a number of reflectors that demonstrate the highly varied nature of the overburden and bedrock interface. This is to be expected as we are dealing with a glaciated, weathered, fractured, dolomitised limestone bedrock which exhibits palaeokarst features.

Other reflectors identified by the GPR can be explained by the highly variable nature of the overburden and bedrock interface and the nature of the clays and glacial till that make up the overburden.

The ERI pseudosections for lines Res L1 and Res L3 to Res L6 show similar resistivity patterns. This similarity collaborates with information provided by the existing mineral exploration boreholes by confirming the highly variable nature of the ground conditions (i.e. an undulating bedrock surface, areas of highly weathered and fractured bedrock and areas of more massive and less well fractured bedrock) underlying the field in the vicinity of the Main Fissure. In contrast, the pseudosection for line Res L2 exhibits more massive, less weathered/fractured rock underlying the public road. The resistivity values and patterns from the start of line Res L6 to chainage 160 m (Figure 27) exhibits similar resistivity values and patterns to the entire length of line Res L2 (Figure 23). This indicates that in general, the rockmass underlying the field in the vicinity of the Main Fissure is naturally more weathered/fractured than that underlying the road. Further evidence for this observation can be found at the orebody horizon where distinct weathering and alteration is associated with the hangingwall of the CW Orebody north of a well-developed NE-SW trending sub-vertical structure (see F3 in Figure 3).

4.0 GROUND MODEL

Reviewing and combining information from borehole logs, underground mapping records and recent geophysical investigations has enabled a robust picture of ground conditions to be developed in the vicinity of the sinkhole.

Overburden in the vicinity of the sinkhole is approximately 6 – 7 m in thickness and is typically comprised of topsoil (ca. 0.2 m), over sub-soil (ca. 0.6 m in thickness), over ca 2.5 – 3 m of sandy glacial till, over a more clay rich, cohesive glacial till (ca.2.5 – 3 m). Figure 28 shows overburden as exposed in the sinkhole.

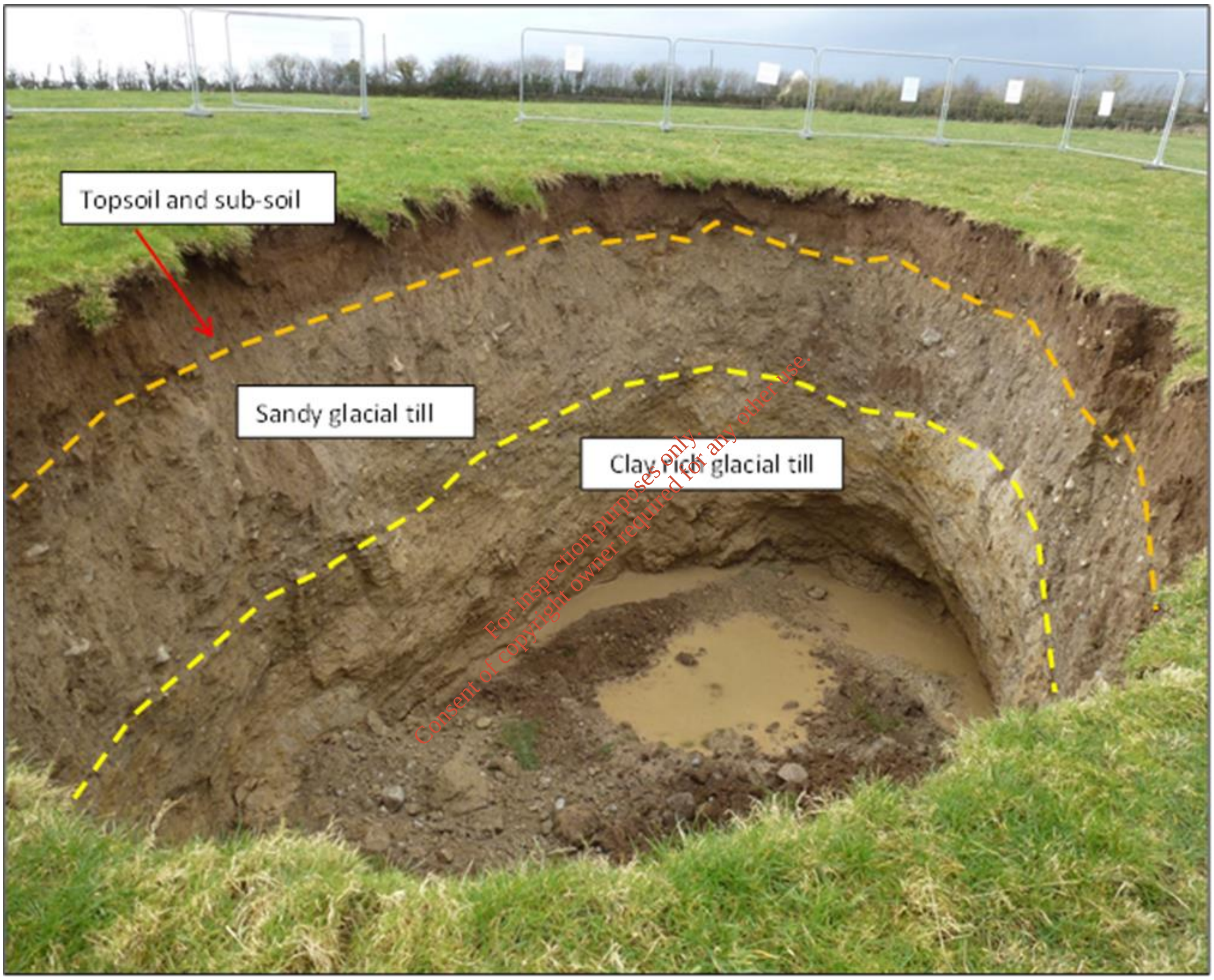


Figure 28: Typical overburden sequence as exposed in the sinkhole

From borehole and underground mapping information the bedrock underlying the sinkhole is comprised of dolomitised Waulsortian limestone, which is approximately 90 m in thickness.

The initial top 20 to 30 m of the Waulsortian tends to have more intensely weathered fractures and joints, with core recovery from boreholes typically less than 100%. Below this weathered zone the rock tends to become more competent, with less weathered and tighter fractures and joints. Within 10 to 20 m of the orebody hangingwall areas of highly weathered ground can occur. These areas of deep seated weathering which developed during Tertiary times are associated with sub-vertical features and sub-horizontal argillaceous bands and can also occur within the orebody itself (Figure 29).

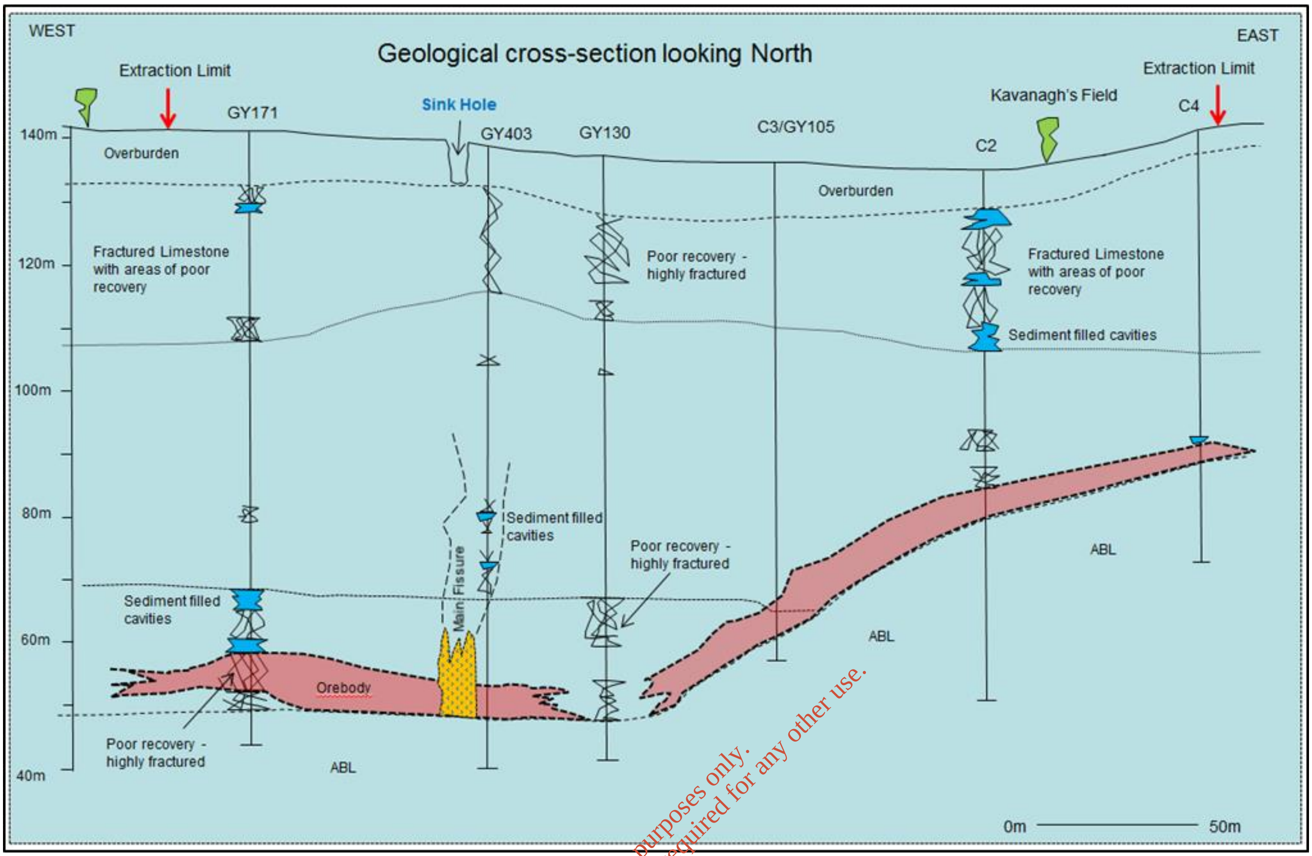


Figure 29: Schematic cross-section CW Orebody showing typical ground conditions in the vicinity of the sinkhole

Figure 30 below presents the location of the Main Fissure and other dominant sub-vertical features from underground mapping records. Palaeokarst sediment filled features and water ingress to the underground workings are predominantly associated with NNW-SSE and N-S trending sub-vertical structures.

Also shown in Figure 30 are areas where there was a ‘run-of-ground’ associated with fissures / fractures (and palaeokarst features) in the CW Orebody that extended typically up to 2 - 3 m above the mining horizon.

In 2002, a series of roof collapses and pillar failures occurred in the CW Orebody resulting in a complete collapse of J and K Stopes, followed by major instabilities in some adjoining stopes to the south. The collapse undermined the rockmass above the stopes and caused it to subside, resulting in surface damage with a crack opening up in the public roadway overhead and several smaller tension cracks developing. The bitumen road pavement was ‘heaved’ into a ridge in two places, forming a pressure ridge. It is notable that no sinkholes formed following the underground collapse.

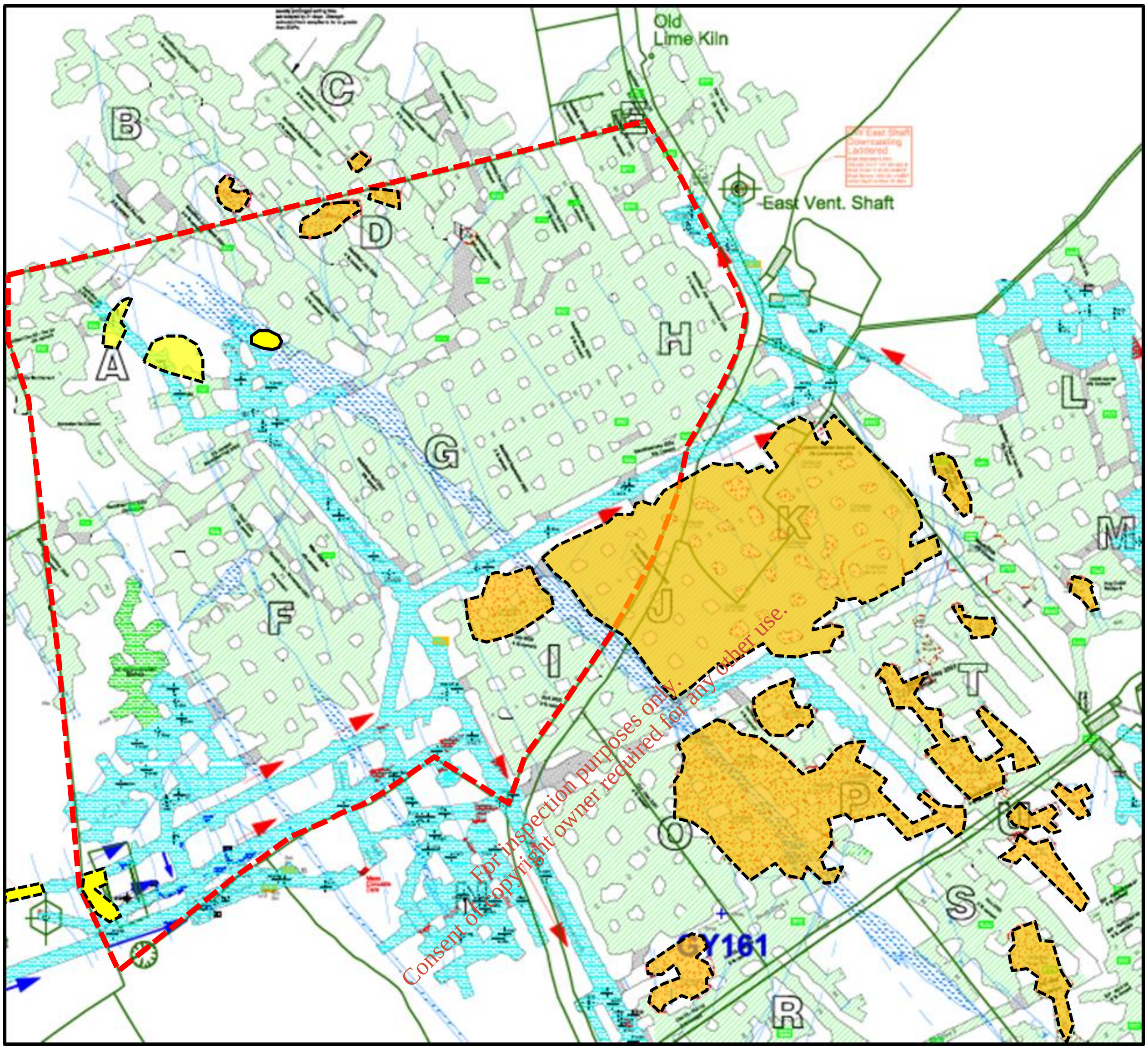


Figure 30: Plan of CW Orebody showing main structural features mapped at orebody elevation with Main Fissure, areas of significant ‘run-of-ground’ associated with fissures/fractures and main palaeokarst features (in yellow) intersected by mining. Failed stope areas from 2002 collapse are shown in orange, with backfilled areas in green (areas in pale blue are not backfilled). Land holding in red dashed line.

5.0 MORPHOLOGY AND FORMATION OF THE SINKHOLE ABOVE THE MAIN FISSURE

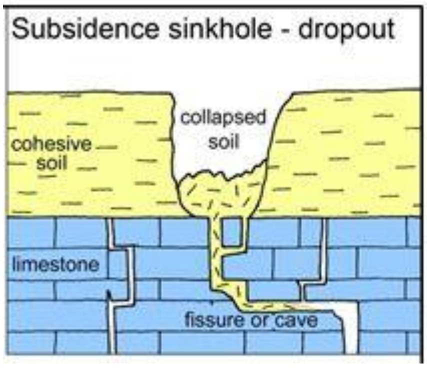
5.1.1 Morphology

The sinkhole is elliptical in plan with its long axis in alignment with the Main Fissure. Its dimensions are; long axis 13 m, short axis 8 m, depth ca 7 m with an approximate volume of 550 m^3. The sinkhole is deep-sided with no bedrock visible in its walls or base, both of which are composed of sandy glacial till.

The sinkhole is at an elevation of ca. 139 m AOD, approximately 80 m above the mine workings. Bedrock is estimated to occur at ca 132.5 m AOD, with the water table at ca 123 m AOD.

Based on the underlying geology, morphology and the rapid (minutes to hours in timescale) nature of the development of the sinkhole over the CW Orebody at Galmoy, it is considered that the sinkhole can be classified as a dropout sinkhole. The evidence for this classification is presented in Table 3.

Table 3: Characteristics of a dropout sinkhole

Diagrammatic representation (after Waltham et al, 2010)	**Key Characteristics (after Waltham et al, 2010)**	**Evidence at Galmoy**
	***Formation process:*** Soil collapse into void over bedrock fissure. ***Host rock types:*** Cohesive soil overlying limestone, dolomite, gypsum. ***Formation speed:*** In minutes, into soil void evolved over months or years. Typical max size: Up to 50 m across and 10 m deep. ***Engineering hazard:*** The main threat of instant failure in soil-covered karst. Other names in use: subsidence sinkhole, cover collapse sinkhole, dropout doline.	Sinkhole appears to be within soil column; in the vicinity of heavily weathered bedrock; no intact bedrock visible in the base. Some evidence in borehole logs of fractures in-filled with poorly consolidated, sandy material. Host is a cohesive glacial till, overlying limestone. Hole was reported to have formed overnight. Approximately 7 m deep and 13 m long. Present in an area of glacial till covered palaeokarst.

The size and morphology of the sinkhole above the Main Fissure (Figure 31) displays dropout sinkhole characteristics including steep sides in cohesive soils with collapsed soil in the base of the hole. The morphology is not suggestive of any bedrock collapse and it appears to be developed entirely within the glacial till.

Figure 31: Main Fissure sinkhole approximately 13 m (long) x 8 m (wide) x 7 m (deep)

5.1.2 Timeline of sinkhole formation

A possible timeline in relation to the formation of the sinkhole:

Table 4: 2014 Sinkhole - Timeline

Date	**Evidence**
Pre-mining	The Midlands of Ireland is a palaeokarst environment. Many millions of years ago during the Tertiary when there was a warm humid environment and lower water-table water moved through and dissolved the limestone bedrock, enlarging the Main Fissure and other smaller fissures/fractures. During the later Tertiary, and then in the Quaternary these now palaeokarst features were filled with sediment including fluvio-glacial deposits rendering them hydrologically inert. During the Holocene there has been limited dissolution of the upper few metres of bedrock but there is no evidence of an integrated conduit drainage system.
May 1995 to early 1997	Dewatering for mine development took place between May 1995 to early 1997 (during which time the CW Orebody was first accessed). The extent of water-table drawdown increased as mining developed over subsequent years. It is noted that no sinkholes formed during the period of dewatering.
1999	The mine workings intersected the Main Fissure zone and a laterally developed palaeokarst feature at the orebody horizon. During mining it was noted that some of the drives intersecting the Main Fissure gave rise to the production of sandy or muddy water and that the orebody and rocks adjacent to the fissure tended to be strongly jointed, oxidised and generally weak. In general when fissures/fractures were intersected underground they inevitably made 'sandy or muddy' water for a period of time. Features were supported and allowed to drain and mining continued. Where possible Main Fissure intersections were not mined or stoped out.
2000 – 2012	Mining continued with subsequent backfilling of the Galmoy orebodies.
Early 2013	Dewatering of the mine operation ceased and groundwater levels started to recover to pre-mining levels.

Early 2014	Groundwater levels recover to pre-mining levels. Exceptional rainfall occurs in December 2013, January and early February 2014.
14 Feb. 2014	Landowner carried out the spreading of soiled water over the land, driving over the area where the sinkhole subsequently formed.
15 Feb. 2014	The sinkhole was reported by the landowner.

5.1.3 Mechanism for sinkhole formation above Galmoy mine workings

It is considered that the failure mechanism for the sinkhole is as a result of a combination of the following factors:

- The presence of a palaeokarstic void system, the Main Fissure, which had been filled with sediment;
- Lowering of the local water-table by dewatering and intersection of the Main Fissure in the mine which together allowed the ancient flow-path down the fissure to be re-activated. Groundwater flowed down the Main Fissure towards the mine, taking with it some of the fissure sediment fill and opening void space within the fissure. The process was enhanced by concentration of drainage at the location of the Main Fissure due to a depression in the rockhead (the solid rock surface under the overburden) along the Main Fissure and an up gradient catchment associated with the Main Fissure;
- The development of open voids within the glacial till due to washout of material through fractures (i.e. palaeokarst features) in the bedrock above the Main Fissure. Underground mapping identified karstification in the vicinity of the sinkhole (Figure 9). Information from borehole GY119 supports this observation (Figure 10); and
- Recent exceptional rainfall and infiltration, coupled with the spreading of soiled water on the field shortly before the sinkhole appeared (ca. within 24hrs) increased the weight of the overburden and acted as the trigger for collapse into the void which formed the sinkhole.

These causative factors are considered below.

The concentration of drainage at the location of the Main Fissure due to a depression in the rockhead surface over the Main Fissure:

Unusually the sinkhole is developed on a slope. Typically sinkholes form on flat ground or at the base of slopes where water drains downs to and then ponds before weeping into the rock. Based on the results of GPR (ground penetrating radar) and ERI (resistivity) surveys of the area around the sinkhole it is noted that there is evidence for a depression, or valley, in the bedrock surface over the Main Fissure (Figure 32 and Figure 33). It is considered that this may represent a small palaeo-valley that acts as a preferential drainage channel for infiltrating rainwater as it moves downslope and towards the underlying limestone, thus concentrating the rainfall recharge in the area of the fissure at this location.

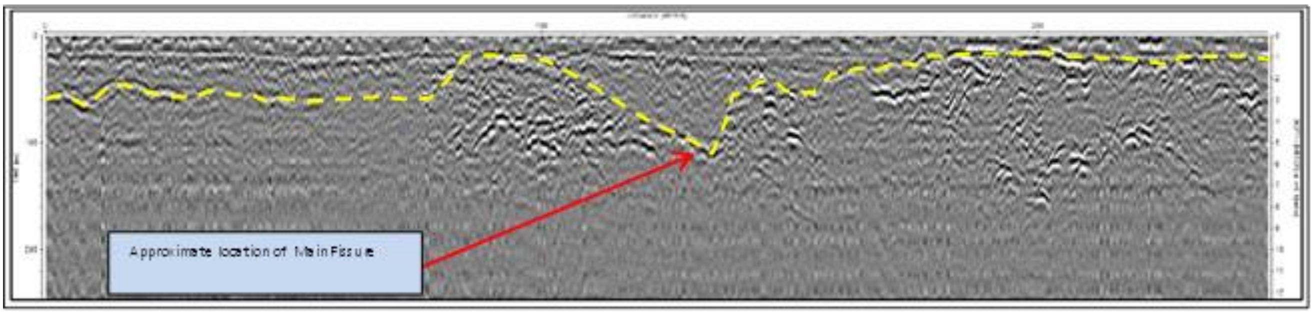


Figure 32: GPR section along the Main Fissure from SW to NE (looking northwest) in the vicinity of the sinkhole showing the presence of a bedrock valley feature associated with the location of the sinkhole.

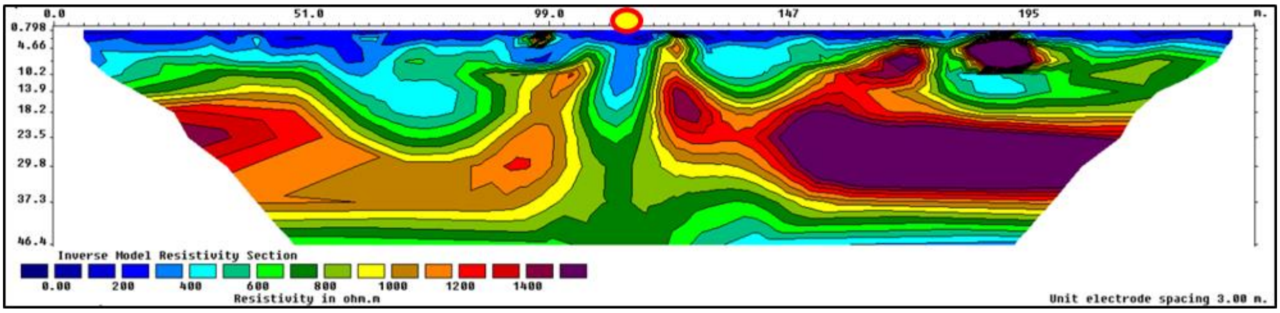


Figure 33: ERI imaging section across the Main Fissure (yellow dot) in the vicinity of the sinkhole, looking northwest

The presence of voids within the Glacial Till due to washout of material through conduits in the bedrock:

It is likely that fractures (evident in boreholes) are present within the palaeokarst and that sediment, from the unconsolidated sediments above, has been washed down through these. In particular, when the mine workings intercepted the Main Fissure, muddy water flowed into the mine drives. For a dropout sinkhole to form it is merely necessary for an efficient pathway to be present for the removal of the ‘washed-down’ sediment; it is possible that a pathway within the vicinity of the Main Fissure facilitated this removal of material. What this indicates is not the rapid wholesale migration of large volumes of material from the surface to the mine voids, but that the Main Fissure at this location may have provided a permeable pathway for water and sediment transport over an extended time period.

The provision of a potential pathway for the washout material which happens to connect to the mine should not be confused with the occurrence of an underground collapse. As mentioned above, no sinkholes formed following the underground collapse in 2002 and it is deemed highly unlikely that the sinkhole formed as the result of such an occurrence based both on that evidence and the morphology of the sinkhole.

Locally enhanced permeability, as a result of dewatering, giving rise to increased void size and enhanced groundwater circulation:

Sinkhole development has been recorded to occur as a result of the lowering of the natural water-table (Ford and Williams, 1989) as a result of:

- A loss of buoyant support in the soil and thus a corresponding increase in effective stress due to this loss of support;
- An increased hydraulic gradient coupled with an increase in flow velocities and gradual erosion of fines in fractures underlying the soil column thus allowing material to migrate from the soil column; and
- A weakening of the overlying unconsolidated soils and gradual erosion by means of wetting and drying due to the fluctuating water levels.

It is noted however that although the withdrawal of water by means of abstraction or dewatering of a quarry or mine and subsequent water-table drawdown is considered to be the most usual cause of dropout sinkhole formation (Waltham et al 2010), no dropout sinkholes developed at Galmoy during the period of active mine dewatering and declining groundwater levels.

In fact, the water-table had almost recovered to the original pre-mining level by January 2014 (by March 2014 pre-mining groundwater levels had been reached) due partially as a result of the recent heavy rain fall (Figure 34).

During the period of active dewatering, and to a lesser extent during the period when the water-table was recovering there would have been removal of material from the superficial deposits down the Main Fissure resulting in a steadily growing void that was eventually the focus for the dropout sinkhole.

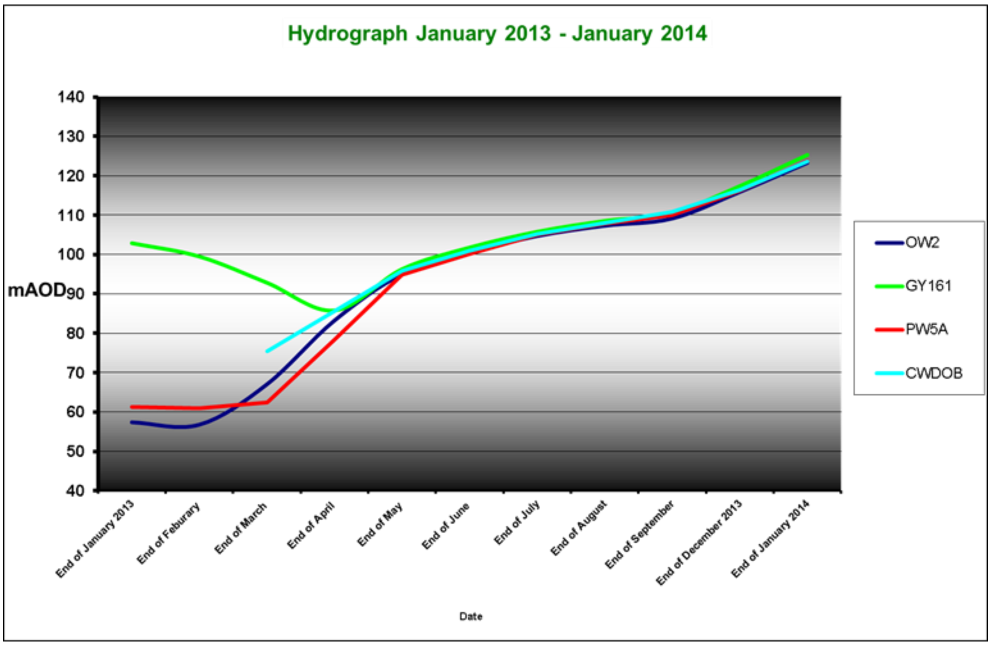


Figure 34: Hydrograph showing groundwater recovery (Lundin Mining)

Dewatering and mining allowing the re-activation of a permeable path from surface down the Main Fissure in to the underground mine workings:

The sinkhole is situated above the Main Fissure and approximately 80 m above the mine workings (Figure 35 and Figure 36).

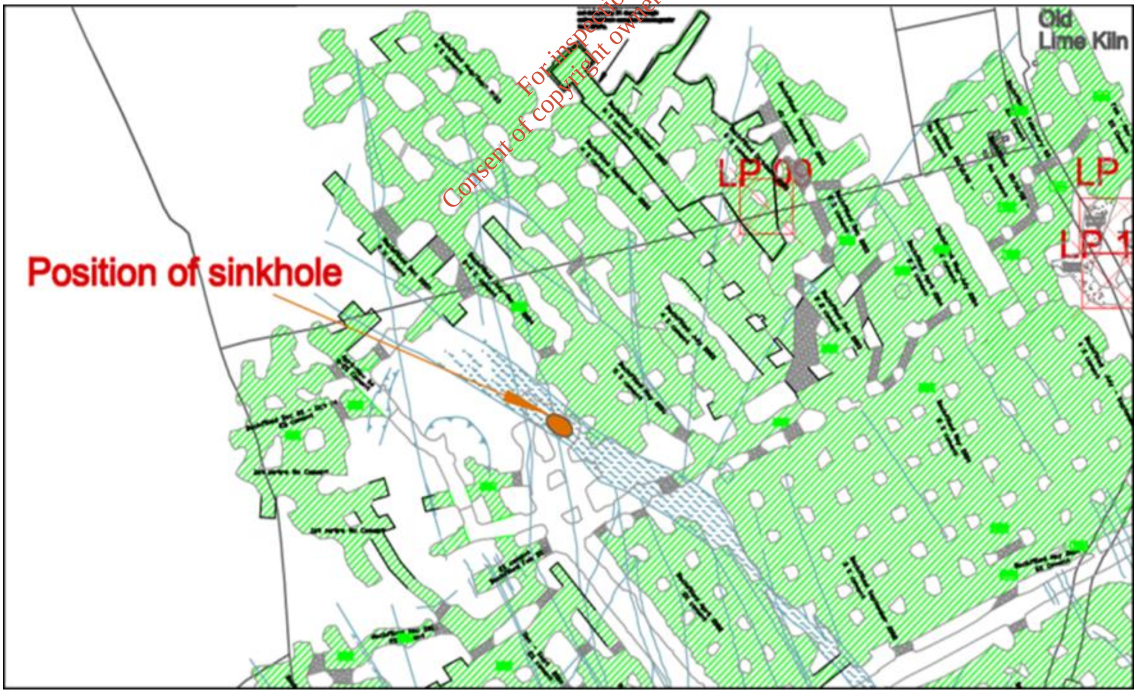


Figure 35: Plan showing relative location of the Main Fissure, sinkhole and mine working

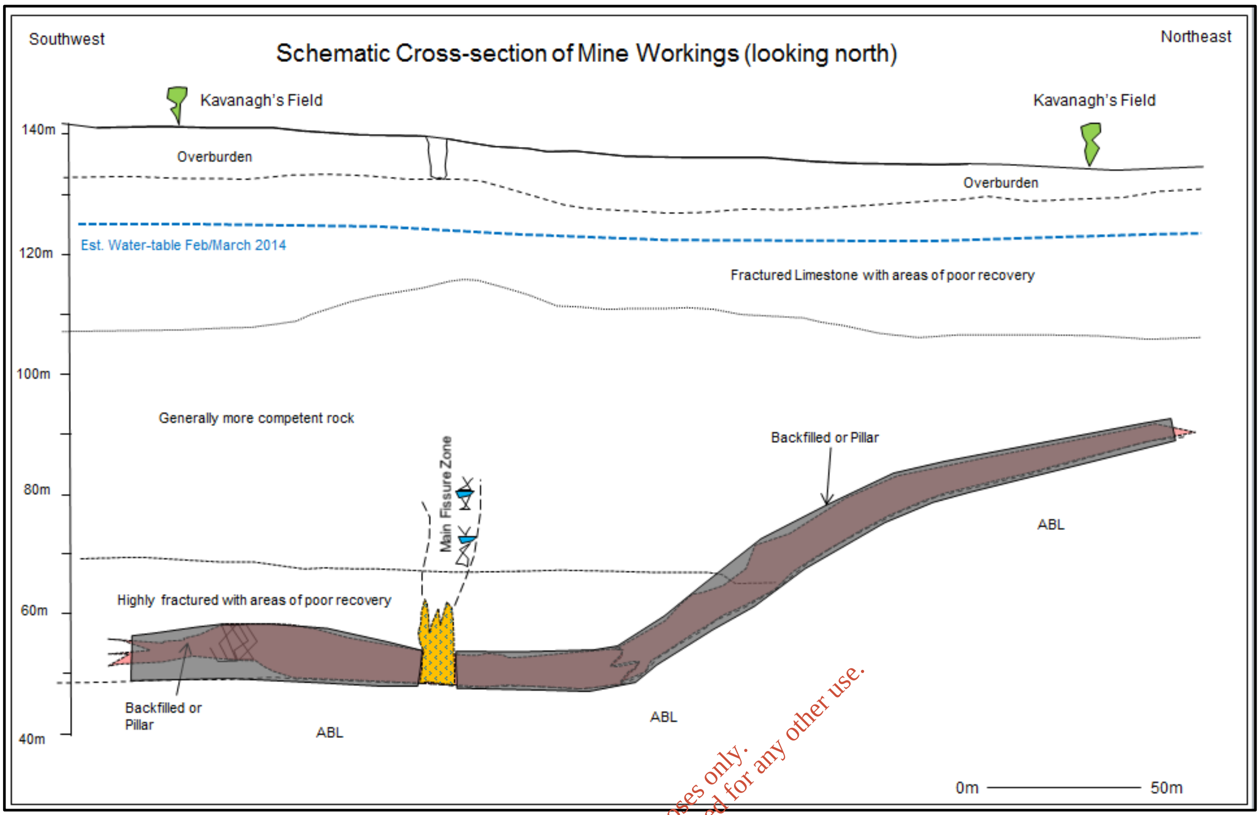


Figure 36: Schematic Cross-section showing groundwater levels as of February/March 2014 and depth of mine workings below ground level

When the Main Fissure was intersected by the mine workings it was found that it generally 'made' water containing sand and silt / clay for extended periods (weeks to months), following intersection. Generally the rock within the Main Fissure required additional support either with shotcrete (Figure 37) and / or the installation of steel arches.

Figure 37: Shotcreted Fissure underground at Galmoy

However, it is considered likely that the presence of the Main Fissure could present a pathway for the removal of the ‘washed-down’ sediment, an important component for the formation of a dropout sinkhole, whilst also giving rise to an area of increased permeability. The mining into the Main Fissure facilitated the formation of the permeable pathway for sediment removal. Indeed, it is fundamental for the formation of the sinkhole morphology observed, that the Main Fissure was able to act as a conduit for the removal of sediment.

The recent exceptional rainfall and infiltration, coupled with the soiled water spread by the landowner:

The void that formed upwards from the superficial deposit-bedrock interface probably grew to close to its final size whilst the mine was being actively dewatered, with the arch close to the threshold of instability. The exceptionally heavy rainfall between December 2013 and February 2014 (Figure 38) would have saturated the soil overlying the void increasing its weight and the additional loading from spreading of soiled water, together with the weight of the tractor, probably caused material to spall from the roof of the void such that it failed that evening.

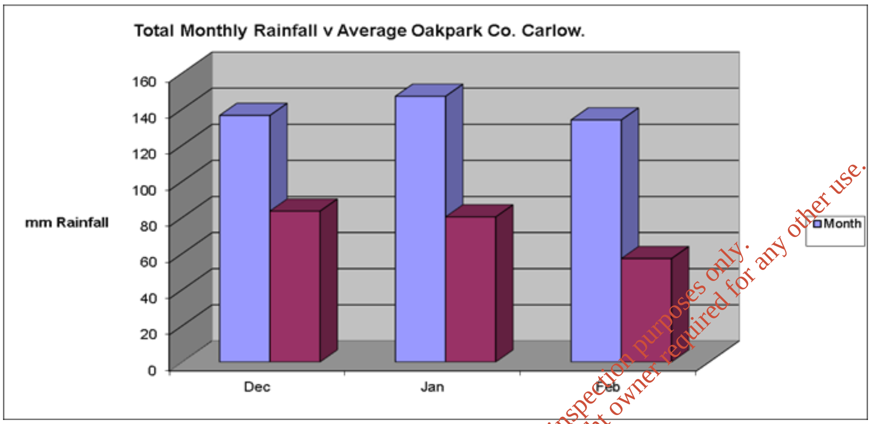


Figure 38: Monthly rainfall data vs average (Lundin Mining)

5.1.4 Summary of main fissure sinkhole formation

The timing for the development and formation of the Main Fissure sinkhole may be considered in four stages (Figure 39).

- **(A) Development of palaeokarst (65.5 million to 12,000 years ago)**: Evidence from mid-Tertiary organic clays in buried sinkholes indicates that there was an active karst at this time and it is considered likely that groundwater was circulating through the Main Fissure. There may have been subsequent periods of active karstification but by 12,000 years ago all the voids in the limestone that had formed in the Tertiary had become clogged with sediment and there was no longer any active groundwater circulation through them;

- **(B) Pre-mining (12,000 to 20 years ago)**: During the Holocene there was slow groundwater flow at shallow depth through immature fissures some of which are likely to have been slightly enlarged by dissolution to form channels and conduits. The water-table would have been similar to that which it has recovered to following cessation of dewatering with very low hydraulic gradients and consequent low groundwater velocities which would have been insufficient to entrain and transport sediment. Hence, no void could have formed in the overburden at this stage;

- **(C) During Mining**: During the mining stage dewatering had the effect of lowering of the water-table and increasing the water velocity giving rise to a greater washout potential. The higher velocity water flows in the Main Fissure accelerated the removal of sediment and water through this route and it is likely that voids formed in the Main Fissure allowing sediment to be moved down from the overburden and development of a void at the base of the overburden; and

- **(D) Current**: Upon cessation of mine related dewatering the water-table began to return to its original pre-mining stage level. Importantly, as water was no longer being removed from the mine active circulation of groundwater ceased and the rainfall recharge gradually filled up all of the voids with a consequent steady rise in the water-table. Observations of turbid water in some wells for a short period suggests that there may have been a final phase of sediment mobilisation as the water-table approached pre-mining levels and groundwater started to flow through pre mining paths. It is likely that the void within the overburden had grown to a size whereby the arch was close to the instability threshold. The period of heavy rain, possibly assisted by application of water to the field, increased the weight of the overburden to such an extent that the unstable arch collapsed suddenly, giving rise to a 'dropout sinkhole'.

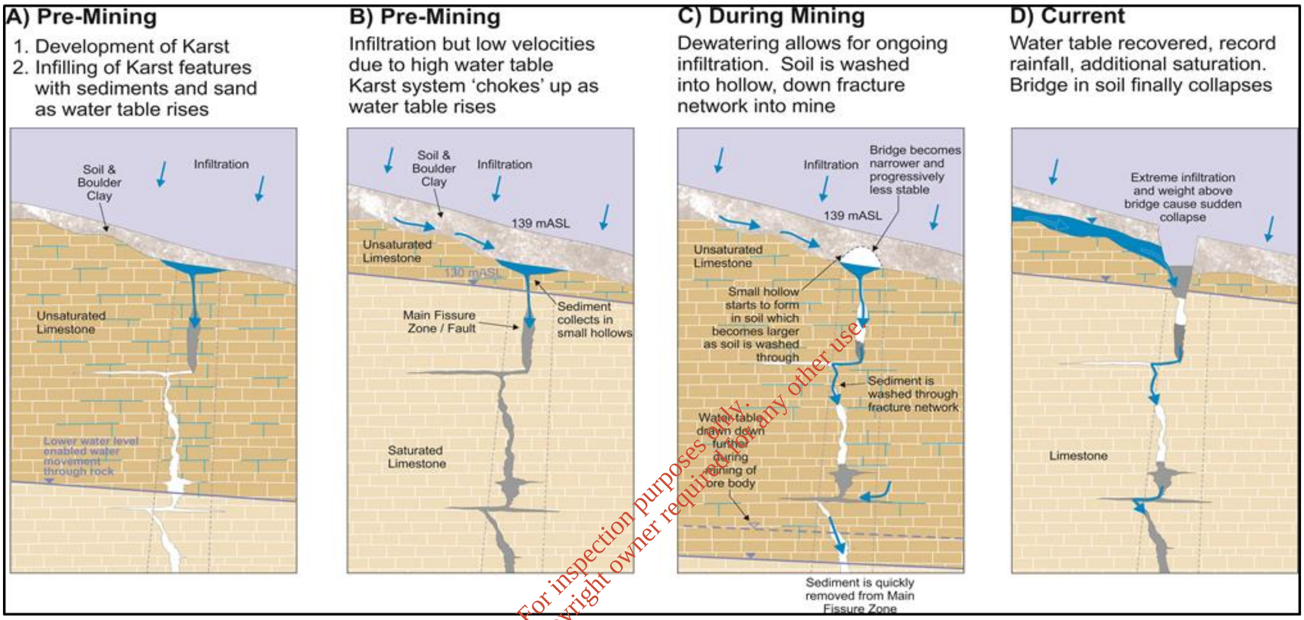


Figure 39: Schematic showing summary of proposed Main Fissure Sinkhole development

6.0 RISK OF FURTHER SINKHOLE DEVELOPMENT

6.1 Risk Logic (Risk Assessment)

The objective of this qualitative risk assessment is to identify and rate areas that are potentially at risk of surface subsidence from sinkhole development, pillar failure or crown failure. This approach enables a targeted strategy for further action toward areas identified as having significant risk.

The risk assessment initially identifies the cause of the adverse event, in this instance, the subsidence expression on surface in the form of a sinkhole. Quantitative values are assigned to the **likelihood** of any given **hazard** leading to an event at any of a number of potential locations. Likelihood values range from 0 to 5, this being 0 for not possible, 1 being highly unlikely and up to 5 being most likely. Where there is more than one hazard affecting an area of interest the likelihood ratings of all possible hazards are summed. This can result in an open-ended scale to the likelihood of a hazardous situation having an effect but this can be manageably constrained by judicious choice of what defines any given area of interest.

The second part of the risk assessment considers the actual environment conditions (in this case land usage) affected by the hazard or hazards and the potential **consequence** if the event should happen and assigns a numerical value depending on the severity of these consequences. Again, individual environments (land usage) are considered on an individual basis rated from 0 to 5 in the same way as likelihood values are assigned. Multiple environment conditions are summed and constrained in the same way as hazards to derive an overall consequence rating.

Further refinement can be made by including any mitigating measures and their likely effectiveness.

Risk is the product of multiplying the likelihood of an event, or series of events, happening by the consequence of its, or their, occurrence (Figure 40). A Risk Matrix is formed by plotting Likelihood on the horizontal axis against Consequence on the vertical axis. Low risk is indicated by the bottom left of the graph and high risk is indicated by the top right of the graph.

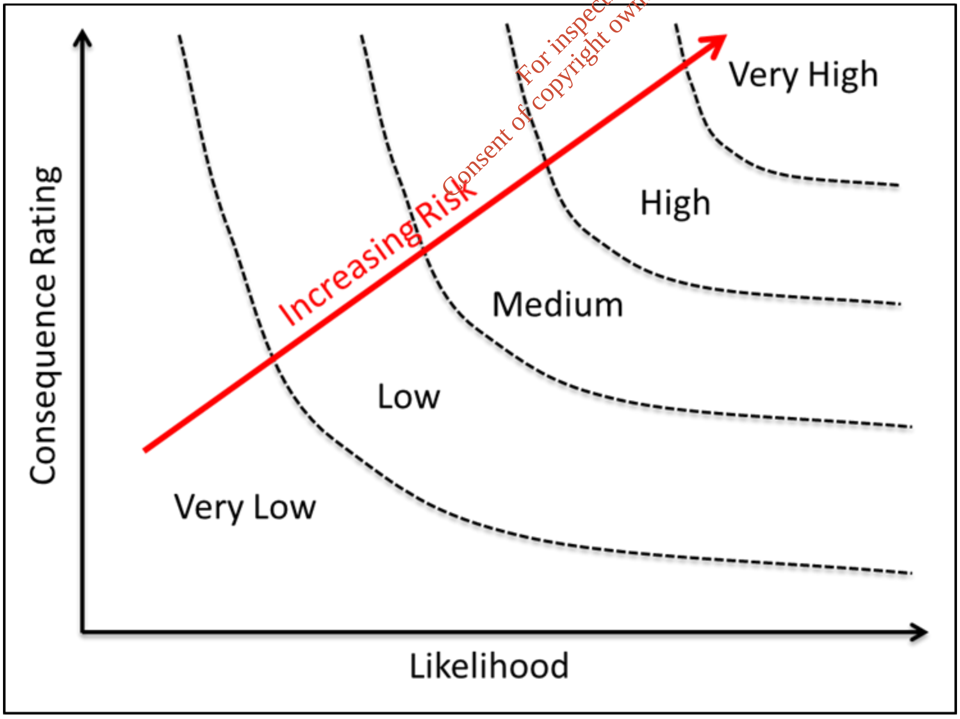


Figure 40: The Risk Matrix in terms of a graph of Likelihood versus Consequence going from Very Low (VL) risk in the bottom left to Low (L), Medium (M), High (H) and Very High (VH) in the top right

In this case, risk has been assessed on the basis of a given land area usage and the possible risk of further sinkhole or other subsidence is rated as Very Low, Low, Medium, High or Very High.

These categories should be interpreted on the basis of:

- **Very Low** – No action required;
- **Low** – Infrequent inspections;
- **Medium** – Frequent Inspections and Regulated Monitoring;
- **High** – Regulated Monitoring and Ground Investigation; and,
- **Very High** – Ground Investigation and remedial work to bring the risk to an acceptable level.

6.2 Likely Relevant Hazards Contributing to Sinkhole Development

As discussed previously there are a number of key potential factors (likely relevant hazards) associated with the occurrence of the sinkhole or failure in the vicinity of the Galmoy Mine. The most important of these factors are:

Table 5: Hazards contributing to sinkhole or failure development

Hazard	Description
Geological Structures	
5	Main Fissure
3	Major structures (G Fault, R Fault) and NNW-SSE (inc. N-S) trending structures
2	NE-SW trending structures
Type of Workings	
3	Open mine workings
2	Backfilled mine workings
1	Collapsed mine workings
Dewatering – blanket influence across the mining area	

6.2.1 Geological structures

A literature review carried out before construction of the tailing management facility (TMF) discussed the likelihood of potential dam failure (Golder 1992). Failure associated with sinkhole occurrence is, or can be related, to certain geological features (Figure 41). The most probable locations ranked most to least likely are (Littlefield et al, 1984);

- Major lineament intersections;
- Along a lineament;
- Not along a lineament, at a fracture trace intersection;
- Not along a lineament, along a fracture trace; and
- In fractured rock.

Known geological features considered significant are discussed below:

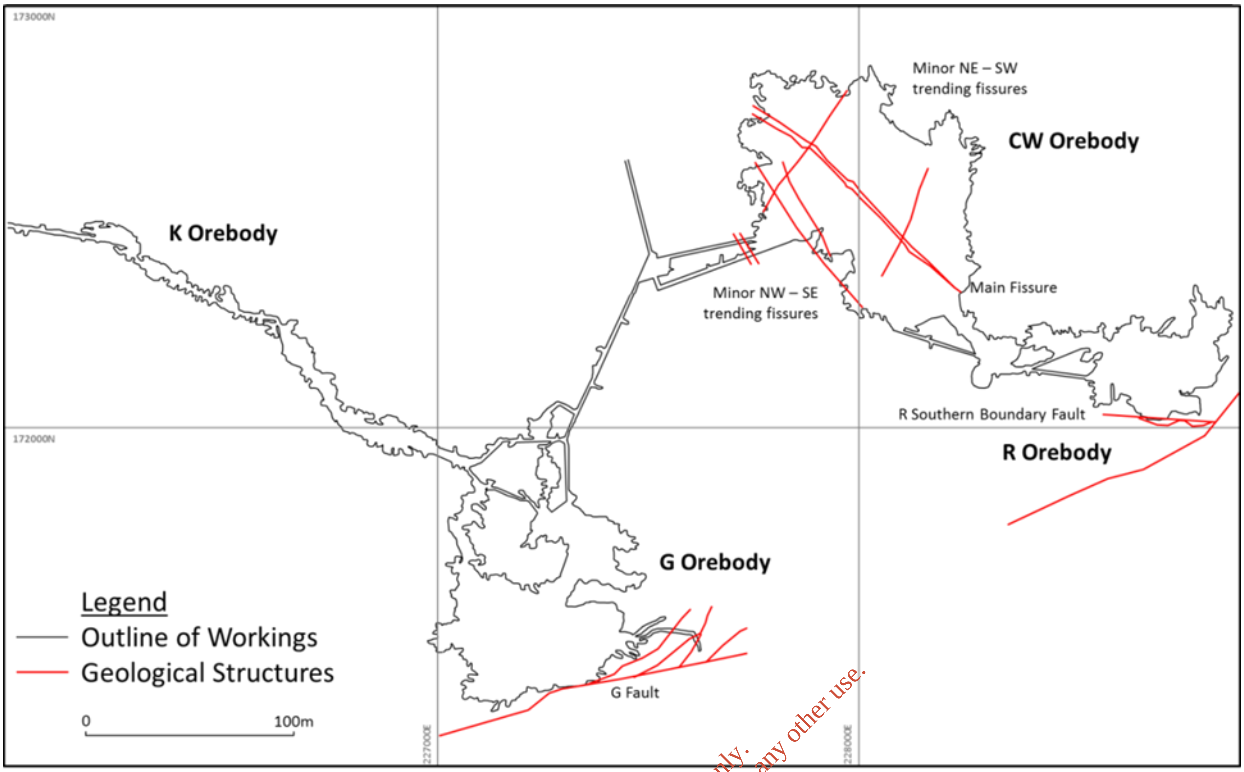


Figure 41: Significant Geological Structures Galmoy Orebodies

CW Orebody Main Fissure: The sinkhole that developed in February 2014 coincided with the mapped underground trace of the Main Fissure. The Main Fissure is a prominent geological structure which was identified during mining of the CW Orebody. The fissure has a strike slip component associated with sub parallel joints. On mining, the intersection of workings with the fissure was associated with locally high ground water inflows. Along the fissure there is locally a high degree of weathering, giving rise to enhanced hydraulic conductivity in that area. For the most part the fissure is downslope of a local drainage / catchment area. A prominent bedrock depression along the strike of the feature has been identified using geophysics. The structure of the fissure pinches and swells both along strike and dip. From underground mapping, the feature is well developed in the CW Orebody.

NNW/SSE (and N/S) Trending Structures: Structures sub-parallel to the Main Fissure, include a prominent fissure along the western edge of the CW Orebody. These features are associated with relatively high ground water inflows and extend for an unknown vertical distance. They also pinch and swell along strike and dip, similar to the Main Fissure. Many of these structures tend to be downslope of local drainage/catchment areas.

NE/SW Trending Structures: These are minor geological lineaments which run obliquely to the Main Fissure. These structures are associated with relatively less water make.

G Fault: The G Fault marks the contact between the ABL/Lisduff Oolite and younger Waulsortian Limestone, and is located to the south of the G Orebody. It is considered a prominent geological structure. There is inferred extensive cavity development. The East-West structure is associated with low ground water inflows. The structure dips at approximately 55 degrees to the north and has a ca. 200 m throw. The impermeable ABL forms the footwall of the fault. Mine workings are approximately 45 m below the surface expression of the fault. Workings within this area have been backfilled from both underground and surface.

R Fault: The R Southern Boundary Fault is an East-West structure to the south of the R Orebody. The feature is relatively less permeable than the structures trending NNW-SSE. This area has been backfilled extensively.

6.2.2 Mine workings

Where mine workings intersect geological structures increased water velocities can occur that are sufficient to erode sediment filled cavities within the fissure network in the palaeokarst subsurface topography. The void space created by the mine workings can then provide a means of removing the sediment, enabling the suffosion mechanism to take place (creating a means for removal of soil and growth of a void space within the soil-overburden).

6.2.3 Water

The area for the considered risk assessment totals the aerial extent of the dewatered area. Higher water volumes and velocities tend to occur along the NNW/SSE trending geological structures.

6.3 Land Usage

An overlay of the land usage, outlines of mine workings and relevant geological structures is shown in Figure 42 The following categories of land usage in the vicinity of the mine workings have been identified (Table 6).

Table 6: Consequence Rating

Rating	Consequence
5	Very High frequency of use, sensitive land uses
4	High frequency of Use
3	Moderate frequency of use
2	Low frequency of use
1	Low frequency access land use

These have been used as the basis of the following risk assessment.

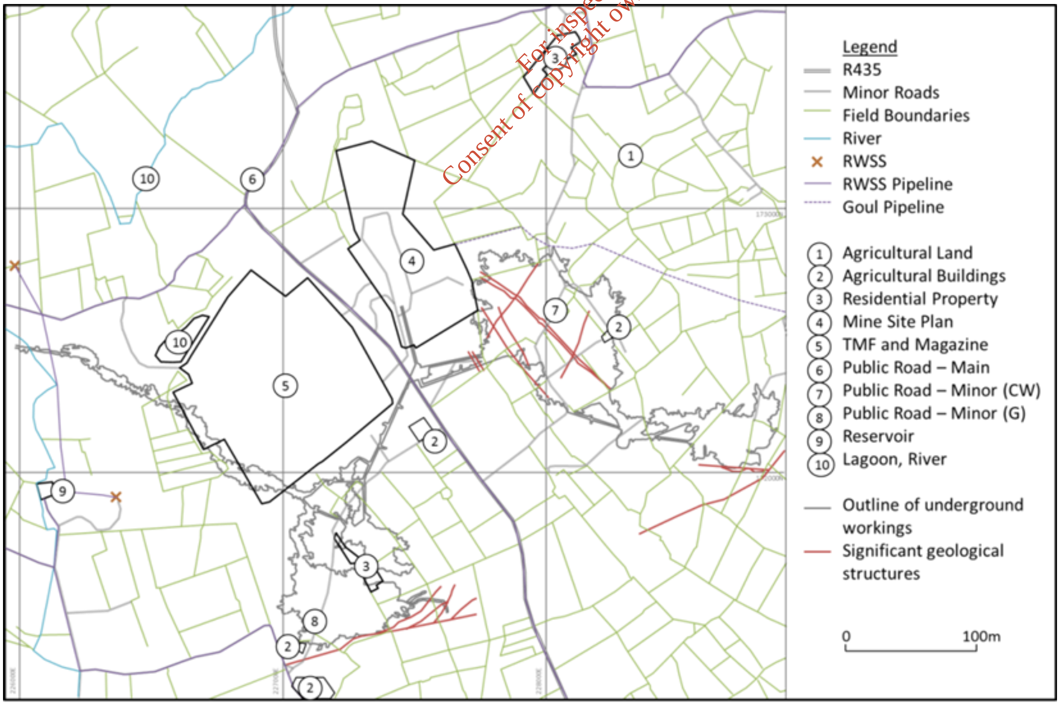


Figure 42: Land uses and underground structures (1-10 described in text)

6.4 Risk Assessment

This risk assessment focuses on land usage as listed above and how relevant hazards might impact upon how the land in this area is used. Numerical values for hazard likelihood and land usage consequence are assigned on the basis of a calibration scale that results in lands with no recognised hazards scoring a low value which results in a “Very Low” risk rating. The Risk Rating scale is given in Table 7 below.

Table 7: The Risk Rating Scale

Rating	Consequence
0 - 8	Very Low
9 - 16	Low
17 - 24	Medium
28 - 32	High
33 - 40	Very High

The risk assessment as applied to the area overlying the Galmoy mining operations is given in Table 8 below.

Table 8: The Risk Rating Scale

		Agricultural Land		Agricultural Buildings	Residential Land		Mine Infrastructure		Roads			Water Courses & Storage		
							Mine Site	TMF	Main	Minor CW	Minor G	RWSS	Pond/Lagoon	River
		1a	1b	2	3a	3b	4	5	6	7	8	9	10	10
Consequence Rating		1	1	3	5	5	3	5	5	3	3	3	3	3
Major Fissure	5	5	5	x	x	x	x	x	x	5	x	x	x	x
NW-SE Trending Structures	3	x	x	x	x	x	x	x	x	x	x	x	x	x
NE-SW Trending Structures	2	x	x	x	x	x	x	x	x	x	x	x	x	x
G Fault	3	x	x	x	x	x	x	x	x	x	x	x	x	x
R Fault	3	x	x	x	x	x	x	x	x	x	x	x	x	x
Open Mine Workings	3	x	3	x	x	x	x	x	x	x	x	x	x	x
Backfilled Mine Workings	2	x	x	2	2	2	2	2	x	x	2	x	x	x
Collapsed Mine Workings	1	x	x	x	x	x	x	x	x	1	x	x	x	x
Likelihood Rating		5	8	2	2	2	2	2	1	6	2	1	1	1
Total Risk Rating		5	8	6	10	10	6	10	5	18	6	3	3	3
Qualitative Rating		VERY LOW	LOW	VERY LOW	LOW	LOW	VERY LOW	LOW	VERY LOW	MEDIUM	VERY LOW	VERY LOW	VERY LOW	VERY LOW
Remedial Risk			LOW							LOW				

1a. Agricultural Land Away From Mine Workings: Very Low Risk:

Agricultural land use covers the majority of the dewatered area and at time of writing the entire area is now almost fully re-watered.

Outside the limits of mine workings there is no risk from void collapse of such workings. Land is located within the seasonal variation region of the dewatering cone.

1b. Agricultural Land above Mine Workings: Low Risk

Land is located overlying mine workings, Main Fissure, G Fault and minor structures. It is possible that if any cavities were present along the Main Fissure they are likely to have been closed due to the compressive loads induced as a result of the pillar collapse that occurred in January 2002.

It may be that anywhere along the surface expression of the Main Fissure a similar sequence of events may occur to cause a sinkhole to develop but this is a natural risk associated with the local palaeokarst subsurface topography where a thick layer of soil is present.

2. Agricultural buildings: Low Risk

Some of the agricultural buildings are over backfilled mine workings but away from significant geological structures.

3a. Residential Land away From Mine Workings: Low Risk

Outside the limits of mine workings there is no risk that voids may have formed in the superficial deposits due to collapse from void development. Property is located within the seasonal variation region of the dewatering cone but there are no faults or solution fissures. In addition, if any narrow fissures are present, the likelihood of soil being consistently washed down and removed is low due to the lack of any void in the bedrock.

3b. Residential Land above Mine Workings: Low Risk

Residential property exists directly above G Orebody workings. The underground workings beneath are of a relatively small span. There are no major faults or solution fissures and ground conditions are considered competent. No significant 'make' of water has been identified in open mine workings below residential property.

4. Mine Site - Mine Site: Very Low Risk

The mine site is not located above any workings. The portal decline is located on site and is now fully backfilled. There are no known faults or solution fissures beneath the mine site. The mine site is located on a watershed for the area. Removal of soil leading to the formation of a sinkhole would require a significant bedrock void. In combination these factors make it highly unlikely that any voids are present in the superficial deposits and there is no mine-related mechanism that could result in future void formation.

5. Mine Infrastructure - Tailings Management Facility (TMF) and Magazines: Low Risk

Palaeokarst features have been identified beneath the TMF. As a result of ground investigations (including geophysical surveys) the ground has been extensively treated. Tailings and water impoundments are lined and therefore do not allow recharge to ground. The TMF is in the process of being closed, and the saturation state of the facility is not anticipated to change post closure. The water-table is close to, if not fully recovered.

6. Public Roads - Main Road R435: Very Low Risk

The R435 traverses North-South across the mining area. The road does not intersect any of the main workings, only minor drives. There is a potential influence of the G Fault if this is inferred east of its known mapped location. However due to its tight nature it has a low ranking.

7. Public Roads - Minor road Above CW Orebody: Medium Risk

The collapse of workings in January 2002 caused subsidence beneath the road over the CW Orebody. The resulting compression is likely to have eliminated any open voids that may have been present. Following remediation of the public road no further repairs have been required. The probability of a sinkhole occurring along the road is likely to be no greater than pre-mining. A recently completed geophysical survey verified this. The mined out areas under the road are either backfilled or have pillars present.

8. Public Roads - Minor road Above G Orebody: Very Low Risk

The G Orebody has been extensively backfilled from both underground and surface. The backfilling procedure will remove the potential for any material to be removed beneath any narrow fissure (if, indeed any are present) and thus avoid the formation of any void within the soil-overburden and subsequent sinkhole formation.

9. RWSS - Water Replacement Scheme: Very Low Risk

The reservoir for the scheme is built into bedrock. The facility is constructed on a topographical high, the two supply wells are drilled on geophysical-resistivity lows. Ongoing pumping creates a lowering of the water-table, therefore increasing the risk of sinkhole development above background level. However, the velocities associated with the pumping of the wells are not considered to be sufficiently high to entrain sediment. If sediment were to be entrained then this would be apparent as turbid water.

10. Natural Features: Very Low Risk

There is a lagoon and a river/stream in the area under consideration but these do not overlie mine workings or the Main Fissure itself.

6.5 Residual Risk

Subsequent to the risk assessment the area above the Main Fissure along the road and the field containing the sinkhole have since been were assessed using geophysical methods. The results of the geophysics show no evidence of cavities forming in the overburden, increasing the confidence that a sinkhole will not occur. As a result of this the risk levels have been downgraded.

6.6 Summary

The Risk Assessment results (Table 9) show a Low to Very Low Risk (shaded in green in Table 9). This is a result of the very limited interaction between the three most likely hazards identified (geological features, water and mine workings) at any given location in the vicinity of the mine.

Due to the nature of the underlying bedrock (i.e. limestone with palaeokarst) it is accepted that there remains a background risk (Very Low to Low Risk) of future sinkhole development in the vicinity pf the mine, as there does elsewhere in the Irish Midlands where limestones (and karst) occur.

Table 9: Summary of Risk Assessment Results

Summary	Land Usage	Geological Structures	Mine Workings	Risk Rating	Control	Residual Risk
1a	Agricultural Land	Main Fissure		VERY LOW		
1b	Agricultural Land	Main Fissure	Open Workings	LOW	Geophysics over Main Fissure	VERY LOW
2	Agricultural Buildings		Backfilled Mine Workings	LOW		
3a	Residential Land not above workings			VERY LOW		
3b	Residential Land above workings		Backfilled Mine Workings	LOW		
4	Mine Site		Backfilled Mine Workings	VERY LOW		
5	TMF		Backfilled Mine Workings	LOW		
6	Main Road			VERY LOW		
7	Minor Road (CW Orebody)	Major Fissure	Collapsed Mine workings	MEDIUM	Geophysics over Main Fissure	LOW
8	Minor Road (G Orebody)			VERY LOW		
9	RWSS			VERY LOW		
10	Natural Features			VERY LOW		

6.7 Conclusions

The risk assessment approach considered all land uses at risk from surface subsidence. There are two feasible mechanisms of surface subsidence these being;

- Sinkholes; and
- Mine Pillar Collapse.

The relevant impact of each of these is discussed in the following two sections.

Sinkhole

- It is highly unlikely that a repeat sinkhole event will occur, similar to that of February 2014;
- The water-table is at, if not near, pre-mining levels, reducing the risk of further changing hydrogeological conditions. Consequently any palaeokarst feature should not be exposed to further water velocities sufficient to entrain sediments in the future. Therefore, the risk of further erosion of sediments in any palaeokarst features is considered to be significantly reduced;
- There was a localised, above background risk of sinkhole formation in isolated areas immediately adjacent to the Main Fissure due to the fact that there is a bedrock surface depression associated with this feature into which surface water can flow. However, findings from geophysical investigations and the fact that groundwater levels have rebounded to near pre-mining levels indicate that this risk is a low;
- Local dewatering activities may pose an increased risk to sinkhole development;
- There is a continued low background risk of sinkhole development in the area due to the natural palaeokarst environment; and
- Control measures above the Main Fissure have not identified any cavities in the overburden increasing the confidence. The risk level has been reduced as a result.

Pillar Collapse

- None of the work carried out in the assessment supersedes the work carried out in relation to risk of a different mechanism of failure such as pillar collapse;
- Implementation of the Underground Failure Prevention Plan (UFPP) following the pillar collapse has ensured the risk of surface subsidence from a collapse of mine workings is low;
- In line with the UFPP, Golder carried out yearly annual audits. The purpose of the audits was to evaluate the conditions of underground stability, the impact of underground mining on surface stability, surface monitoring and the performance of the backfill system. It was found that mitigation measures have been put in place to prevent a repeat collapse event during mining (stope stability assessments, enhanced ground support system, comprehensive ground control records, improved backfill delivery, specific pillar performance assessments and effective subsidence monitoring) and since closure (backfill and monitoring), it is possible to state that if the UFPP has been followed the "potential for repetition is **extremely low**" (Golder 2002).

7.0 SINKHOLE REMEDIATION

Golder conducted a site visit to Galmoy on 5 March, 2014 to inspect the Main Fissure sinkhole and meet with Galmoy staff and the intended civil works contractor for the repair (Eamon Darmody of TMB Plant Hire Ltd. (TMB)). TMB are currently working for Galmoy on the TMF Cell 3 modification works and on the remediation of the Mine Plant site.

7.1 Sinkhole Description

The sinkhole appeared in a field east of the Mine Site over the CW Orebody where there are disused mine workings, following a prolonged period of excessive, and frequently intense, rainfall during the months of December 2013 and January/February 2014.

The following information on the sinkhole was provided by Galmoy and observed during the site visit on 5 March 2014:

- **Ground Level:** ca. 139 m AOD;
- **Overburden:** Glacial Till (Silty Clay with cobbles) – ca. 6 m to 9 m deep;
- **Bedrock:** ca. 132.5 m AOD;
- **Current Water-Table:** estimated at 123 m AOD (15 m to 16 m below OGL);
- **Nearest Drive of Mine Workings:** ca. 57 m AODL (ca. 82 m below OGL);
- **Location:** The sinkhole is ellipse-shaped, positioned parallel to the Main Fissure Zone along the major axis. It is located on a sloping part of the field with an estimated elevation difference of 1 m across its minor axis;
- **Dimensions:** It is estimated to be ca. 13 m in the major axis and 8 m in the minor axis and to be ca. 7 m in depth; and
- **Current Status:** As inspected on 5 March, 2014 at 1pm; the sinkhole appeared to be as originally discovered. There was no evidence of further collapse of the sides of the hole or cracking appearing on the surface back from the edge of the hole.

7.2 Remedy Technique

A simple bridging mechanism, over the throats between the limestone pinnacles, is proposed for the remedy of the sinkhole; the lower section comprises a permeable rip rap and ballast plug encapsulated in a geotextile. The upper section of repair entails compacted layers of rock fill / glacial till and a final capping layer of appropriate subsoil and topsoil to rehabilitate the agricultural surface.

A permeable plug is recommended to conserve the drainage pathway and to help alleviate the formation of further sinkholes in the vicinity. The repair of the sinkhole is recommended to commence without excessive delay to alleviate the risk of collapse of the sides of the sinkhole.

7.3 Earthwork Material Specifications

Soil materials required for the works shall be supplied in accordance with the Standards and Procedures set out in BS 1377:1990 British Standard Methods of Test for Soils for Civil Engineering Purposes.

Materials supplied shall meet the requirements of this Specification and shall demonstrate compliance to the satisfaction of the CQA Inspector. The Contractor shall be responsible for off-loading from delivery trucks, storing and protecting the materials until they are incorporated into the Works. If the materials are damaged while under the Contractors care, the Contractor shall replace the materials to the same specification.

7.3.1 Earthwork definitions

The following definitions shall apply to this Specification:

a) "Topsoil" shall mean the top layer of soil that can support vegetation;

b) "Suitable Materials" shall comprise all that which is acceptable in accordance with the Contract for use in the Works, and deemed by the Engineer to be suitable.

Suitable foundation sub grade material shall be undisturbed compact material which in the opinion of the Engineer has the bearing capacity and permeability required.

Suitable fill material shall be free from deleterious material and shall be capable of being compacted as specified to form a stable mass having side slopes as indicated on the Drawings and having the characteristics specified for the different fill materials;

c) "Non-suitable material" shall mean other than suitable material and shall include:

1) Material from swamps, marshes or bogs;

2) Peat, logs, stumps and perishable material;

3) Material susceptible to spontaneous combustion;

4) Material in a frozen condition;

5) Clay of liquid limit exceeding 80% and/or plasticity index exceeding 55%;

6) Materials having moisture content greater than the maximum or less than the minimum permitted for such materials in the Contract unless otherwise permitted by the Engineer;

7) Such clinkers, cinders ashes, fly ashes and domestic ashes which by virtue of their physical or chemical composition or their moisture content will not compact to form a stable fill; and

8) Cobbles and boulders with minimum dimension greater than 75 mm.

Materials of Class (4) if otherwise suitable shall be classified as suitable when unfrozen. Materials of Class (6) if otherwise suitable shall be classified as suitable when wetted or dried out sufficiently as appropriate; and

d) "Rock" shall mean those geological strata indicated in the Contract to be regarded as such, and other masses of hard material which cannot be removed from an excavation up to 5 m deep with a Caterpillar 245, or equivalent excavator, in good working order.

7.3.2 Contaminated non-suitable material disposal

Any contaminated non-suitable materials encountered in carrying out the Works shall be removed and disposed of at a designated area to be indicated by Galmoy.

7.3.3 Material storage

Galmoy intend to supply all materials for the works. The concrete yard owned by Galmoy located east of the field with the sinkhole (as indicated on Drawings 1 and 2) has been designated as the storage area for the delivery and tipping of materials. The contractor shall load materials from this yard and haul to the work area using 20 Tonne Dumpers, accessing the field through either Gated Entrance 1 or 2 (as indicated on Drawings 1 and 2).

7.3.4 Properties of earthwork materials

7.3.4.1 General

The Sinkhole Remediation will require the use of five material types:

- **Type B (Rip Rap)**, Processed Rock fill – Base layer of Permeable Plug;

- **Type D (Ballast)**, Processed Rock fill – Capping layer over Type B;
- **Type E (2” Down),** Processed Rock fill – compacted in a single layer over geotextile encapsulated plug;
- Glacial Till, Silty Clay with cobbles – compacted in layers over Type E; to be sourced from Galmoy stockpiles and/or excavated material;
- **Subsoil**, riddled to less than < 75 mm – landscaping of rehabilitated area; to be sourced from Galmoy stockpiles at Cell 3 of the TMF; and
- **Topsoil**, riddled to less than < 75 mm – landscaping of rehabilitated area; to be sourced from Galmoy stockpiles at Cell 3 of the TMF.

The specification details for the five different types of fill materials are outlined below.

7.3.4.2 Type B - boulder rock fill

Crushed and processed rock fill used for the construction of the permeable plug shall consist of hard, durable well graded rock with a minimum particle size of 300 mm and a maximum particle size of 500 mm, well-graded and free of deleterious materials.

7.3.4.3 Type D - ballast rock fill

Crushed and processed rock fill uses for the capping layer of the permeable plug shall consist of hard, durable well graded rock well-graded and free of deleterious materials.

Type D material shall be deemed suitable if complying with the following:

- Maximum particle size of 100 mm; and
- Minimum particle size of 75 mm.

7.3.4.4 Type E - rock fill

Type E material shall consist of well-graded crushed rock that is hard, durable, free from deleterious materials, and conforming to the following particle size distribution limits.

Table 10: Type E Particle Size Distribution Limits

Sieve Size (mm)	% Passing
63	100
31.5	80 – 90
16	55 – 85
8	35 – 65
4	22 – 50
2	15 – 40
1	10 – 35
0.500	0 – 20
0.063	0 – 7

2” Down may be deemed acceptable on the production of a typical grading analysis from the source quarry for the material.

7.3.4.5 Glacial till

The Silty Clay with cobbles removed during the excavation works may be re-used in the formation of the plug. Additional glacial till may be sourced from the downstream slopes and the dam walls of Cell 3 of the TMF or from Galmoy stockpiles and/or excavated material elsewhere on the mine site.

7.3.4.6 Subsoil

The subsoil material removed from the downstream slopes and the dam walls of Cell 3 of the TMF shall be suitable for the works if screened to < 75 mm.

7.3.4.7 Topsoil

The topsoil material removed from the downstream slopes of dam walls of Cell 3 of the TMF shall be suitable for the works if screened to < 75 mm.

7.4 Geotextile

A non-woven geotextile shall be placed:

- Above the stripped subsoil at the access point to the field; and
- To line the base and sides of the sinkhole following cleanout by the excavator and fold over the permeable plug to encapsulate it.

Geotextile shall comprise Terram T2000 / Bontec NW15 or equivalent. Acceptance criteria for the physical and mechanical properties of the geotextile are given below.

Table 11: Geotextile – Physical and Mechanical Property Acceptance Criteria

Parameter	Test Method	Specification
CBR Puncture Resistance	ISO 12236	Min 2400 N
Wide Width Tensile Strength	ISO 10319	Min 14 kN/m
Dynamic Cone Puncture	ISO 13433	Min 19 mm
Elongation at break	ISO 10319	Min 25%
Thickness	EN 964-1	Min 1 mm
Mass per unit area	EN 965	Min 200 g/m2

Geotextiles shall comprise polymeric yarns or fibres, seamed or drawn strands oriented into a stable network which retains its structure during handling, placement, and long-term service. Geotextiles shall be nonwoven, needle punched and resin or heat bonded.

Material data sheets from the supplier shall be provided by the supplier to demonstrate compliance with the above requirements.

7.4.1 Geotextile deployment

The Contractor shall handle all geotextiles in such a manner as to ensure they are not damaged in anyway, and the following shall be compiled with:

- Geotextiles shall be cut by a geotextile cutter (hook blade) only. A cutter shall only be used by personnel with appropriate training and using cut-proof gloves In place, special care shall be taken to protect other materials from damage which could be caused by the cutting of the geotextiles;
- During placement of geotextiles, care shall be taken not to entrap, in or beneath the geotextile, stones, excessive dust, or moisture that could cause clogging, or hamper subsequent seaming; and
- A visual examination of the geotextile shall be carried out over the entire surface, after installation, to ensure that no potentially harmful foreign objects are present.

7.4.2 Seaming / overlapping procedures for the geotextile

The geotextile shall be overlapped a minimum of 1 m. No seaming is required.

7.4.3 Defects and repairs

Any holes or tears in the geotextile shall be repaired as follows:

On slopes, a patch made from the same geotextile shall be sewn into place in accordance with the project specifications. Should any tear exceed 10% of the width of the roll, that roll shall be removed from the slope and replaced.

Care shall be taken to remove any soil or other material which may have penetrated the torn geotextile.

7.4.4 Geotextile protection

Material placed on top of a geotextile shall be deployed in such a manner as to ensure:

- The geotextile material is not damaged;
- Minimal slippage of the geotextile on underlying layers occurs; and
- No excess tensile stresses occur in the geotextile.

7.4.5 Temporary surcharge

The Contractor shall be responsible for the geotextile at all times during the Contract and shall adopt whatever measures are necessary to ensure its stability and protect it from damage. These measures shall include the use of sufficient temporary surcharge in the form of sandbags, tyres or similar weights placed on the geotextile immediately after laying and before seaming to prevent slipping and damage by wind or other agents prior to covering. Any problems arising from the Contractor's failure to secure the geotextile during the Contract shall be remedied at the Contractor's expense.

7.5 Materials Quantities

Table 12 below provides details on the estimated quantities of earthworks materials used in the project.

Table 12: Material Quantities for the Sinkhole Remediation

Material	Estimated Quantity (m^3)
Type B	260
Type D	35
Type E (sinkhole)	70
Type E (access to field)	30
Glacial Till	240
Subsoil	200
Topsoil	100
	Estimated Quantity (m^2)
Non-Woven Geotextile (sinkhole)	450
Non-Woven Geotextile (access to field)	100

7.6 Method Statement for Sinkhole Remediation

Golder shall provide a suitably qualified on-site CQA Engineer for the duration of the works and shall compile a CQA Report following the completion of the remediation works.

7.6.1 Plant

Following the preliminary discussion with Galmoy and the intended contractor, the listed plant is recommended for the works:

- 1 x 22 Tonne Long-Reach Tracked Excavator;
- 1 x 20 Tonne Tracked Excavator;

- 1 x Trench-Whacker Extension for the 20 Tonne Excavator; and
- 2 x 20 Tonne Dumper Trucks.

7.6.2 Preliminaries

The following items are required to take place prior to the start of the works:

- Haulage of specified quantities of materials to the designated storage area;
- Strip and prepare the access areas to the field at the Gated Entrances. Topsoil shall be stripped back and stockpiled, a layer of Terram T2000 / Bontec NW15 geotextile placed above the subsoil and the area dressed with a minimum 300 mm layer of Type E rock fill for an area measuring not less than 10 m x 10 m;
- Erect warning signs at 100 m and 50 m intervals on the road from the gated entrances indicating construction works and plant crossings ahead; and
- Materials shall be hauled to the working area as required during the works and stored downslope of the sinkhole and the main fissure.

7.6.3 Construction

The **Construction Steps** listed below are detailed graphically in Drawings 1 to 5 of Appendix C.

- **Step 1:** Approach the sinkhole with the long-reach excavator on the downhill side of slope and perpendicular to the Main Fissure. The security harris fencing shall be reinstated following the entry of the excavator to prevent access to the works;
- **Step 2:** Excavate upslope to create a working platform at an approximately 3 m depth from the base of the sinkhole;
- **Step 3:** Position the excavator on the working platform, back from the estimated edge of the main fissure, and clean out the material from the base and sides of the sinkhole. The base of the sinkhole shall be visually inspected from a safe distance following clean-out to determine the extent of fractured bedrock and the location of 'throats'. Following inspection, the sides and base of the sinkhole shall be shaped as direct by the Engineer. No access of personnel is permitted into the sinkhole;
- **Step 4:** Excavate a 2 m wide bench at the working platform elevation around the perimeter of the sinkhole. Additional benching may be necessitated as directed by the Engineer on the upslope side of the sinkhole to allow for safe installation of the geotextile. The excavator may have to be re-positioned on the upslope side of the sinkhole to complete the benching for the permeable plug. The positioning of the excavator directly over the Main Fissure on the sides of the sinkhole will be assessed following reference to the geophysical investigation conducted by Golder;
- **Step 5:** Install non-woven geotextile from the excavated benches allowing sufficient length of material to encapsulate the rock fill permeable plug and allowing for a minimum 1 m overlap between adjacent rolls of geotextile. No access of personnel is permitted into the sinkhole;
- **Step 6:** Place and gently compact the Type B rock fill into the sinkhole over the installed geotextile using bucket of the long-reach excavator. Continuing placing the Type B material to a minimum of 0.8 m depth above the 2 m wide bench;
- **Step 7:** Place and compact the Type D (Ballast Rock fill) to a minimum 0.3 m depth above the Type B rock fill. Fold over the geotextile to wrap and encapsulate the permeable rock fill plug;
- **Step 8:** Place and compact a single layer, 0.3 m in depth, of the Type E rock fill encasing the geotextile encapsulated plug;

- **Step 9:** Place and compact glacial till in layers not greater than 0.3m above the Type E rock fill to within 0.8 m of the final surface elevation. Place and compact two 0.3 m deep layers of subsoil above the glacial till and finally loosely place and grade a 0.3 m deep layer of topsoil. The material shall be mounded to approximately 100 mm above the surround area to allow for settlement; and

- **Step 10:** De-compact and rehabilitate routes to the working areas and access points to the field with subsoil / topsoil as required and re-seed areas.

7.7 Risk Assessment

7.7.1 Estimated timescale

Estimated timescale of Work on the Construction Site: 1 week.

Note: The proposed duration of works advised above are provisional, pending confirmation by the Project Supervisor (Construction Stage) that they are practicable.

This timescale is estimated based on the Designers experience and by comparison with the timescale of jobs of similar complexity and size.

7.7.2 Particular risks to safety and health

The “Particular Risks” identified for these works are listed below. The minimum controls required demand a Safe System of Work.

- **“Work which puts persons at work at risk of falling from a height where the risk is particularly aggravated by the nature of the work or processes used by the environment at the place of work on site.**

  There is a risk of falling from height when:

  - Accessing the working area in the vicinity of the sinkhole;
  - Inspecting the clean-out of the sinkhole; and
  - Installing the geotextile in the base of the sinkhole.

- **“Overturning of Construction Vehicles”.**

  There is a risk of overturning of construction plant:

  - The field has a significant slope from the gated entrance points to the working area; and
  - Plant will be operating on the edge of the sinkhole.

- **“Work which puts persons at risk in an excavation”.**

  There is a risk of engulfment by the sinkhole when:

  - Installing the geotextile.

The above list of particular risks is non-exhaustive and other risks may present during construction that could not be reasonably foreseen by the PSDP.

7.7.3 Recommended / specific measures for reducing particular risks

- Experienced personnel and adequate supervision shall be provided by the Contractor;
- Site inductions and training shall be undertaking by all Contractors staff; and
- Suitable working practices are adopted by the Contractor together with any contingency plans to deal with potential incidents.

7.8 Compliance with General Safety Requirements

The Contractor shall comply with all relevant Statutory requirements such as The Safety, Health and Welfare at Work Act 2005, The Safety, Health and Welfare at Work (Construction) Regulations 2006 (SI 504 of 2006) and The Safety, Health and Welfare at Work (General Application) Regulations 2007 (S.I. No. 299 of 2007).

In addition, the Contractor shall comply with all the reasonable safety requirements of the Client, the Project Supervisor for the Design Stage and the Project Supervisor for the Construction Stage.

The health, safety and security of our employees is of primary importance to Golder. Prior to any site visit, a detailed Health and Safety and Environmental Plan (HASEP) is carried out. This includes detailing travel and emergency arrangements, an assessment of any potential HSE risks that may be encountered and what mitigating measures must be taken to reduce the risk to an acceptable level. Golder employees are not permitted to enter any unsafe areas. The Golder Health and Safety Protocol for Site Work forms part of our terms and conditions.

We will ensure that field personnel are equipped with both basic and task specific personal protective equipment (PPE) required for completing the project work on site. All field personnel will attend and actively participate in regularly scheduled safety meetings during any fieldwork activities and will be alerted to and become familiar with the emergency procedures in effect for various areas of the site prior to the commencement of any work on the project site. Furthermore, all vehicles driven by field personnel on site will carry the required safety equipment. Our commitment as a team is to ensure that we do all in our power to attain a goal of “Zero incidents, zero injuries, zero fatalities, and zero job-related illnesses” and by thinking safety in all that we do.

Although we apply the principles of our own EHS policies we also implement our Clients’ policies, procedures, instructions and standards.

Final Comment: The information contained in the preliminary sections of this document has been prepared prior to the commencement of work on site. It does not take account of any matters or information which may come to light after that time.

8.0 CONCLUSIONS

Typically dropout dolines form early-on during dewatering. At Galmoy this did not happen, because the existing palaeokarst system was ‘choked’ and there was nowhere for sediment to move.

Dewatering and subsequent mining into the Main Fissure (and associated palaeokarst features) at the orebody horizon provided a pathway for sediment to move downwards through the system throughout the life of mine. The bedrock depression associated with the Main Fissure provided a drainage point in to the structure for water ingress.

Dropout sinkholes are common in Ireland (Hickey, 2013) occurring both naturally and as a consequence of human activity. Most occur on farmland and are infilled soon after they form. Aerial photographs and geophysics provide evidence for the occurrence of sinkholes/dropout dolines existing in the landscape around Galmoy pre-mining. The presence of palaeokarst and a thick cover of cohesive superficial material means that there is a natural potential for dropout sinkhole formation indicating that there is a natural background for the potential development of sinkhole/dropout doline in Galmoy area.

It is considered that the sinkhole formed due to a combination of the following factors:

- The presence of a palaeokarstic void system, the Main Fissure, which had been totally filled with sediment;
- Lowering of the local water-table by dewatering and intersection of the Main Fissure in the mine which together allowed the ancient flow-path down the fissure to be re-activated. Groundwater flowed down the fissure towards the mine, taking with it some of the fissure sediment fill and opening void space within the fissure. The process was enhanced by concentration of drainage at the location of the Main Fissure due to a depression in the rockhead (the solid rock surface under the overburden) along the Main Fissure and an up gradient catchment associated with the Main Fissure;
- The development of open voids within the glacial till due to washout of material through fractures (i.e. palaeokarst features) in the bedrock above the Main Fissure; and
- Recent exceptional rainfall and infiltration, coupled with a spread of soiled water on the field shortly before the sinkhole appeared (ca. within 24hrs) increased the weight of the overburden and acted as the trigger for collapse into the void which formed the sinkhole.

As part of the current study, it has been demonstrated that the Main Fissure which is located beneath the sinkhole, has developed enhanced weathering of the bedrock. Historically this led to an increase in karst formation locally and created a subsurface geomorphology which concentrated flow towards and through the Main Fissure in the vicinity of the sinkhole prior to the system being choked. The Main Fissure is a unique feature within the Galmoy deposit and so comparable conditions are unlikely to occur elsewhere in the vicinity of the mine. This provides a unique set of circumstances that coincide at this particular location and which are not (to our knowledge) repeated elsewhere in the vicinity of the mine at Galmoy.

The water-table has now recovered to a level close to that which pertained pre-mining and there is no deep groundwater circulation associated with the mine workings. Groundwater flow velocities will have returned to those in pre-mining times with slow water movement at relatively shallow depth (top 10 - 12 m of bedrock) through fissures and channels that were present pre-mining. Hence, there is no potential for the development of new voids by transfer of sediment from the base of the superficial deposits. The mine no longer has any influence on groundwater flow and the water-table but if other human activities in the area were to cause a future fall in the water-table or to increase groundwater flow velocities this would increase the risk of sinkhole formation.

A geophysical survey has not found evidence of any large voids in the superficial deposits that could have started to develop during active dewatering but had not reached the instability threshold. Hence, it is considered highly unlikely that there will be any future dropout sinkholes in the Galmoy area that are a consequence of mine related activities.

It is considered that the potential of future sinkhole development at Galmoy will remain at historical background levels, provided the water-table remains close to its pre-mining level that will prevent flow rates developing that can entrain sediments.

9.0 REFERENCES

Bottrell S H, Gunn J & Lowe D J, (2000). Calcite dissolution by sulphuric acid. In Klimchouk A et al. (Editors) Speleogenesis : Evolution of karst aquifers. National Speleological Society. Pp 156-157.

Ford, D. and Williams, P., (1989). Karst Geomorphology and Hydrology. Unwin.

Golder Associates Inc. (1992) Assessment of Palaeokarstic Features on the Development of the Galmoy Project, Ireland. REF. IC3-2054.

Golder Associates UK. (2002) Report on Investigation into the Causes of Surface Subsidence at Galmoy Mine, CW Orebody REF. 021-9302.

Hickey, C. 2013. Sinkholes in Ireland. http://www.gsi.ie/newsletters/sinkholes+in+ireland.htm

Littlefield, J.R., Culbreth, M.A., Upchurch, S.B., Stewart, M.T., (1984). Relationship of Modern Sinkhole Development to Large-Scale Photolinear Features. *In:* Sinkholes Their Geology, Engineering, and Environmental Impact; Proceedings of the First Multidisciplinary Conference on Sinkholes, Barry F. Beck ed. p. 189-196.

Lowther, J.M; Balding, A.B; McEvoy, F.M., Dunphy, S., MacEoin, P., Bowden, A.A., and McDermott. The Galmoy Zn – Pb orebodies: structures and metal distribution – clues to the genesis of the deposits. *In:* Europe’s Major Base Metal Deposits, Kelly, J.G., Andrews, C.J., Ashton, J.H., Boland, M.B., Earls, G., Fusciardai, L and Stanley, G. Irish Association for Economic Geology (2000).

Waltham, T., Bell, F. and Culshaw, M., (2010). Sinkholes and Subsidence: Karst and Cavernous Rocks in Engineering and Construction. Springer.

Waltham T, (2008). Sinkhole hazard case histories in karst terrains. Quarterly Journal of Engineering Geology and Hydrogeology, 41, 291-300.

Waltham T, Bell F & Culshaw M., (2005). Sinkholes and Subsidence. Springer.

Report Signature Page

GOLDER ASSOCIATES IRELAND LIMITED

Barry Balding
Senior Geologist

Gareth Digges La Touche
Senior Scientist

Author: Barry Balding/GLDT/aw

Registered in Ireland Registration No. 297875
Town Centre House, Dublin Road, Naas, Co. Kildare, Ireland
Directors: M. Gilligan, A. Harris (British)
VAT No.: 8297875W

APPENDIX A

Schlumberger Water Services: Analysis of Groundwater Conditions Relating to the Recent Sinkhole Occurrence

GALMOY MINE

ANALYSIS OF GROUNDWATER CONDITIONS RELATING TO THE RECENT SINKHOLE OCCURRENCE

May 2014

51471/R2

Prepared for:

Galmoy Mines Ltd
Galmoy
Via Thurles
Co Kilkenny
Ireland

Prepared by:

Schlumberger Water Services
The Pump House
Coton Hill
Shrewsbury
SY1 2DP

REPORT REVIEW SHEET

GALMOY MINE **ANALYSIS OF GROUNDWATER CONDITIONS RELATING TO THE RECENT SINKHOLE OCCURRENCE**	
Report no:	51471/R2
Client name:	Galmoy Mines Ltd
Client contact:	John Stapleton
SWS Project Manager:	Geoff Beale
SWS Technical Reviewer:	Geoff Beale
Main Author:	Simon Sholl

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EXECUTIVE SUMMARY

Background

Underground mining at Galmoy began in 1996 and continued to early 2013. Most mining occurred between 80 and 150 m depth. The pre-mining groundwater table in the area of the sinkhole was between 7 and 10 mbgl (below ground level). In order to allow mining to proceed in a safe and efficient manner, it was necessary to dewater the mine at a pumping rate of between 10 and 15 MLD, with the pumping rate fluctuating mostly in response to changes in the rainfall pattern.

Re-watering of the mine workings began in March 2010. The final phase began in February 2013 when the last dewatering pumps were switched off. Groundwater rebound was rapid and the water table had fully recovered to above pre-mining conditions by March 2014.

Geology

The Galmoy mining district occurs within a tightly-bounded block of Waulsortian dolomite about 8 to 10 km² in extent. Drawdown due to pumping was limited to a well-defined area and was mostly localised within this "Galmoy Block". The upper 10 to 30 m of Waulsortian is variably weathered and contains abundant palaeokarst features. Natural sinkholes and other palaeokarst features are evident both locally around the mine and regionally within the Waulsortian. The palaeokarst was formed by the dissolution of the carbonate rock during the Tertiary period.

Quaternary-age unconsolidated overburden (mostly glacial till) overlies the weathered bedrock and palaeokarst across most of the Galmoy area. The till has a variable depth; between less than 2 m and up to 15 m, depending on the underlying bedrock surface.

Mining of the CW zone encountered a prominent sub-vertical linear geological structure termed the "Main Fissure". The Main Fissure is aligned with a NNW-SSE trend and was mapped underground over a distance of around 760 m. It was the largest geological structure of its kind encountered at Galmoy. Available drill holes logs and recent ground penetrating radar (GPR) surveys show there is a tendency for an increased weathering and oxidation along the alignment of the Main Fissure.

Exploration borehole logs for the CW zone show a greater frequency of shallow sediment-filled cavities within the upper weathered zone of the Waulsortian to a depth of about 30 mbgl, and also the presence of deeper filled cavities at the level of the ore horizon (around 80 mbgl). There are few cavities between these two zones and the available data suggest that there is limited hydraulic connectivity between the shallow palaeokarst and the deeper cavities at the ore horizon, except through diffuse and tortuous jointing.

The only other major geological structure encountered during mining was the G zone fault, which trends ENE-WSW. However, the G zone fault has a shallower dip than the Main Fissure and has the low permeability (ABL) rocks on its footwall, so less oxidation and fewer cavities were encountered.

Development of the sinkhole

Sinkholes are natural enclosed depressions that have a wide range of sizes and depths. In Ireland, they are the most common landform in karst areas. A sinkhole appeared in a field above the CW mining zone during the night of 14/15th February 2014. The centre of the sinkhole occurred immediately above the Main Fissure and was elliptical in plan, with the long axis in alignment with the fissure. The sinkhole was 13 m (long axis), by 8 m (short axis) and 7 m deep; with an approximate void volume of 550 m^3. The sinkhole had vertical sides within cohesive glacial till. There was no bedrock exposed in the walls or base. There was no cracking or other surface disturbance noted in the surrounding area. The dimensions of the sinkhole did not change after its initial development.

The sinkhole showed the characteristic features of a “dropout doline” feature. These occur when (i) a pathway exists in the upper part of the weathered karstified bedrock that allows water to flow with sufficient velocity to carry sediment, (ii) sediment from the overburden is internally eroded and transported through the pathway to allow a void to form above the bedrock surface in the overburden, and (iii) the upper part of the overburden suddenly collapses into the void.

Above the location of the sinkhole, the topographic slope of the field allowed shallow subsurface flow to move downslope above the bedrock surface and become concentrated in a natural bedrock depression that occurred above the Main Fissure. For the last 10,000 years or so, this would likely have led to increased infiltration and development of cavities in the shallow weathered bedrock below that location. Since dewatering began, it would have likely have caused recharging water to have turbulent flow within joints and cavities above the water table, leading to an increased potential for internal erosion and downward transportation of sediment at that location, and the development of open void space at the base of the overburden due to washout of material into the underlying cavities.

At the location of the sinkhole, the pre-mining groundwater level was about 10 m below surface, so some internal erosion, transportation of sediment and development of void space above the water table would likely have occurred prior to mining. However, the lowering of the water table as a result of mine dewatering probably accelerated the process. The drill holes logs show generally tight rock below the upper weathered palaeokarst zone. Therefore, it is reasonable to assume that most transport of sediment and creation of void space to form the sinkhole occurred mostly within the shallow upper weathered zone.

The winter of 2013-2014 was exceptionally wet, with significant rainfall occurring in the weeks and days prior to the development of the sinkhole. The wet weather would likely have caused increased infiltration and transportation of sediment from the overburden, potentially enlarging the void in the overburden. In addition, the increased saturation would have provided additional weight which was probably the trigger for the sinkhole.

Thus, the contributing factors at the location of the sinkhole can be summarised as follows.

1. The presence of the Main Fissure which is a line of natural geological weakness with increased potential for infiltration, weathering, and karst formation.

2. The natural depression of the bedrock surface above the Main Fissure at that location, causing water to collect and leading to a concentration of infiltration.

3. The groundwater table that was 10 m below surface prior to mining, meaning that the concentrated infiltration would have likely been causing

internal erosion and transportation of sediment from the overburden over a long period of time.

4. The artificially reduced groundwater table as a result of mine dewatering, which would have led to (i) consolidation of material filling existing cavities in the palaeokarst zone thereby creating additional bedrock void space (ii) increased velocities of the infiltrating water in the palaeokarst zone causing re-mobilization and transport of the infilling material in the cavities, and also creating additional bedrock void space, and (iii) an accelerated rate of internal erosion and sediment transport from the overburden into the underlying bedrock, leading to an increased rate at which void space developed at the base of the overburden.

The void space at the base of the overburden eventually became large enough to cause the overlying material to collapse into it. The overlying material was abnormally heavy because of the saturation caused by the wet weather, thus triggering the collapse.

Potential for future void development

There is potential for natural sinkhole development over large areas of the Irish Midlands where palaeokarst features have been mapped by the GSI. There are many examples of dropout dolines in Ireland and historic collapses are evident in the landscape around Galmoy Mine today. Thus, under specific conditions, there is a natural background potential for sinkhole development in the Galmoy area. The exact locations where sinkholes may develop are determined by a combination of factors, such as those described above. However, the background potential of sinkhole development is extremely low because the karst system is naturally choked with sediment and the water table is near surface.

As part of the current study, it has been demonstrated that the Main Fissure beneath the sinkhole had locally enhanced weathering of the bedrock. This increased the karst formation locally and created a subsurface geomorphology which concentrated flow towards those features. The Main Fissure was a unique feature, so comparable conditions are unlikely to occur elsewhere in the vicinity of the mine. Therefore, provided the water table remains close to its pre-mining state (about 10 m below surface), it is considered that the potential of future sinkhole development will remain at background.

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1 INTRODUCTION

1.1 Background

Galmoy Mine is a recently-closed lead and zinc mine located in Co. Kilkenny approximately 6 km south of Rathdowney. Dewatering of the underground mine began in 1996 and ceased in 2013. The main ore bodies (“zones”) covered a geographical area of around 0.5 km².

Reflooding of the mine workings began in March 2010 when plugs were installed and dewatering pumps switched off in the K zone. R zone pumps were switched off in late-2012, followed by G zone in February 2013, and finally CW zone in March 2013. A monthly groundwater level and quality programme has remained in place for the duration of the mine closure process to monitor the reflooding process.

Baseline hydrogeological studies at Galmoy were undertaken by KT Cullen in 1989 and 1992. In 2011, Schlumberger Water Services (SWS) were retained by Galmoy to assess the impacts of rewatering the mine workings in consultation with the EPA and Kilkenny County Council.

1.2 Report objectives

Overnight between the 14th and 15th February 2014, a sinkhole (dropout doline) appeared in a field above the CW zone. The aim of this report is to provide the hydrogeological background and the mechanisms for the collapse, and to review the potential for these mechanisms to induce future development of doline features.

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2 HYDROGEOLOGY

2.1 Main stratigraphical units

Galmoy is located within a northeast-southwest-trending belt of Lower Carboniferous limestone known as the Rathdowney Trend. Three key lithologies occur at the mine (Figure 2.1), these are summarised below from youngest to oldest.

Waulsortian Limestones (WA) are also known as Waulsortian Reefs. The mine is located within dolomitised Waulsortian Limestones. In the area of the mine workings, the thickness ranges from approximately 70 to 150 m, thinning to the north. Around one kilometre to the north (where the dolomitisation front occurs) the thickness is between 50 and 64 m. Further north, the (undolomitised) Waulsortian continues to thin and transitions into the Ballysteen Formation.

The dolomitisation front has an ENE-WSW trend and part of the regional dolomitisation of the northeastern portion of the Rathdowney Trend. All of the Galmoy orebodies are hosted towards the base of the dolomitised Waulsortian Limestones. The approximate depths of the mining zones are:

- K zone 73 m (NW) to 114 m (SE);
- G zone 44 to 113 m;
- C/CW zone 45 to 126 m; and
- R zone 97 to 159 m.

Where dolomitised, the Waulsortian is a Regionally Important Karstified Bedrock Aquifer. In undolomitised areas it is a Locally Important Aquifer - Bedrock which is Moderately Productive only in Local Zones.

Ballysteen Formation (ABL or BA) – well bedded, nodular, shaley calcarenites. It is the local equivalent of the **Argillaceous Bioclastic Limestone** (ABL). It is a Locally Important Aquifer - Bedrock which is Moderately Productive only in Local Zones. It forms a low permeability base to the overlying Waulsortian, and forms a barrier between the Waulsortian and the underlying oolite.

Lisduff Ooolite Member (BAld) – thick bedded, well jointed oolite up to 100 m thick in the Galmoy area. It is a Locally Important Aquifer - Bedrock which is Generally Moderately Productive. It is known to be fractured and to yield groundwater in the vicinity of the main geological structures, and has provided a sustained source of inflow to the decline at the nearby Lisheen Mine. The degree of fracturing and groundwater flow away from the main structural zones is uncertain. At Lisheen, mining in the oolite to the south of the Killoran fault (in Main Zone South) has been carried out to date without experiencing any significant groundwater inflow.

2.2 Overburden

Quaternary-age overburden (or “sub-soils”) overlies the bedrock across most of the Galmoy area. Glacial till is the principal overburden with cutover peat also present near the mine. The tills (also known as Boulder Clays) at Galmoy are primarily composed of limestone clasts with a clay matrix, with some sand and gravel lenses. Some pockets up to 15 m thickness of glacial material occur locally, for example in borehole GY136. Within 500 m to the south and east of the mine, there are small areas where there is karstified bedrock at surface i.e. there is no overburden present (Figure 2.2).

The sinkhole has occurred entirely within glacial till deposits – there is no evidence of bedrock within the walls or base. The overburden is freely draining in the area of the sinkhole evidenced by the low number of ditches, absence of standing water (even after heavy rain) and lack of indicative vegetation such as rushes. However, following periods of wet weather, temporary saturation of the overburden materials may occur, with the water ultimately draining downward into the underlying Waulsortian bedrock.

2.3 Main structures

Two important structural trends are evident in the Galmoy district: an ENE-WSW structural set, and a NNW-SSE structural set. A subordinate east-west structural set has also been recognized elsewhere in the region.

The G zone fault is the most important ENE-WSW structure in the Galmoy area. The structure bounds the southern end of the G zone mineralisation. It is a normal fault, dipping at about 55° to the northwest, can be up to 30 m in width with a throw of between 150 and 200 m. At Galmoy it forms the southern boundary of the Waulsortian (Figure 2.1) bringing ABL and BAld rocks on the footwall side into contact with the Waulsortian on the hangingwall. To the south of the G zone fault, the ABL and oolite dip at between 5 and 7° to the south towards the River Goul. The Killoran and Derryville faults at Lisheen are also aligned along this trend.

The NNW-SSE fault set is prominent through many of the carbonate regions of Ireland. It is seen to be a significant fault set for controlling groundwater, both at Galmoy and at Lisheen (and also at Tara Mines). At Lisheen, there is a tendency for drawdown to be anisotropic along this structural trend. The Main Fissure, above which the sinkhole formed, was the largest structure discovered at Galmoy from this fault set. It shows pinching and swelling along its length, both along horizontal strike and sub-vertical plane, with cavities occurring close to surface in the upper weathered zone and at depth associated with mineralisation. Based on the evidence from the local drill logs, there are very few cavities in the intervening rock. In addition to the regional structural trends, there are numerous northwest-southeast trending joints and minor faults, often with intense fracturing at the level of the mining horizon.

Palaeokarst development is common in the region and typically occurs within the upper 20 to 30 m of weathered limestone bedrock. The palaeokarst zone is evident in many of the local limestone quarries in Laois, Kilkenny and Tipperary. No cave systems have been identified within the local Galmoy area.

2.4 Galmoy Block conceptual groundwater model

2.4.1 Extent and hydrogeological boundaries

The Galmoy mining district (including all of the Galmoy orebodies) occurs within a tightly-bounded block of Waulsortian dolomite, hereon in referred to as the “Galmoy Block”. All of the orebodies occur close to the southern end of the Galmoy Block, reasonably close to the G zone fault. During dewatering, the boundaries of the block acted to localise the area of drawdown, which was very well defined around the mine area. The Galmoy Block is around 8 to 10 km² in extent, the boundaries of which are described as follows.

- **South**: G zone fault and the contact between the ABL and the Lisduff Oolite. This is a similar situation to the Main zone and the Killoran fault at Lisheen.
- **West**: a prominent NNW-SSE trending structure which was well defined by the baseline studies and has proven to be accurate.
- **East**: NNE-SSW structure and a contact with ABL; the eastern boundary was less well defined by the baseline studies but more recent geological mapping identifies a fault zone.
- **North**: thinning Waulsortian Limestone and by the transition to non-dolomitised limestone.

2.4.2 Groundwater recharge

Groundwater recharge to the Galmoy Waulsortian block is mostly derived from infiltration of precipitation and local runoff. The national groundwater recharge map indicates that natural recharge of the Galmoy Block may locally range between 55 and 470 mm/yr. This is based on rainfall datasets held by the Geological Survey of Ireland (GSI) including annual rainfall, and actual evapotranspiration, soil drainage, subsoil permeability, groundwater vulnerability and bedrock aquifer class. Most of the block has a natural recharge of between 200 and 350 mm/yr. This is consistent with other estimates in the area, such as nearby Lisheen where water balance estimates provide a “dewatering” recharge rate to the Waulsortian of about 275 mm/yr.

Recharge in Ireland primarily occurs between October and March when rainfall exceeds evapotranspiration i.e. when the soil water is at field capacity. From March to October, the opposite is often true when the soil moisture is in deficit. A typical seasonal cycle of the soil moisture balance and recharge may be as follows.

- **Summer**: high rate of evapotranspiration and soil water removal; increasing soil moisture deficit; rainfall events cause near-surface infiltration, but the water is quickly removed from the soil profile by evapotranspiration.
- **Autumn**: high soil moisture deficit, which has been gradually built up over the summer months; infiltration from rainfall events is stored in the near-surface soils, even though evapotranspiration rates are low; little water percolates downward below the extinction depth to recharge.
- **Winter**: the soil moisture deficit that was built up during the summer months becomes progressively replenished by on-going infiltration due to precipitation events. At some point, the soil moisture deficit is used up, breakthrough occurs, and the percolating water moves downward below the capture zone of the root system. The water is able to move downward below the extinction depth and become recharge to the groundwater system.
- **Spring**: the soils are fully saturated and any rainfall or snowmelt is transmitted rapidly downward below the root zone to become recharge. This may also be the period of high water availability, so most or all of the annual recharge may occur during this period. As ambient air

temperatures increase, so evapotranspiration rates also rise, and the soil moisture deficit starts to build up as summer approaches.

It should be appreciated that both the annual rainfall amounts, and the seasonal pattern of rainfall, have been variable over recent years, so the actual recharge in any one year is likely to be significantly different from the above number. Likewise, low rainfall in winter may lead to lower than average recharge while a wet summer may produce a large amount of recharge.

The doline above the CW mining zone occurred following a period of extremely wet weather during the winter months when there was minimal evapotranspiration and thus the soils and overburden would be at the highest water content.

2.5 Pre-mining conditions

2.5.1 Groundwater flow

All groundwater movement in the limestone bedrock units at Galmoy occurs under fracture flow conditions. For this reason, groundwater flow paths are irregular and tend to follow discrete interconnected fracture zones. The magnitude of flow within the limestone is controlled by the inter-connectivity of the fracture zones and the ability of the groundwater to cross boundaries.

Pre-mining (1992) groundwater levels in the Galmoy district were generally between 7 and 10 mbgl (below ground level) although many locations showed relatively high seasonal variation. Most continuous fracturing and groundwater flow occurred within the weathered horizon (around 10 to 65 mbgl). Many of the exploration borehole logs show enhanced jointing and fracture development in this zone.

Pre-mining groundwater levels (July 1992) and hydraulic gradients were used to conceptualise the boundaries of the Galmoy Block (see Section 2.4). Groundwater levels in the Galmoy Block were relatively flat, around 130 mAOD across most of the area (Figure 2.4). This shows a strong hydraulic inter-connection within the defined block. It is reported that there were a number of operating domestic and agricultural wells within the area of the Galmoy Block prior to the onset of mine dewatering activities. Therefore, it is considered likely that the observed pre-mining groundwater levels within the block may have been somewhat lower than their natural condition.

The hydraulic gradients indicate that pre-mining groundwater flow from the Galmoy Block was to the north towards the Glasha Stream and River Erkina. To the south, the Lisduff Oolite has a poor hydraulic connection with the block due to the G zone fault and ABL. There appears to be a good connection between the groundwater within the Lisduff Oolite immediately on the footwall side of the fault and flow is towards the River Goul.

The fault zone controlling the eastern and western boundaries are almost entirely within Waulsortian rock and parallel to the main groundwater flow direction. Therefore, it is likely that these represent leaky boundaries, with minor cross groundwater flow across the boundary from west to east.

All of the Galmoy orebodies occur close to the southern end of the Galmoy Block, reasonably close to the G zone fault. Therefore, when flooded, groundwater within the mine workings will be in a "backwater" and will tend to become laterally isolated from the regional groundwater flow system.

2.5.2 Water chemistry

There is a good pre-mining groundwater chemistry database for the Galmoy area, including both groundwater and surface water. The baseline work was carried out by KT Cullen and is reported in *Hydrogeology and dewatering of the Galmoy mine* (November 1992). The original surveys were carried out in early 1989. A further monitoring program was carried out in 1992.

The pre-mining groundwater hydrochemistry showed considerable variability as a result of the proximity to the mineralised area and due to agricultural contamination. It is reported that 26 out of 54 sampled baseline wells had elevated metals values that were higher than the EU limits or guidelines.

Nitrate concentrations in groundwater were generally within the range <1 to 20 mg/L and in surface water from 5 to 25 mg/L. These are expected values for agricultural areas and show that the groundwater bodies are likely to be unconfined and recharged locally within the Galmoy Block.

Sulphate concentrations in groundwater were variable but generally within the range <5 to 48 mg/L. Values reported for the Lisduff Oolite were often lower than those reported for the Waulsortian. In surface water the concentrations ranged from 5 to 55 mg/L, with the highest values often reported for the tributary streams immediately to the north of the Galmoy area. This suggests that the orebodies were the source of the higher sulphate concentrations in groundwater and that groundwater from this area flowed north, discharging to local streams.

Zinc concentration was elevated in a number of groundwater wells with a range between 0.35 and 1.2 mg/L. In the wells with elevated concentrations, other metals were generally low or below detection limit. In surface water the zinc concentrations were within the range <0.01 to 0.17 mg/L. The highest values were from headwater tributaries of the Glasha stream immediately north of the orebodies. This is consistent with the concept that naturally mineralised groundwater discharges into the surface water system and groundwater flow in the Galmoy Block is to the north.

Two shallow wells had zinc concentrations greater than 3 mg/L, the World Health Organisation Drinking Water Guideline (WHO DWG). They were both within the overburden so the source of zinc is unlikely to be the natural mineralisation that is observed in the bedrock groundwater system.

Lead concentrations were generally below detection limit (0.05 mg/L) in both groundwater and surface water samples. In total, three groundwater samples had concentrations up to 0.019 mg/L and one surface water had 0.8 mg/L.

2.6 Operational pumping rate

Dewatering of the Galmoy mine workings commenced in 1996 and finished in March 2013. The rate was generally within the range of 11,500 to 14,500 m³/d (Figure 2.5). A close correlation with rainfall can be seen both seasonally and annually. The ‘dry’ years (such as 2004 to 2006 and 2011) show lower dewatering rates while the wet winter of 2006-2007 shows a large increase in dewatering rate. Approximately two thirds of dewatering can be attributed to recent recharge. The remaining third is due to local-scale lateral flow and drawdown in the overburden around the margins of the Galmoy Block.

The drainable porosity of the Waulsortian limestone is known to be low (<0.015), meaning that the formation itself naturally contains relatively little groundwater in storage. This and the close correlation with rainfall support the conclusion that two thirds of the water pumped from the mine workings was derived from on-going groundwater recharge. It can be approximated that the total overall bedrock groundwater storage contained within the Galmoy Block prior to mining would have been no more than about 10 million m³.

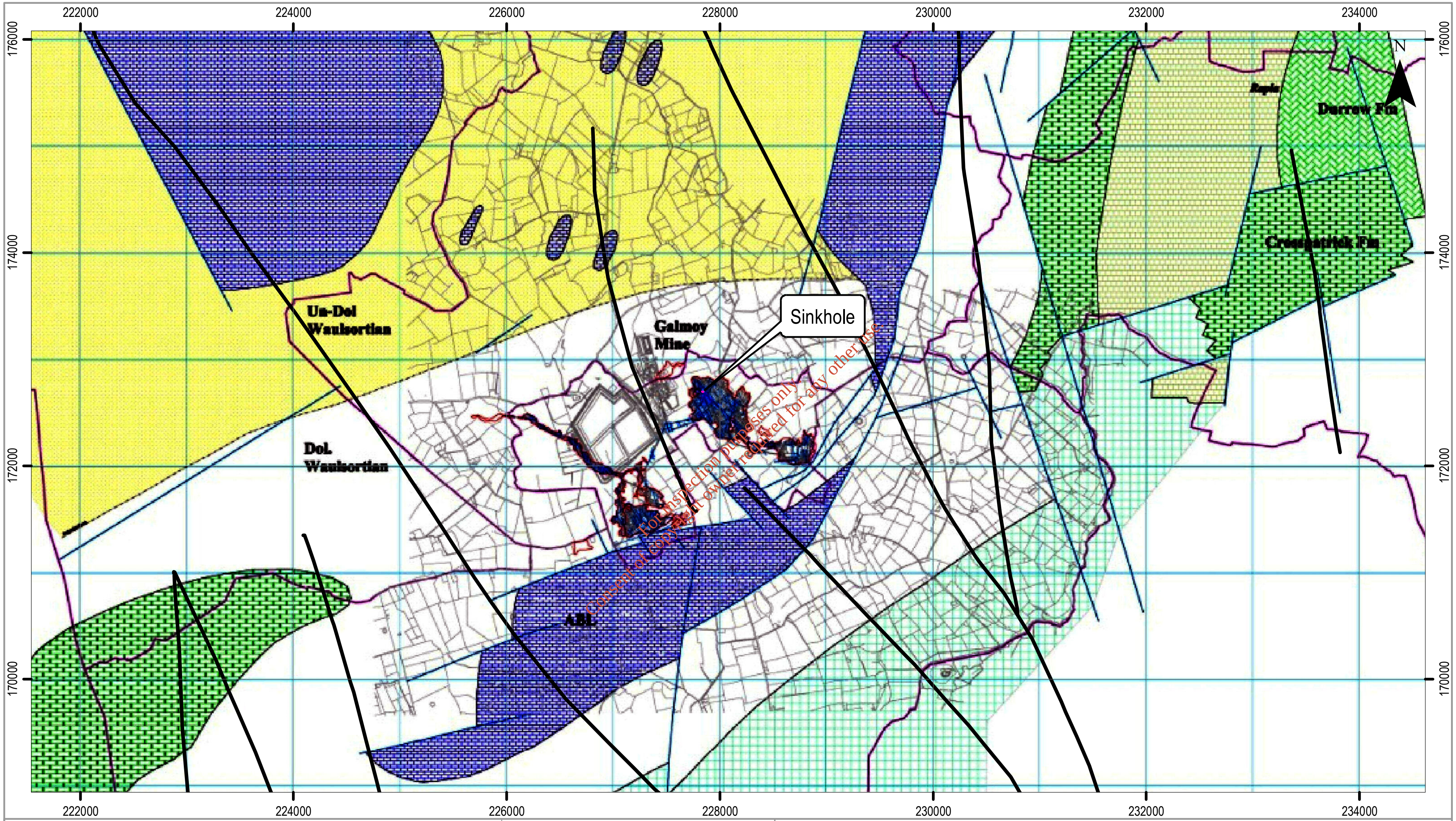
Mining of the CW zone encountered a prominent sub-vertical linear geological structure termed the “Main Fissure”. The Main Fissure is aligned with a NNW-SSE trend and was mapped underground over a distance of around 760 m. It was the largest geological structure of its kind encountered at Galmoy and produced large inflows to the CW workings.

2.7 Operational drawdown maps

Once the drawdown became established by the initial pumping in the late 1990s, the area of drawdown (around 18 km²) did not change significantly as the mine was progressively developed (Appendix A). This is also reflected in the long-term hydrographs (Figure 3.4), and is indicative of the strongly-bounded nature of the Galmoy Block.

Many of the observed changes to the area of drawdown are around the periphery of the block in the overburden. The precise extent of the drawdown area is difficult to determine because the periphery has a drawdown of less than a metre, which is within the normal range of seasonal water table fluctuation. Therefore changes in the drawdown area were generally associated with the amount of rainfall and the season.

Under dewatering conditions, all recharge occurring within the area of drawdown was ultimately captured by the mine dewatering system.



NNW-SSE structures mapped by Geological Survey of Ireland

Datum:TM65
Scale 1:50,000 at A4

0 1 2 Kilometres

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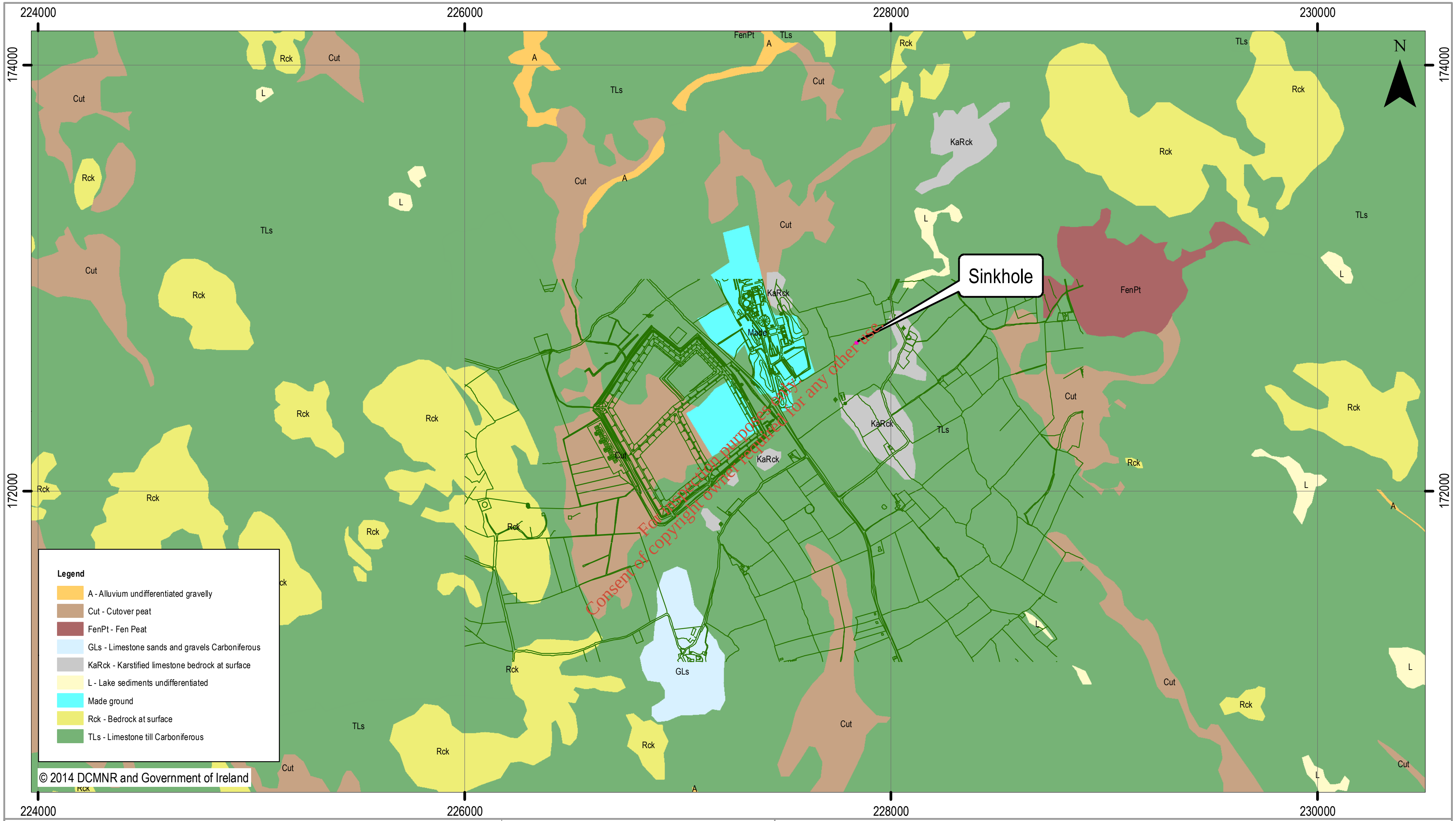
Solid Geology of the Galmoy District

CLIENT:	Galmoy Mines Ltd.	PROJECT:	Hydrogeology		
JOB:	51471	DRAWN:	SS	CHECKED:	GB
DATE:	March 2014	FIGURE:	2.1		



Datum:TM65
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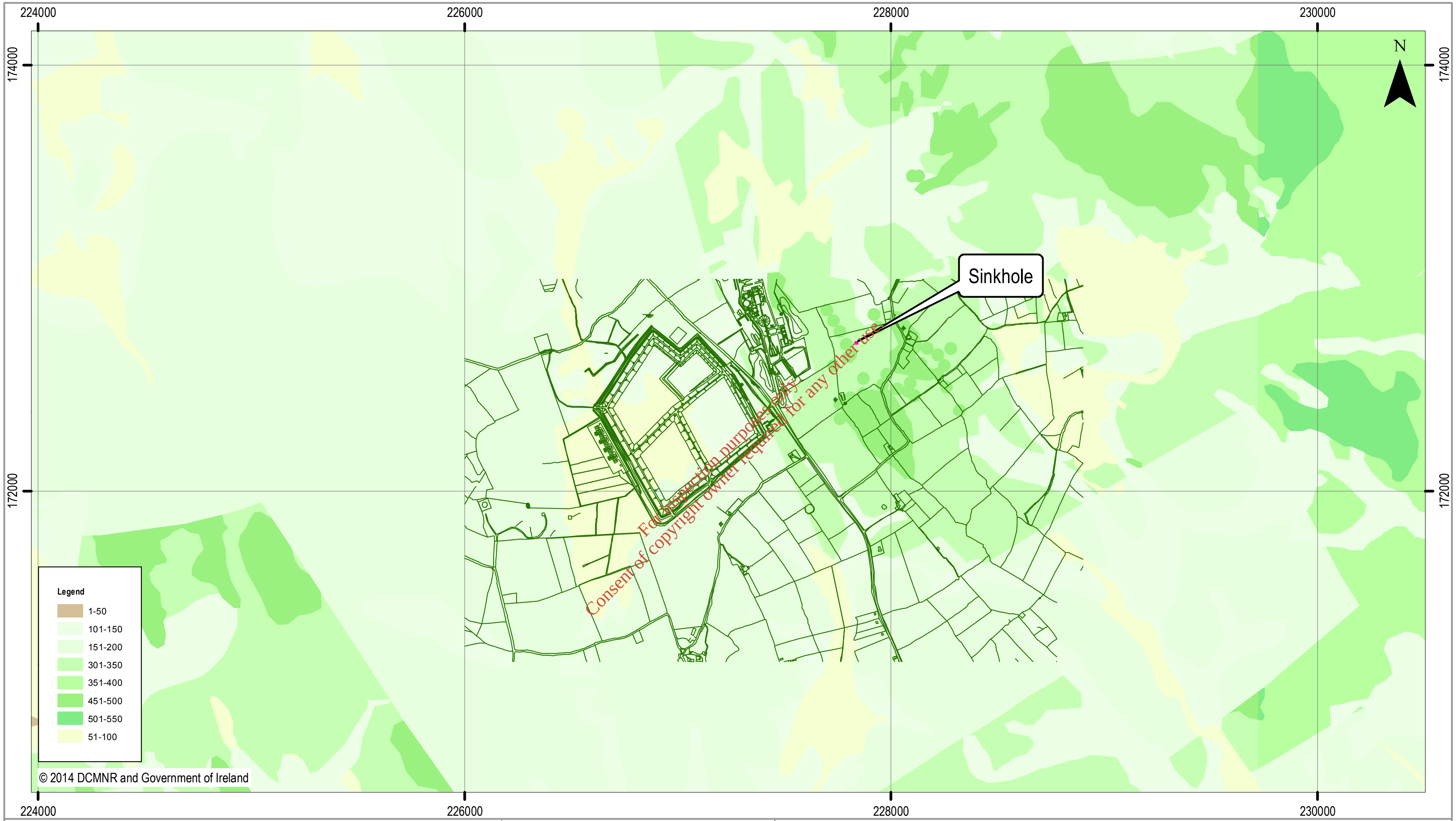
Overburden of the Galmoy District

CLIENT:	Galmoy Mines Ltd.	PROJECT:	Hydrogeology		
JOB:	51471	DRAWN:	SS	CHECKED:	GB
DATE:	March 2014	FIGURE:	2.2		

P:\51471 Galmoy\600_Reports and Tech Memos\51471 R2 Sinkhole\Figures\Figure2.2_Overburden.mxd



© 2014 DCMNR and Government of Ireland

Datum:TM65
Scale 1:25,000 at A4

0 0.5 1 Kilometres

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Annual average recharge of the Galmoy District

CLIENT: Galmoy Mines Ltd.
PROJECT: Hydrogeology
JOB: 51471
DRAWN: SS
CHECKED: GB
DATE: March 2014
FIGURE: 2.3

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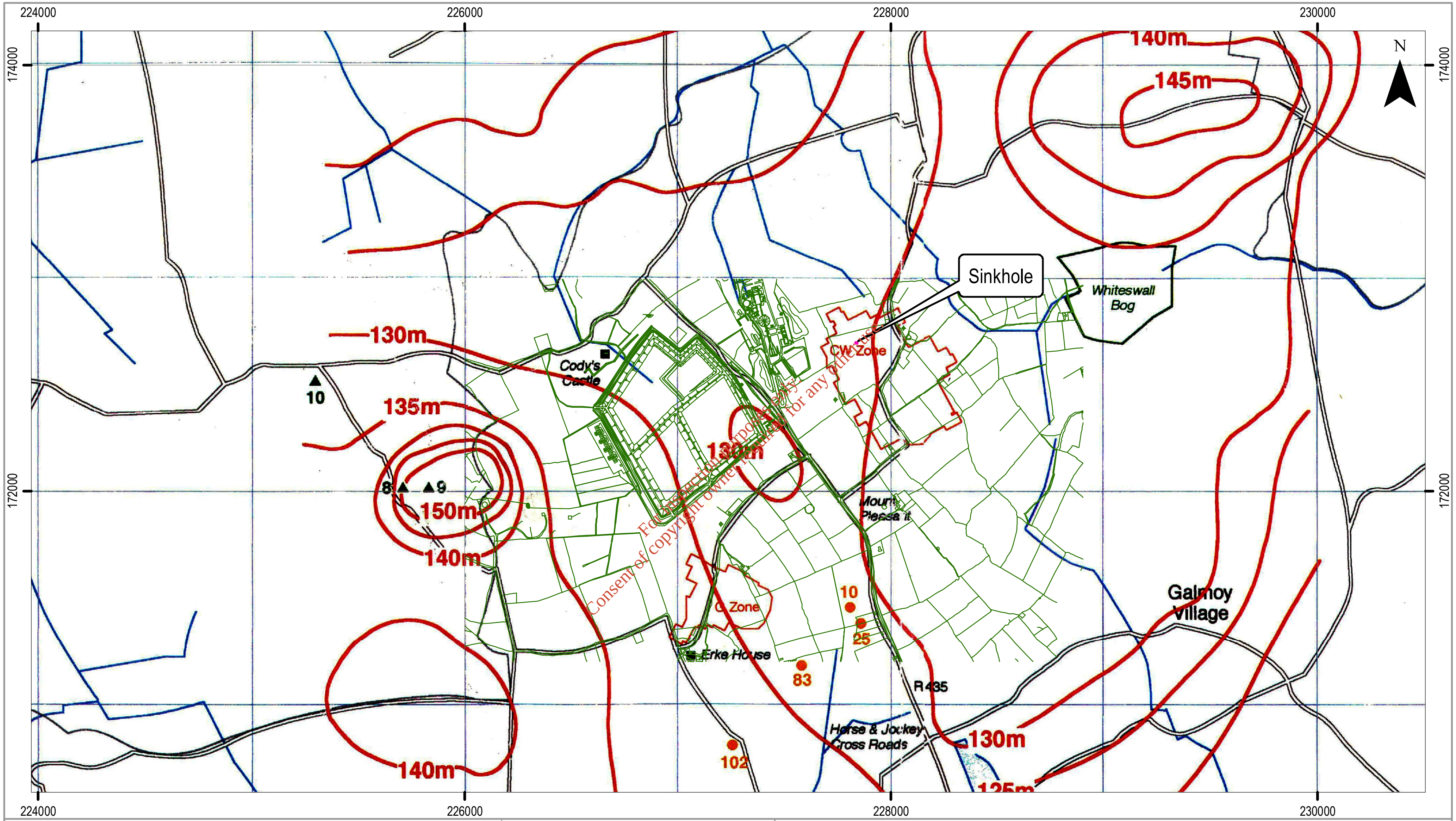

Source: KT Cullen, 1992

Datum:TM65
Scale 1:25,000 at A4
0 0.5 1 Kilometres

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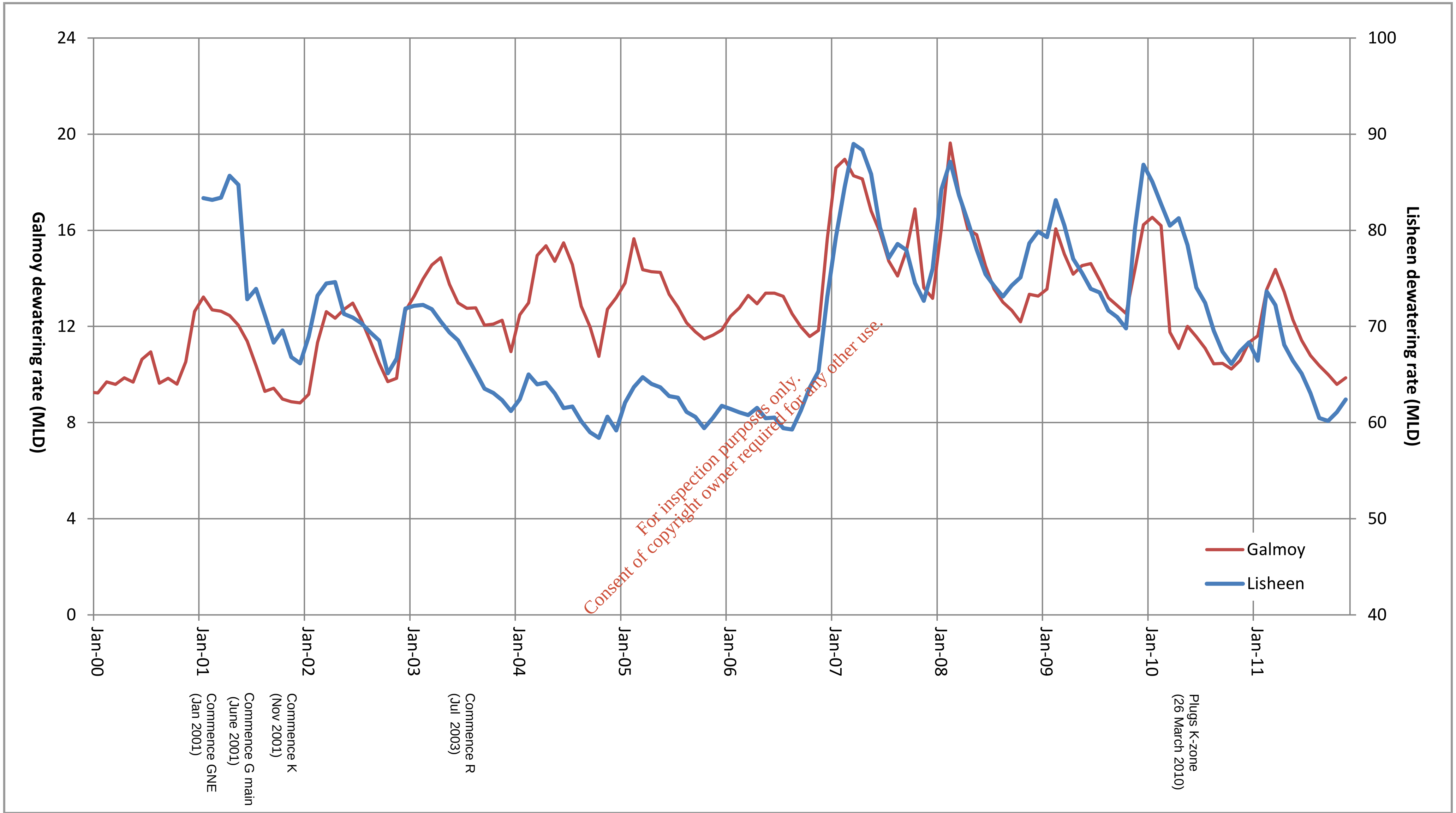
Pre-mining ("baseline") groundwater levels

CLIENT:	Galmoy Mines Ltd.	PROJECT:	Hydrogeology		
JOB:	51471	DRAWN:	SS	CHECKED:	GB
DATE:	March 2014	FIGURE:	2.4		



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Galmoy and Lisheen dewatering records 2000 to 2011

CLIENT: Galmoy Mines Ltd.
PROJECT: Hydrogeology
JOB: 51471
DRAWN: SS
CHECKED: GB
DATE: March 2014
FIGURE: 2.5

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3 MINE CLOSURE

3.1 Groundwater recovery curve

All mine workings have been flooded and groundwater in the area has now recovered to pre-mining levels (Figure 3.1, Figure 3.2 and Figure 3.3). A baseline groundwater level of 130 mAOD has been used in this assessment because the baseline 130 mAOD contour passes through three of the main orebodies: CW, G and K (Figure 2.4).

The monitoring data during closure support the conceptual hydrogeological model. The groundwater recovery was rapid and the rate of recovery was dependent on the rainfall pattern. This is indicative of a strongly bounded groundwater system with little regional or district-scale flow.

3.2 Mine water chemistry

Baseline surveys carried out pre-mining show that there are a limited number of parameters which may be potentially elevated relative to environmental or drinking water standards. These are lead, zinc, arsenic, cadmium, sulphate, nitrate and ammonia. In addition, some domestic wells showed elevated nitrates and ammonia probably as a result of land spreading and/or septic tanks.

During dewatering and most of the recovery period, the mine workings were a groundwater sink i.e. all groundwater gradients surrounding the mine are inward toward the mine workings (Appendix A). Under these conditions, the potential for solutes in the mine workings to migrate into the surrounding groundwater system was very low.

As the groundwater levels approached the pre-mining baseline with the mine re-flooding, groundwater gradients began to return towards ‘natural’ conditions (Figure 2.4). This increases the potential for the migration of solutes away from the mine workings, primarily to the north. For this reason, the monthly water quality monitoring programme of mine workings, monitoring boreholes and local water supply wells remained in place for the duration of closure. In addition, monitoring locations in streams to the north of the mine have been re-established to monitor baseflow water quality as this recovers.

The programme was put in place to monitor water quality of the following key areas:

1. groundwater resource (including mine workings);
2. community groundwater supply boreholes WW1A and WW2B;
3. domestic groundwater supply boreholes; and
4. baseflow to streams.

The results to date show that groundwater quality within the flooded mine workings generally meets relevant Irish and WHO drinking water guidance and the groundwater-related success criteria in the Closure, Restoration and Aftercare Management Plan (CRAMP) objectives. In the limited occasions where a standard has not been met, it can be demonstrated that either the trend is decreasing or consistent with background/pre-mining baseline concentrations. These are summarised as follows.

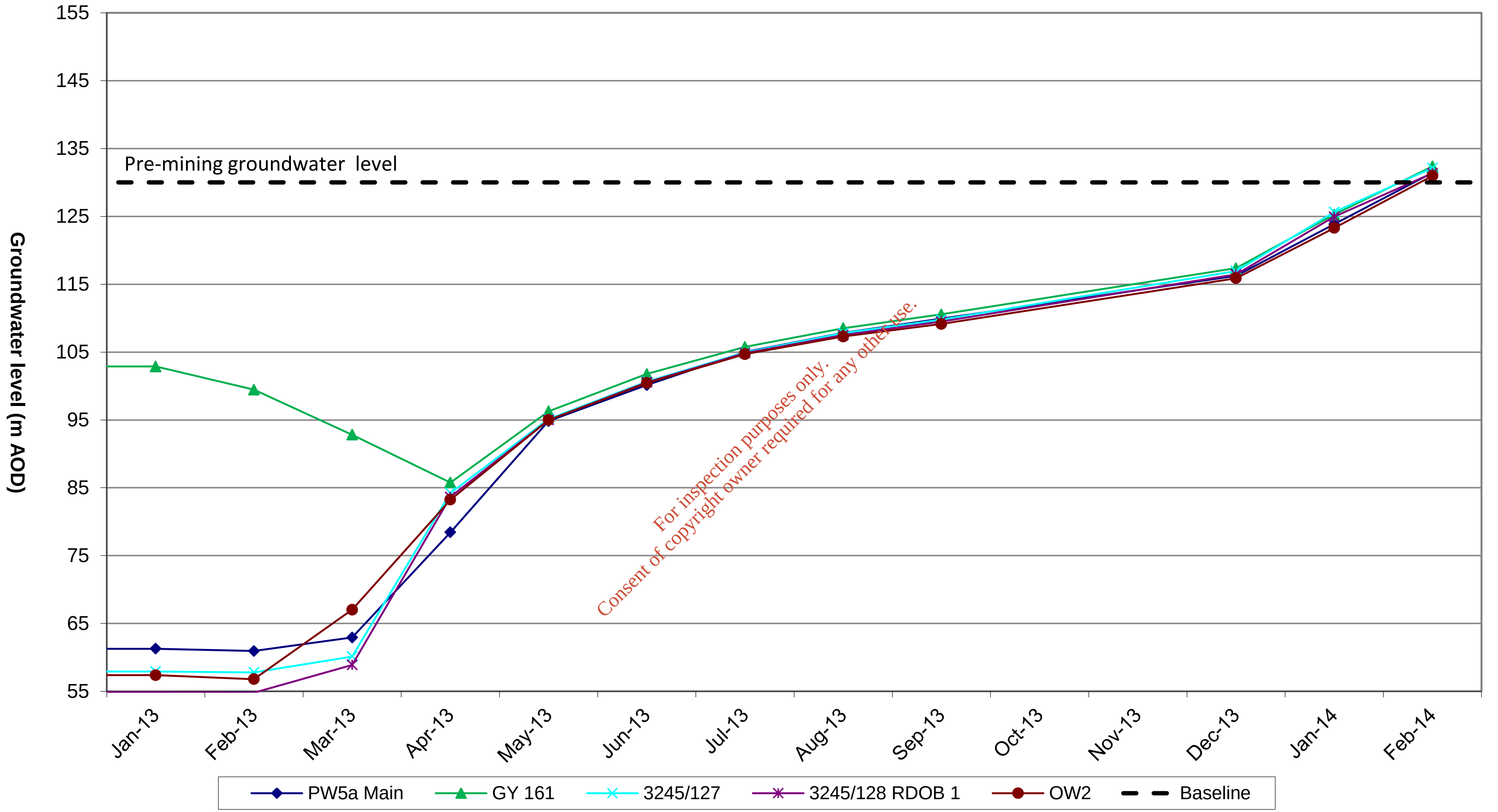
- In the G zone and CW zone workings, there were some reported values of sulphate, nickel and arsenic that were elevated above drinking water guidelines. This was predicted and was the result of the inflowing water contacting the wall rocks of the mine workings. As flooding continued and the oxygen levels became depleted, the reported concentrations have decreased with time. Decreasing or stable trends are expected to continue in the future.

- Domestic water supplies show occasional exceedance of nitrogen-species (nitrate and ammonia). Baseline data showed the same trends so the source of is likely to be land spreading or septic tanks.

Replacement Water Supply Scheme (RWSS) boreholes WW1A and WW2B have never exceeded Irish drinking water standards for any parametric value recorded. There have been no trends in water quality as a result of re-flooding of the mine workings.

In addition to the RWSS boreholes, there are no adverse trends in water quality at any other groundwater or surface water monitoring location.

In the future, it is expected that the water within the flooded workings will be isolated from the active groundwater circulation in the Galmoy area. The flooded workings occur at the south end of the Galmoy Block, so they will tend to be isolated from the active groundwater flow system which will mostly be to the north. Furthermore, most natural groundwater flow occurs within the upper weathered zone of interconnected joints, fractures and palaeokarst which is above the level of the mine workings.



Borehole locations shown in Appendix A

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CW and R zone groundwater recovery hydrographs

CLIENT:	Galmoy Mines Ltd.	PROJECT:	Hydrogeology		
JOB:	51471	DRAWN:	SS	CHECKED:	GB
DATE:	March 2014	FIGURE:	3.1		

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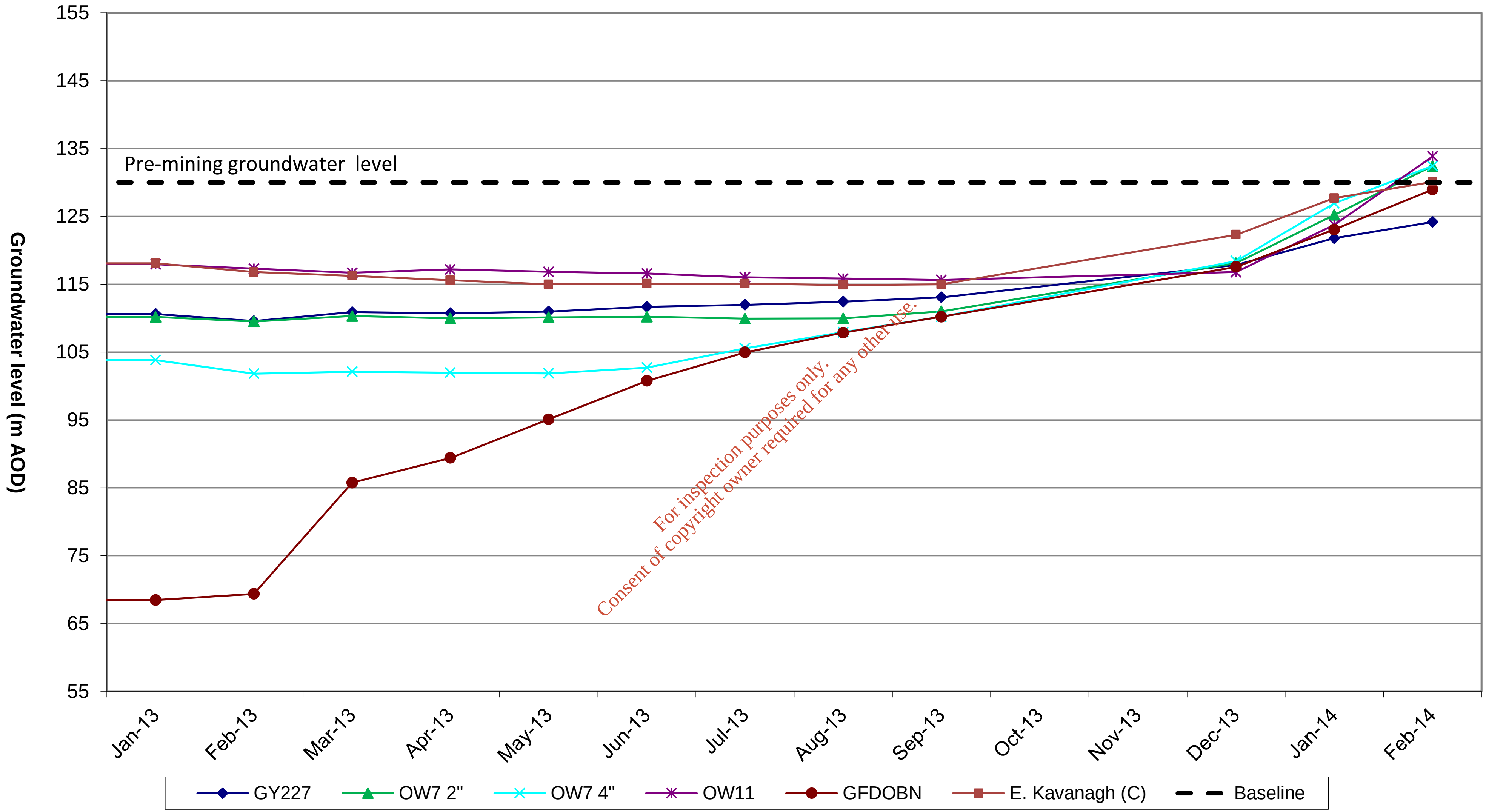

Borehole locations shown in Appendix A

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G zone groundwater recovery hydrographs

CLIENT:	Galmoy Mines Ltd.	PROJECT:	Hydrogeology		
JOB:	51471	DRAWN:	SS	CHECKED:	GB
DATE:	March 2014	FIGURE:	3.2		

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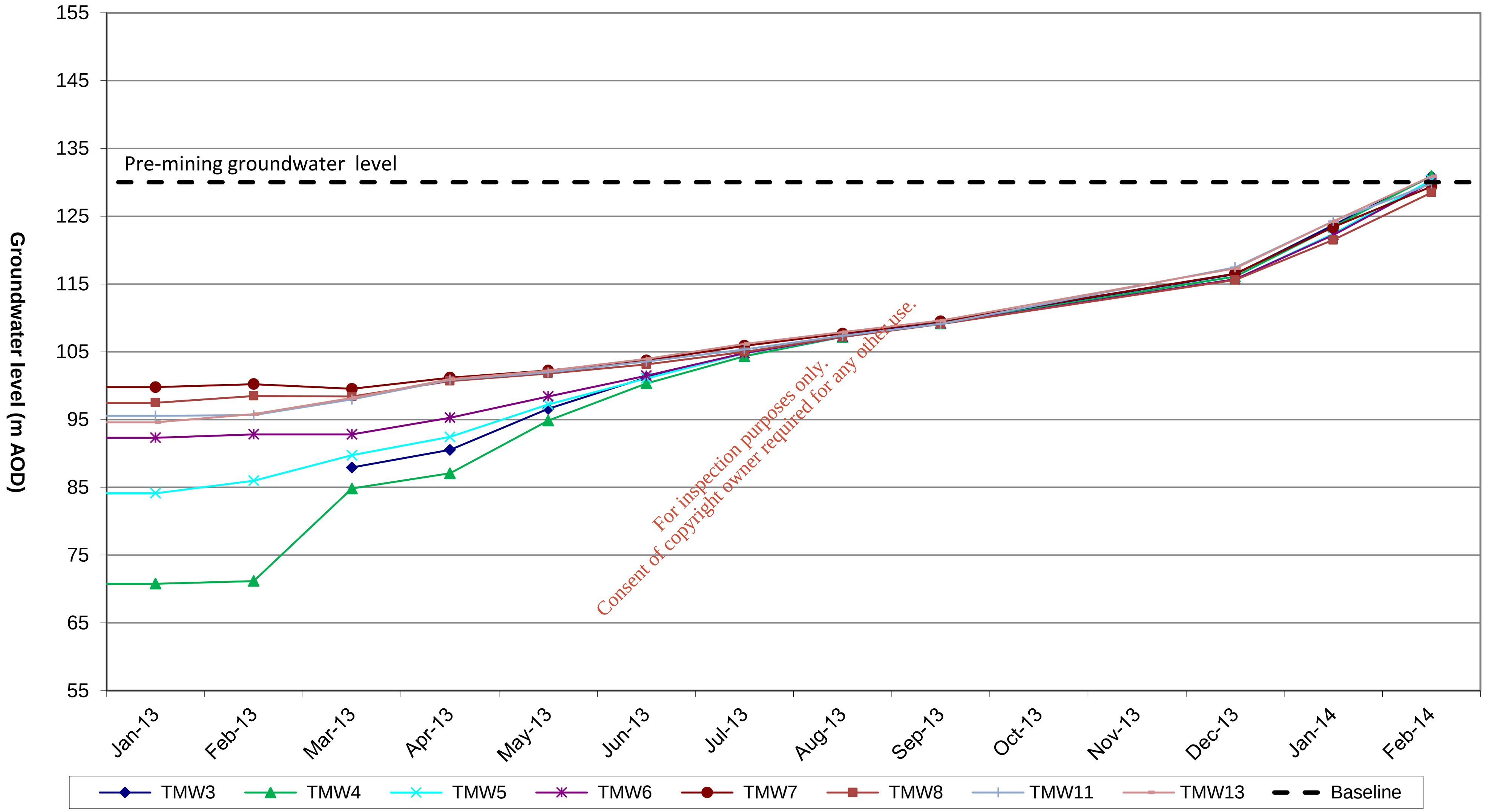

Borehole locations shown in Appendix A

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K zone groundwater recovery hydrographs

CLIENT:	Galmoy Mines Ltd.	PROJECT:	Hydrogeology		
JOB:	51471	DRAWN:	SS	CHECKED:	GB
DATE:	March 2014	FIGURE:	3.3		

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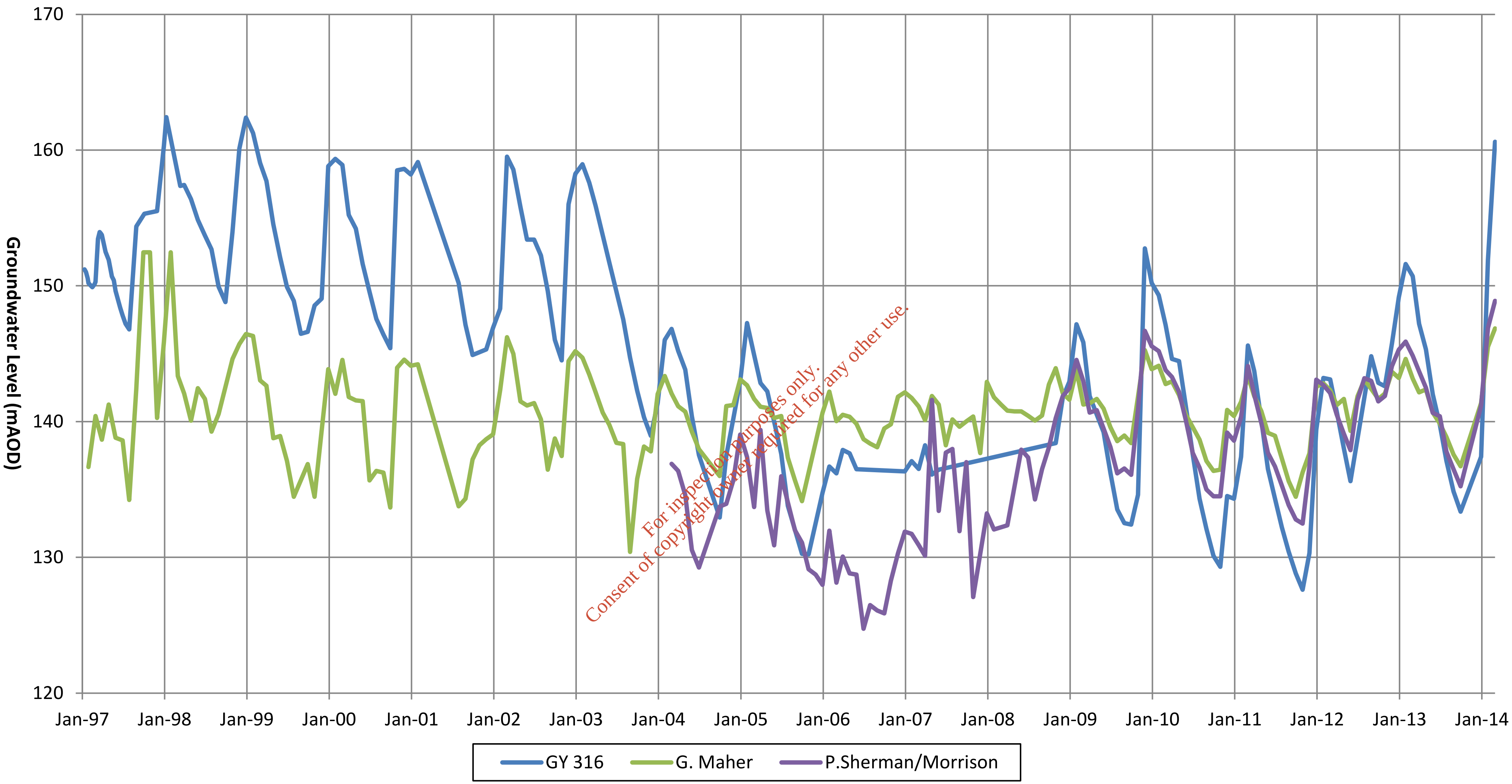

Borehole locations shown in Appendix A

Schlumberger
Water Services

Long term groundwater hydrographs

CLIENT:	Galmoy Mines Ltd.	PROJECT:	Hydrogeology		
JOB:	51471	DRAWN:	SS	CHECKED:	GB
DATE:	March 2014	FIGURE:	3.4		

P:\51471 Galmoy\600_Reports and Tech Memos\51471 R2 Sinkhole\Figures\Figure3.1to3.4_RecoveryHydrographs.xlsx

4 SINKHOLE DEVELOPMENT

4.1 Sinkhole characteristics

Karst is used to describe geological features formed by the dissolution of rock. The most common rock types for karst to occur in are carbonates (e.g. limestone or dolomite); although the presence of carbonate rocks does not mean that karst features will occur. Karst features include turloughs, caves, some springs and sinkholes (also known as dolines).

Sinkholes are enclosed depressions that may have a wide range of size and depth. In Ireland, they are the most common landform in karst areas. Natural sinkholes may occur as isolated features or in clusters causing a pock-marked land surface (Figure 4.1). They can form due to a large number of mechanisms; however, six main types are commonly referred to: solution, collapse, dropout, buried, caprock and suffosion (Figure 4.2).

Approximately 50% of the Republic of Ireland is underlain by limestone, the majority of which is Carboniferous in age (300 to 340 million years ago). For this reason, karst features are a common occurrence – there are estimated to be over 6,000 dolines (Hickey, 2013).

4.2 Galmoy sinkhole

4.2.1 Description

Since the initial formation of the Galmoy sinkhole overnight between 14th and 15th February, no further subsidence has occurred and there is no evidence of any cracking or ground movement in the surrounding area. The centre of the sinkhole has National Grid coordinates 227838, 172695 and is immediately above a major geological fault zone (Figure 4.3) – termed the "Main Fissure". The Main Fissure is the largest sub-vertical geological structure encountered at Galmoy. The sinkhole is elliptical in plan with the long axis in alignment with the Main Fissure. The dimensions are: long axis 13 m, short axis 8 m, depth 7 m and approximate volume 550 m^3.

The sinkhole is steep sided with no bedrock visible in the walls or base, both of which are composed of glacial till (Figure 4.4). Following the collapse, a minor amount of water was present in the base of the hole. This is unlikely to have been groundwater because levels in the area were estimated to be between 10 and 15 mbgl at the time (approximately between 125 and 130 mAOD). Therefore it is likely to have been standing water, indicating that the till was saturated at the time. Saturation of the till was also evident in the walls of the sinkhole below about 4 mbgl.

Around 100 m southeast of the sinkhole and close to the line of the Main Fissure, there is an enclosed depression (Figure 4.3 and Figure 4.4). It is approximately 15 m in diameter and 1 m deep at the centre. As part of the current study, Golder carried out ground penetrating radar (GPR) surveys across this feature (Figure 4.5). A major change in the character of the reflector is apparent within the depression, giving the impression of a steep sided feature approximately 5 m deep. This has been interpreted to be an old suffosion doline of comparable size and geometry to the recent sinkhole, demonstrating that sinkholes have previously occurred in the region of the Main Fissure.

4.2.2 Classification

The morphology of the Galmoy sinkhole strongly suggests that it is a dropout doline (also known as cover collapse sinkhole). Such features are usually characterised by vertical or steep-sided collapses, with a very sharp break in slope and no bedrock exposure in the walls or base.

Dropout dolines occur when the overburden collapses into a void within the overburden itself. They are common in Ireland (Figure 4.6) because the prerequisites are cohesive soils (such as glacial till) overlying karst features. The generalised formation of a typical dropout doline is as follows (Figure 4.6).

1. Water percolates through the soil.
2. The underlying bedrock surface provides a low permeability barrier to downward flow, so the water moves laterally downslope at the base of the overburden to an area of higher permeability (the karst feature).
3. Concentration of percolation water occurring within the unsaturated zone (above the main water table), causes the flow to become non-Darcian (commonly referred to as “turbulent”), i.e. capable of carrying sediment. The high velocities increase the potential for piping (internal erosion of the soil grains), transport of sediment and formation of an internal void above the karst feature. At the surface, there are often no visible signs of this occurring.
4. Void formation often concentrates the water seepage, thus accelerating the internal erosion process.
5. The eroded soil material is transported downwards into the karst feature and into interconnected joints, fractures or open cavities within the underlying limestone bedrock. The open cavities are present because of the gradual dissolution of the limestone due to percolating water over long periods of geological time, primarily during the Tertiary period. In the limestone areas of the Irish Midlands, the upper part of the bedrock may be strongly weathered and contain interconnected cavities which were formed when the water table was lower than it is currently, and when the rate of dissolution of the rock was higher. Such systems are often termed palaeokarst because the dissolution of the rock is occurring at a much reduced rate.
6. A critical point is reached where the soil can no longer support its own mass and it suddenly collapses.

The soil collapse often occurs during or following periods of heavy rainfall when the percolating water adds more weight to the overlying soil, triggering the collapse.

Sinkholes are a natural phenomenon although are sometimes induced or accelerated by human activities. The initial karst feature may be only a few centimetres across and the downward transport of sediment from the overburden may be very slow, so the void may take many tens or hundreds of years to form. The acceleration of the process is often the result of drawdown of the water table which may be due to water supply abstraction, quarrying or mining. When the water table is drawn down, it allows (i) a greater thickness of unsaturated material where turbulent flow, piping and transport of sediment may occur, and (ii) remobilisation and transport of sediment which may already be filling the joints, fractures or cavities in the underlying limestone rock as a result of earlier erosion and transport.

4.2.3 Contributing factors

The sinkhole at Galmoy is a natural feature; however, it is likely that the following factors contributed to the collapse.

- The presence of the Main Fissure.
- The geomorphology of the bedrock surface and local topography, allowed infiltrating and percolating water to become concentrated above the Main Fissure at the specific location where the sinkhole occurred.
- The relatively deep pre-mining water table (approximately 10 m below surface), meant that percolation, internal erosion and transport of soil material from the overburden was likely occurring for many years prior to the sinkhole development.
- The mine dewatering contributed to an increased void space and sediment sink in the upper weathered bedrock into which the in-situ overburden material could be transported. This is because dewatering caused an increase in recharge flow velocity (sufficient to carry sediment) within the unsaturated zone of the upper bedrock and probably caused consolidation of material that filled existing joints, fractures and bedrock cavities in the palaeokarst zone; together these increased the potential for erosion and transport of the infilling material.
- The extremely high rainfall from December 2013 to February 2014, which added weight to the overburden above the void and provided the trigger for the collapse.

Main Fissure

The "Main Fissure" was encountered during mining of the CW zone. It is a sub-vertical fault zone with a NNW-SSE trend. With the exception of the G zone fault (which is much shallower dipping and has the low permeability ABL as its footwall) it is the largest geological structure discovered during mining.

As is typical of such features, it pinches and swells along its fault plane (i.e. laterally along the strike and vertically along the dip). Exploration boreholes in the area of the Main Fissure show that it has caused the presence of palaeokarst cavities in the upper weathered zone (up to 30 mbgl or 110 mAOD) and close to the orebody (around 80 to 95 mbgl or 45 to 60 mAOD). There are few cavities between these two zones (Appendix B and illustrated in Figure 4.7) so there is limited hydraulic connectivity except through diffuse and tortuous jointing. Most cavities encountered during drilling were filled with clay or sand.

Mine dewatering

Dewatering of the CW zone decreased the level of the water table in the area by up to 65 m. In the area of the sinkhole, the water table was reduced from 130 mAOD (around 10 mbgl) to about 65 mAOD (75 mbgl) (Figure 3.1). Therefore, the mine workings in the area of the Main Fissure were up to 15 m below the water table, even during active dewatering. Approximately two thirds of dewatering water can be attributed to recent recharge; the remaining third being primarily derived from lateral inflows from the surrounding overburden (Section 2.6).

The reduction in the water table elevation meant that the palaeokarst cavities of the upper weathered zone became dewatered causing unsaturated groundwater flow (i.e. movement of water above the water table) through the interconnected joints, fractures and cavities. Unsaturated flow is more likely to be turbulent thus increasing the sediment-carrying potential. Following the onset of mine dewatering, it is considered likely that previously-transported material that had accumulated in voids within the upper bedrock may have become re-mobilised, thus creating additional void space within the upper bedrock, which may have in turn provided the sediment-sink into which the in-situ overburden material could be transported. This is assumed to be the main mechanism for the creation of the overburden void below the sinkhole.

As the mine workings were below the water table, unsaturated (turbulent) flow could only occur where cavities were encountered by mining. Therefore sediment washout was likely to have been localised around the mine workings and would probably not have extended significant distances from them. The available evidence does not support a rapid connection between the sediment-filled cavities at the mining horizon with the cavities in the upper part of the bedrock. Any flow or transport of sediment between the two zones would likely have been diffuse and would have occurred through a complex flow pathway.

Extreme rainfall

The winter of 2013-2014 was exceptionally wet. Between December 2013 and February 2014, 460 mm of rain was recorded at Oakpark, Co. Carlow (45 km east of Galmoy). Records from the same location show that the mean (1996 to 2013) rainfall for December to February is 194 mm (Table 4.1 and Figure 4.8). The annual average rainfall at the Oakpark station is 846 mm.

Recharge is the principal component of dewatering at nearby Lisheen Mine making it a good proxy for Galmoy. The two dewatering records have consistently mirrored one another (albeit with different magnitudes), again demonstrating their similarities (Figure 2.5). As a response to the extreme rainfall, the dewatering rate at Lisheen increased from an all-time low (55 MLD) in November 2013 to their all-time high (106 MLD) in March 2014 due to the extreme rainfall (S. Wheston 2014, pers. comm. 18 March). The dewatering data from Lisheen (Figure 4.9) show a steady increase from late December 2013 demonstrating that the high rainfall was generating significant volumes of recharge. It can be assumed that similar large volumes of recharge were also being generated at Galmoy prior to the sinkhole occurrence.

Greater recharge means greater downward percolation of groundwater through the unsaturated zone increasing the potential for sediment transport. In addition, greater saturation of the soil zone increases the weight, providing the likely trigger for the sinkhole.

Table 4.1 Recent rainfall records from Oakpark, Co. Carlow

Date	Rainfall (mm)	1996 to 2013 mean (mm)	Percent of monthly mean
October 2013	170.0	98.7	172
November 2013	27.7	92.6	30
December 2013	136.6	71.9	190
January 2014	147.2	78.7	187
February 2014	176.7	52.7	335

Bedrock surface geomorphology and local topography

The sinkhole is located in an area where there is increased potential for groundwater recharge due to the bedrock geomorphology and the local topography. Together these concentrate the percolating waters in the area of the sinkhole, increasing the flow of water within the palaeokarst cavities.

The field above the sinkhole provides a significant up gradient catchment area for the percolating water. This causes shallow subsurface flow to move downslope above the bedrock surface towards the sinkhole location.

GPR surveys were undertaken by Golder as part of the current study. The survey results showed that the bedrock surface forms a large depression in the area of the sinkhole (Figure 4.10). The depression is over 100 m wide and is elongated along the strike of the Main Fissure, which is the likely catalyst for its formation. The depression would likely concentrate any percolating waters towards its centre, i.e. the centreline of the Main Fissure.

4.2.4 Sinkhole collapse

Based on the above discussion, the most likely series of events that caused the collapse of the Galmoy sinkhole are as follows.

1. The presence of the Main Fissure caused a line of weakness in the bedrock, so that weathering over geological time produced an increased density of karst features (now palaeokarst) and cavities along its length. The drill hole logs in the area indicate that the palaeokarst mostly occurs up to 30 m depth.

2. For a few thousand years rainwater-recharge has percolated vertically downward through the overburden until it encounters the low permeability bedrock surface. Upon reaching the bedrock surface, the percolating water moves laterally downslope at the base of the overburden towards the centre of the bedrock depression, concentrating the groundwater flow above the Main Fissure.

3. In recent history (10s to 100s of years), the water table was around 10 mbgl; therefore, the upper 10 m of overburden and bedrock is unsaturated. Thus, the processes of percolating water and transport of sediment within this shallow zone (less than 10 m depth) were likely occurring prior to mine development.

4. Dewatering of the CW zone from 1998 to March 2013 reduced the water table elevation in the area from around 10 mbgl to 75 mbgl causing percolation of water through previously-saturated cavities in the upper weathered zone. The increased flow velocities as a result of unsaturated flow during the period of mine dewatering likely caused the water to become turbid. Dewatering during mining likely lead to the re-mobilisation of some of the previously-transported fill material that was present within the cavities in the palaeokarst zone of the upper bedrock. This, in-turn, provided a sediment sink for the overburden material that was transported from the void space which caused the sinkhole collapse. Groundwater levels have now recovered to their baseline levels.

5. A small void developed in the overburden above the Main Fissure at the location of the sinkhole. The void may have started to form many hundreds of years ago but is likely to have become more pronounced during the period of mine dewatering.

6. The void further focused the rainwater-recharge on the karst feature, increasing the rate of erosion, sediment transport and development of the void space.

7. Extraordinarily high rainfall from December 2013 to mid-February 2014 lead to an increased weight of the soil above the void. On the night of 14th February, the additional weight and total stress reached a critical point and the soil collapsed to form the dropout doline.

4.3 Potential for future sinkhole development

Dropout dolines are common in Ireland and historic collapses are evident in the landscape around Galmoy today. There is a natural background potential for sinkhole development in the Galmoy area.

However, the series of events outlined in Section 4.2 was caused by the combination of specific factors. The potential for another collapse to occur depends on similar circumstances arising again. For this reason, the four key contributing factors have been reviewed for their potential to cause another sinkhole.

Main Fissure

The Main Fissure is a well-defined, discrete feature – the largest of its kind seen during the mining at Galmoy and geological mapping of the surrounding area. The increased depth to weathering and oxidation along the alignment of the Main Fissure increases the potential for recharge along its strike.

There are no other known major sub-vertical structures at Galmoy so this will reduce the potential for similar sinkhole mechanisms occurring elsewhere. During the Galmoy tailings management facility (TMF) design process, Golder (1992) undertook an assessment into the potential for karst to cause near-surface stability issues. The assessment showed that (i) the karst system in the TMF area is immature, (ii) the minor cavities that occur are mostly filled with in-situ derived residual material, and (iii) it is highly unlikely that continuous cavity systems occur underneath TMF footprint area.

Bedrock surface geomorphology and local topography

The sinkhole occurred at the specific location along the Main Fissure because there was a depression in the bedrock surface at that location. The GPR surveys showed that the depression is local to (and very likely caused by) the presence of the Main Fissure. Typically, fault zones are areas of rock weakness with increased fracturing which makes the rock at surface more easily erodible. Being the largest sub-vertical fault in the Galmoy area, these characteristics have produced a relatively large depression along the strike of the Main Fissure at the location of the sinkhole.

Drilling programmes and mining have not encountered any other faults like the Main Fissure therefore the potential for sinkhole development is limited to this location.

Mine dewatering

Dewatering at Galmoy ceased in March 2013 and the water table has now fully recovered to its baseline level (Section 3.1). The potential for turbulent flow conditions above the water table is now limited to the upper 10 m, as it was during pre-mining conditions. Groundwater flow velocities in the palaeokarst zone below 10 m depth are much reduced and are more likely to create deposition of sediment rather than washout. However, unsaturated flow conditions still occur in the upper 10 m of overburden and bedrock, so there is still a background potential for further sinkhole development.

Provided the water table remains close to its pre-mining level (about 10 mbgl), it is considered that the potential of future sinkhole development will remain at background. Any future lowering of the water table as a result of increased pumping of domestic water supply wells in the area may marginally increase the potential for future sinkhole development, as is the case in limestone areas over much of the Irish Midlands.

Extreme rainfall

The greatest increase in the potential for future sinkhole development is during and immediately following periods of extreme rainfall. The backfill design for the sinkhole is to place large boulders on the bedrock surface with the grain size being reduced as overlying layers are added. This will allow rainwater to percolate into the ground and through the karst feature but will prevent the movement of sediment, reducing the potential for erosion and further sinkhole development.

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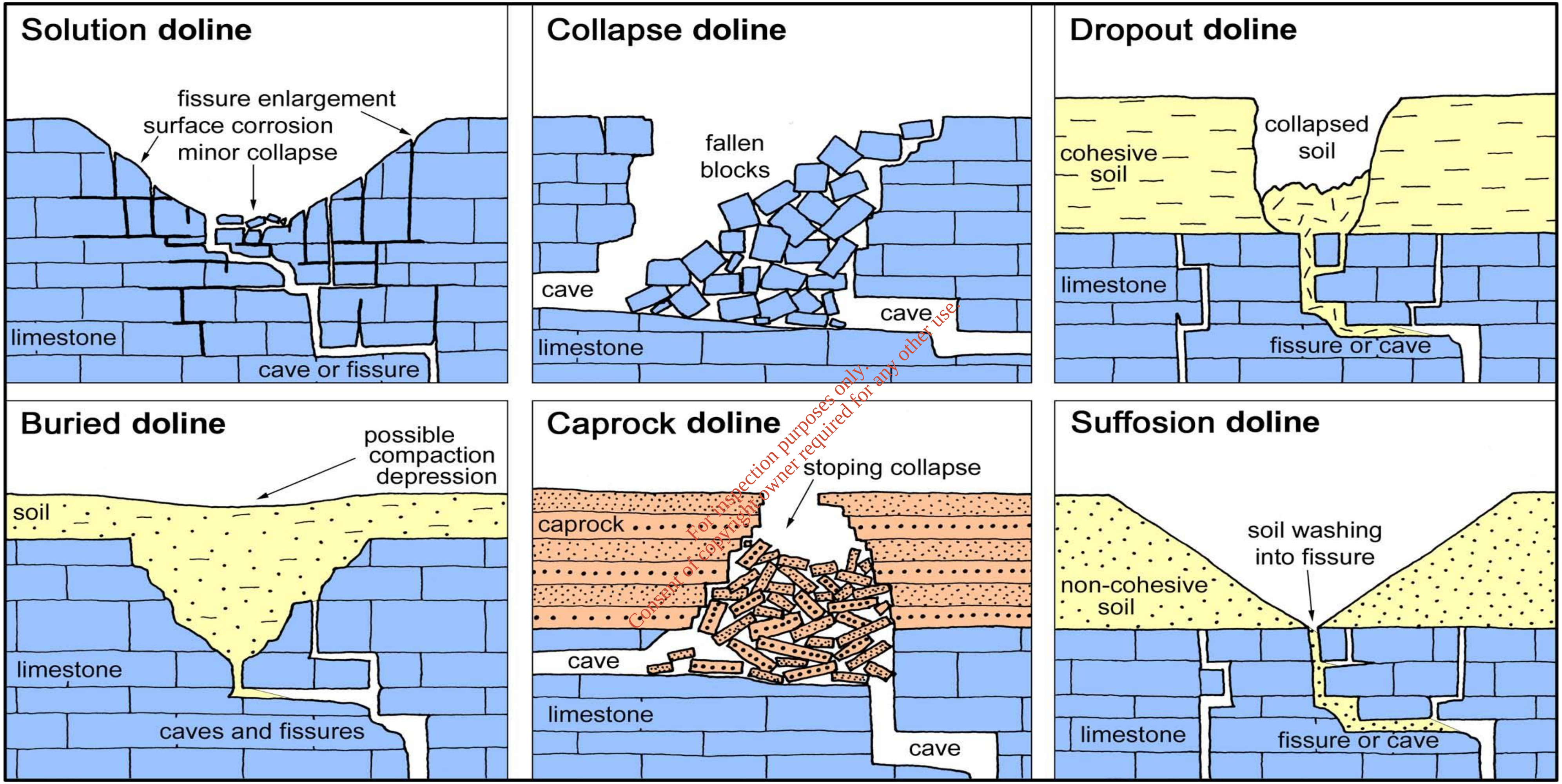
Source: Meehan and Kelly, 2011

Schlumberger
Water Services

Dolines in Thomastown, Co. Mayo

CLIENT:	Galmoy Mines Ltd.	PROJECT:	Hydrogeology		
JOB:	51471	DRAWN:	SS	CHECKED:	GB
DATE:	March 2014	FIGURE:	4.1		

P:\51471 Galmoy\600_Reports and Tech Memos\51471 R2 Sinkhole\Figures\Figure4.1to4.2_Sinkholes.xlsx



Source: Williams, 2004

Schlumberger
Water Services

Six main types of doline/sinkhole

CLIENT:	Galmoy Mines Ltd.	PROJECT:	Hydrogeology		
JOB:	51471	DRAWN:	SS	CHECKED:	GB
DATE:	March 2014	FIGURE:	4.2		

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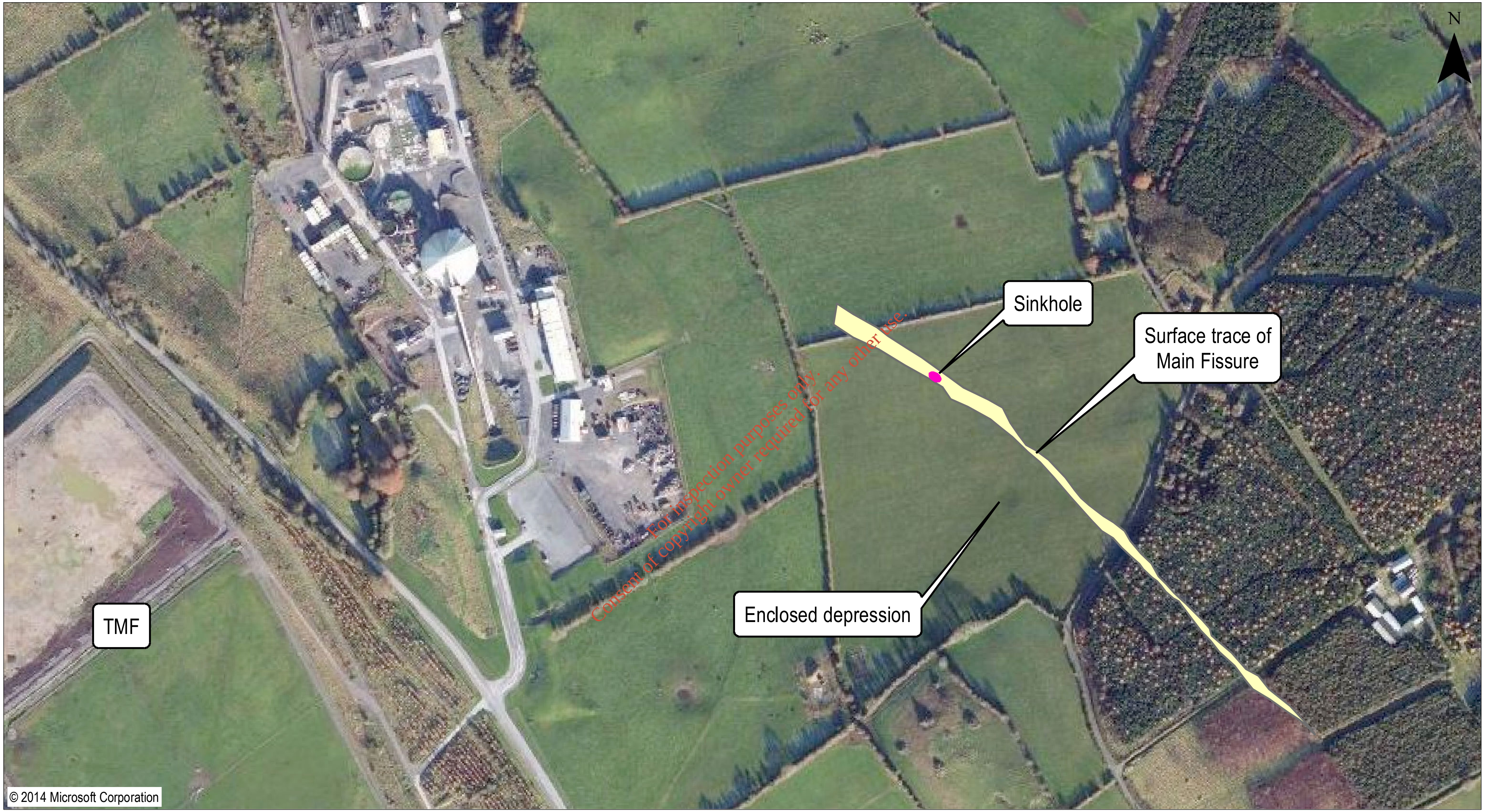

© 2014 Microsoft Corporation

Datum:TM65
Scale 1:5,000 at A4

0 100 200 Metres

Schlumberger
Water Services

Location of sinkhole relative to the Main Fissure

CLIENT:	Galmoy Mines Ltd.	PROJECT:	Hydrogeology		
JOB:	51471	DRAWN:	SS	CHECKED:	GB
DATE:	March 2014	FIGURE:	4.3		

Schlumberger
Water Services

Galmoy sinkhole

CLIENT:	Galmoy Mines Ltd.	PROJECT:	Hydrogeology		
JOB:	51471	DRAWN:	SS	CHECKED:	GB
DATE:	March 2014	FIGURE:	4.4		

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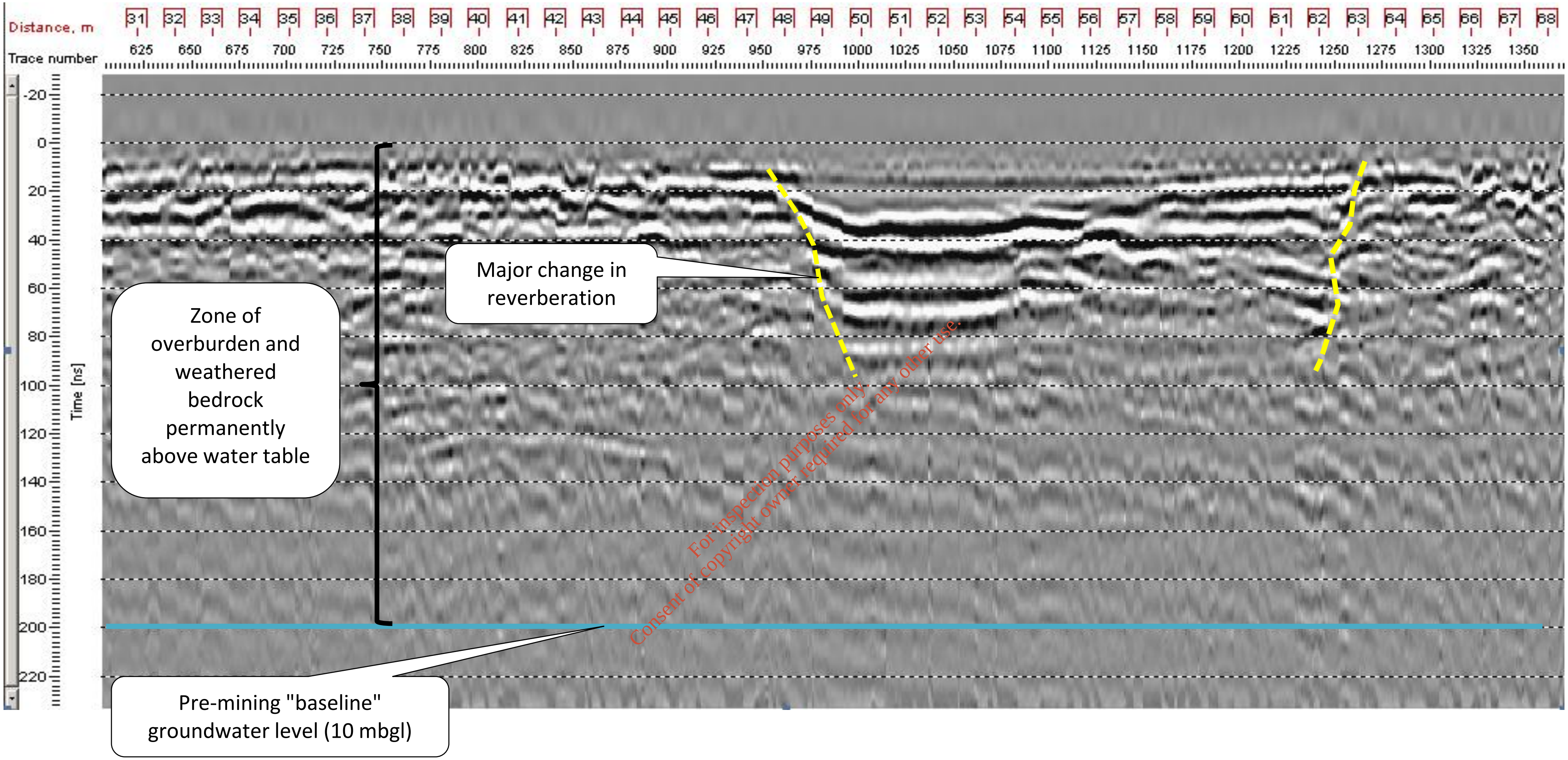

Image source: Golder Associates

Schlumberger
Water Services

GPR cross section of "enclosed depression"

CLIENT:	Galmoy Mines Ltd.	PROJECT:	Hydrogeology		
JOB:	51471	DRAWN:	SS	CHECKED:	GB
DATE:	March 2014	FIGURE:	4.5		

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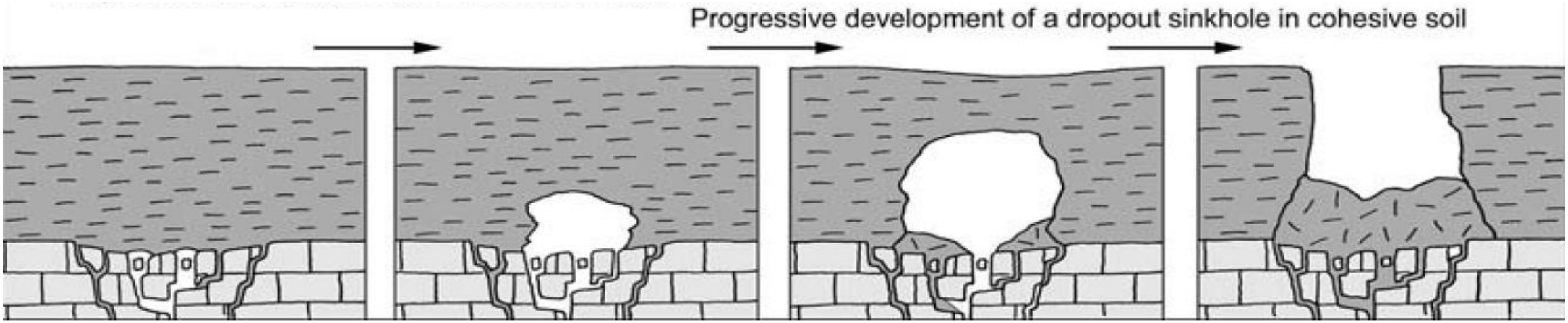

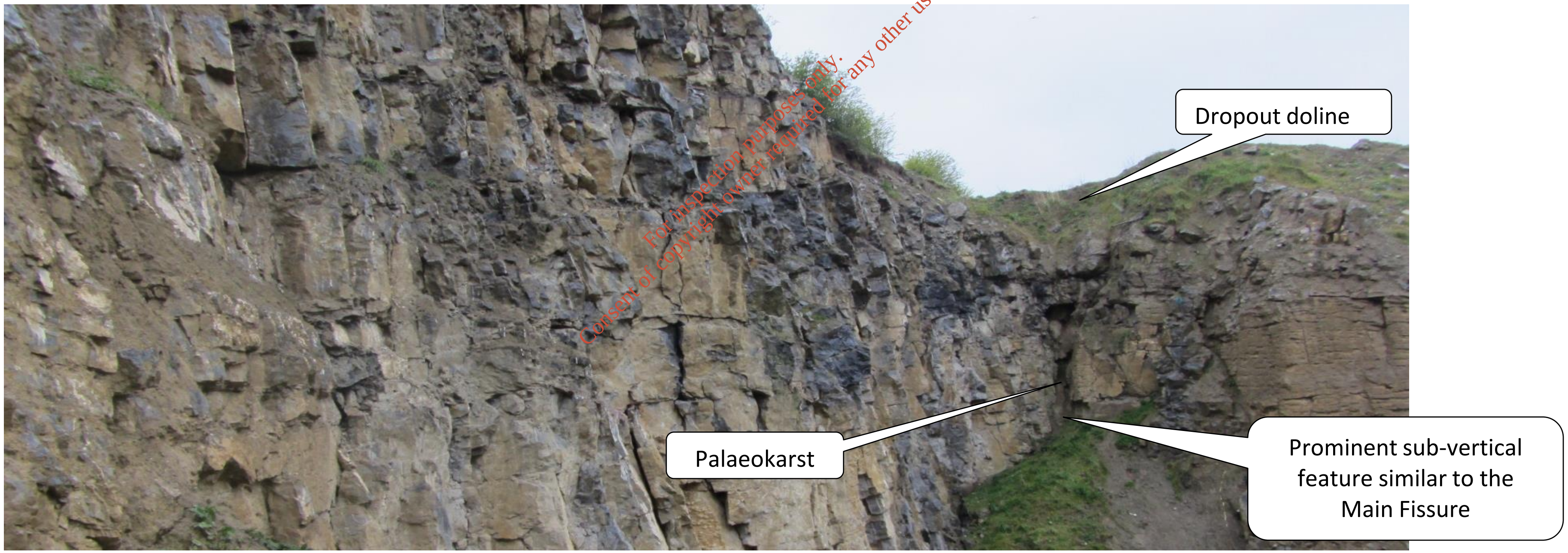

Sources: Waltham *et al.* , 2005
and University College Dublin

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Water Services

Dropout doline formation and cross sections

CLIENT: Galmoy Mines Ltd.
PROJECT: Hydrogeology
JOB: 51471
DRAWN: SS
CHECKED: GB
DATE: March 2014
FIGURE: 4.6

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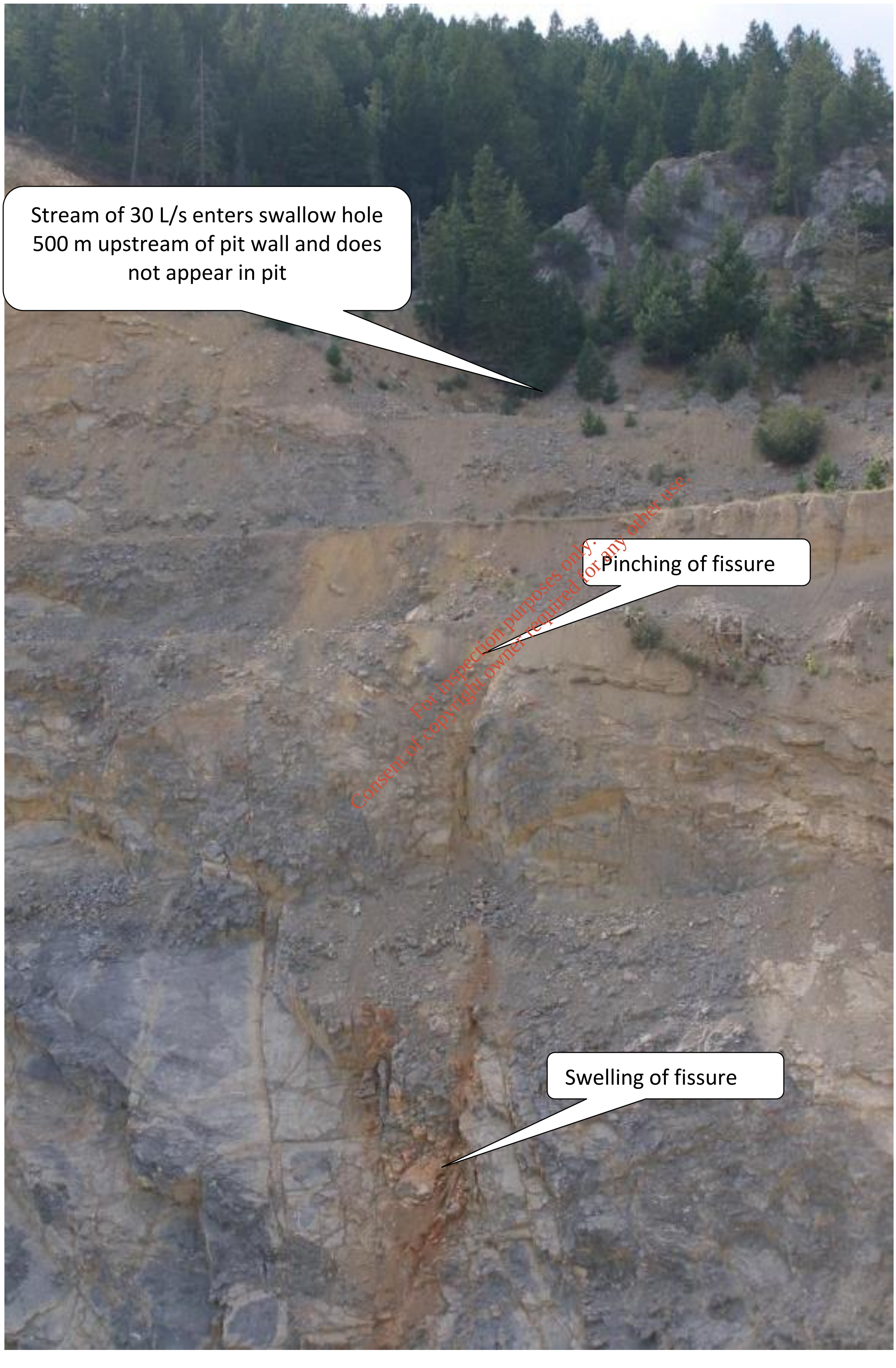

Example of disconnection between shallow and deep cavities

CLIENT: Galmoy Mines Ltd.
PROJECT: Hydrogeology
JOB: 51471
DRAWN: SS
CHECKED: GB
DATE: March 2014
FIGURE: 4.7

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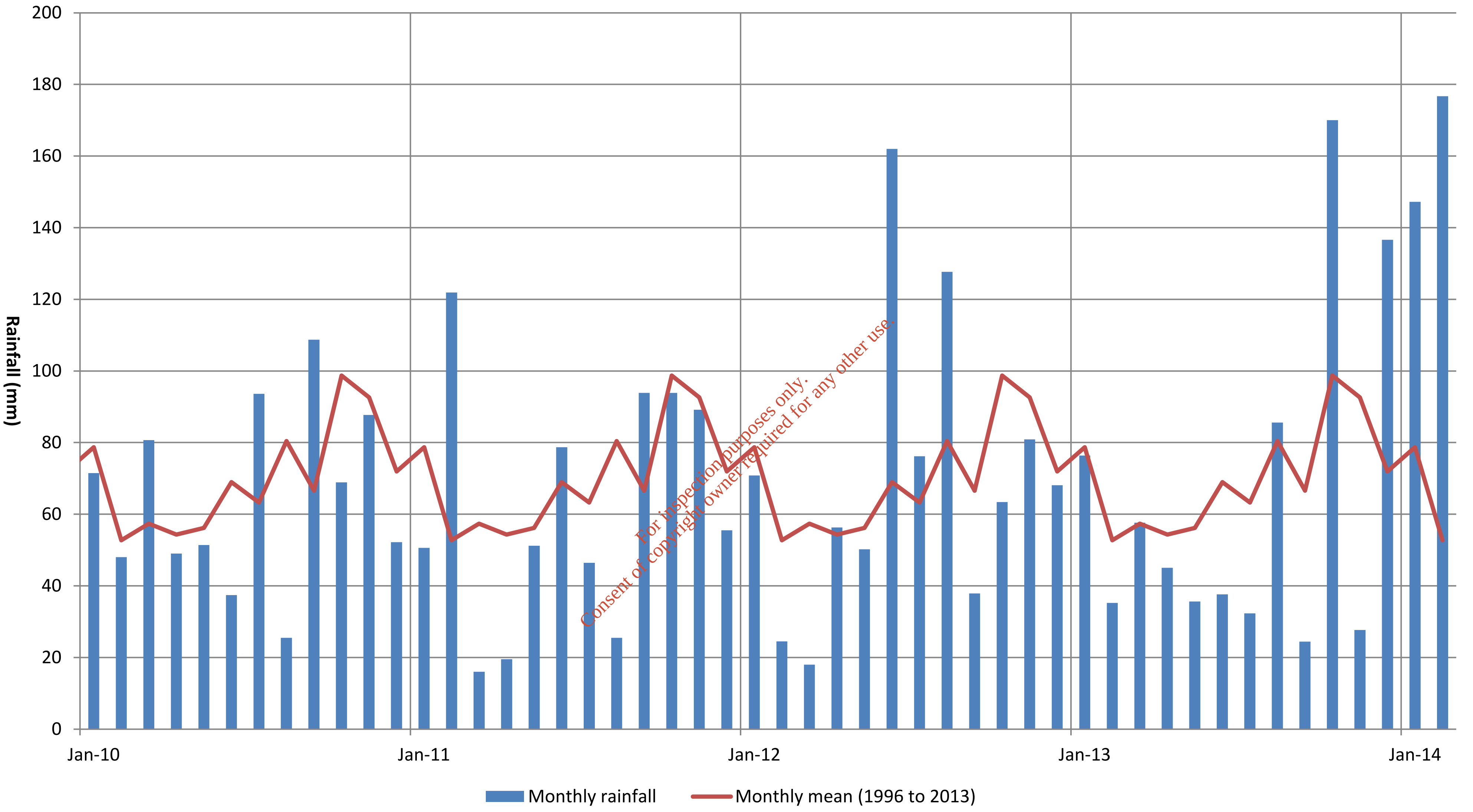

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Water Services

Monthly rainfall recorded at Oakpark, Co. Carlow

CLIENT:	Galmoy Mines Ltd.	PROJECT:	Hydrogeology		
JOB:	51471	DRAWN:	SS	CHECKED:	GB
DATE:	March 2014	FIGURE:	4.8		

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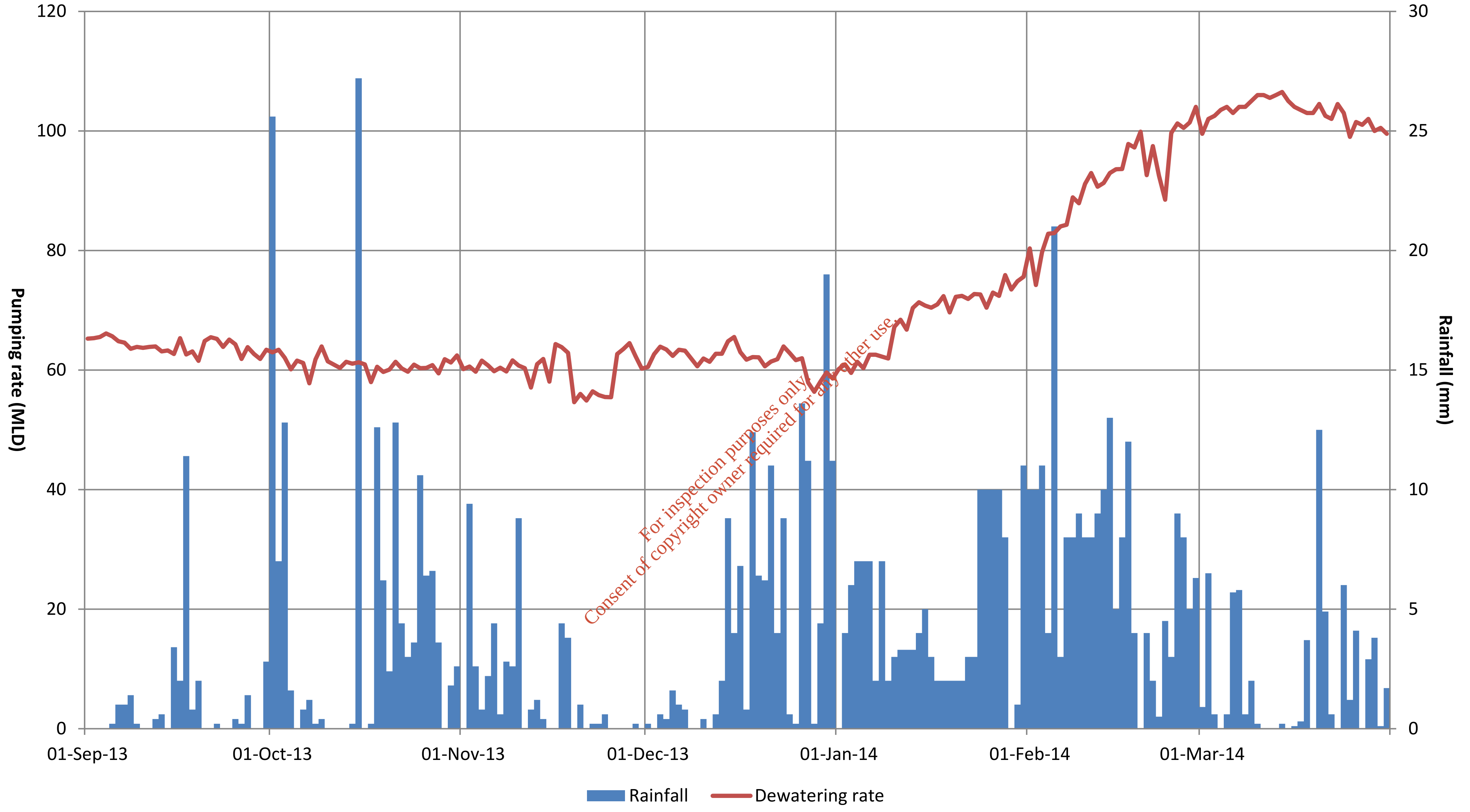

Schlumberger
Water Services

Recent rainfall and pumping rates at Lisheen Mine

CLIENT:	Galmoy Mines Ltd.	PROJECT:	Hydrogeology		
JOB:	51471	DRAWN:	SS	CHECKED:	GB
DATE:	March 2014	FIGURE:	4.9		

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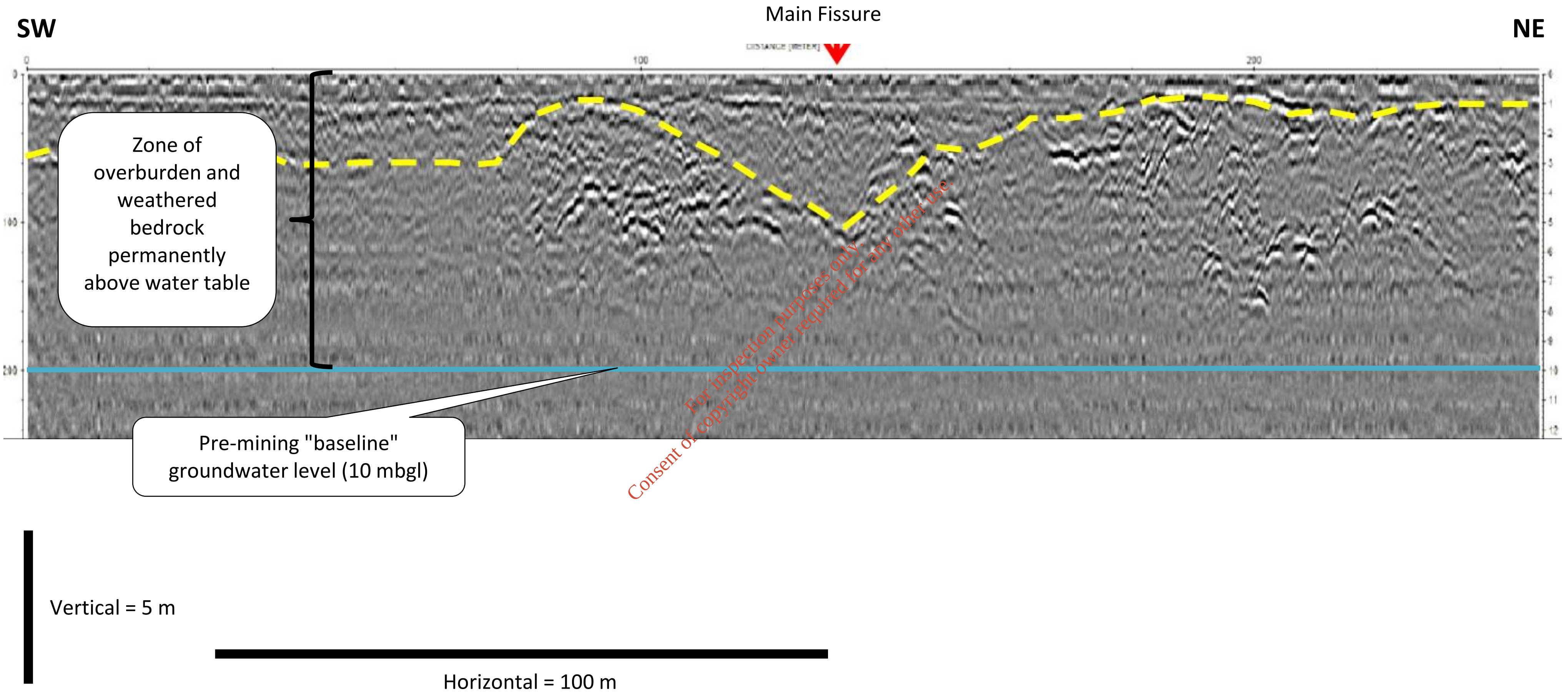

Schlumberger
Water Services

GPR cross section adjacent to the sinkhole

CLIENT: Galmoy Mines Ltd.
PROJECT: Hydrogeology
JOB: 51471
DRAWN: SS
CHECKED: GB
DATE: March 2014
FIGURE: 4.10

5 REFERENCES

Golder, 1992. Assessment of palaeokarstic feeatures on the development of the Galmoy project, Ireland. Report number IC3-2054. Golder Associates, USA.

Hickey, C., 2013. Sinkholes in Ireland. Geology Matters. Newsletter of the Geological Survey of Ireland. Issue 14, Summer 2013. Accessed at: www.gsi.ie/Newsletters/Sinkholes+in+Ireland.htm

Meehan, R. and Kelly, C., 2011. Karst mapping programme at Cregduff Spring, Ballinrobe, County Mayo. In: Managing Karst, proceedings for the IAH (Irish Group) 2011 annual field trip p 2-30.

Waltham, T., Bell, F. and Culshaw, M., 2005. Sinkholes and subsidence. Karst and cavernous rocks in engineering and construction. Springer and Praxis Publishing.

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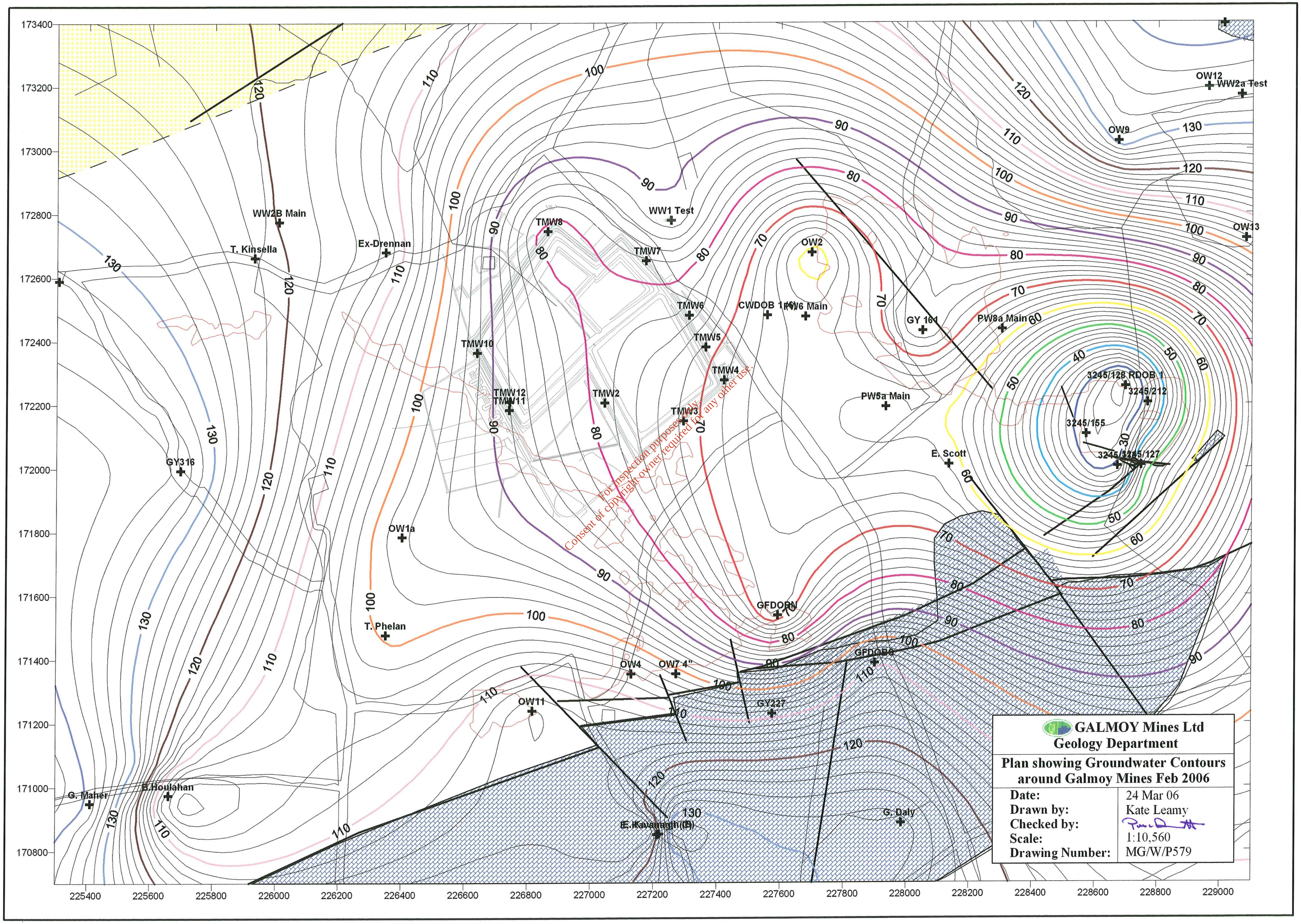
Appendix A
Plans showing groundwater contours around Galmoy Mines



GALMOY Mines Ltd
Geology Department

Plan showing Groundwater Contours around Galmoy Mines Feb 2006

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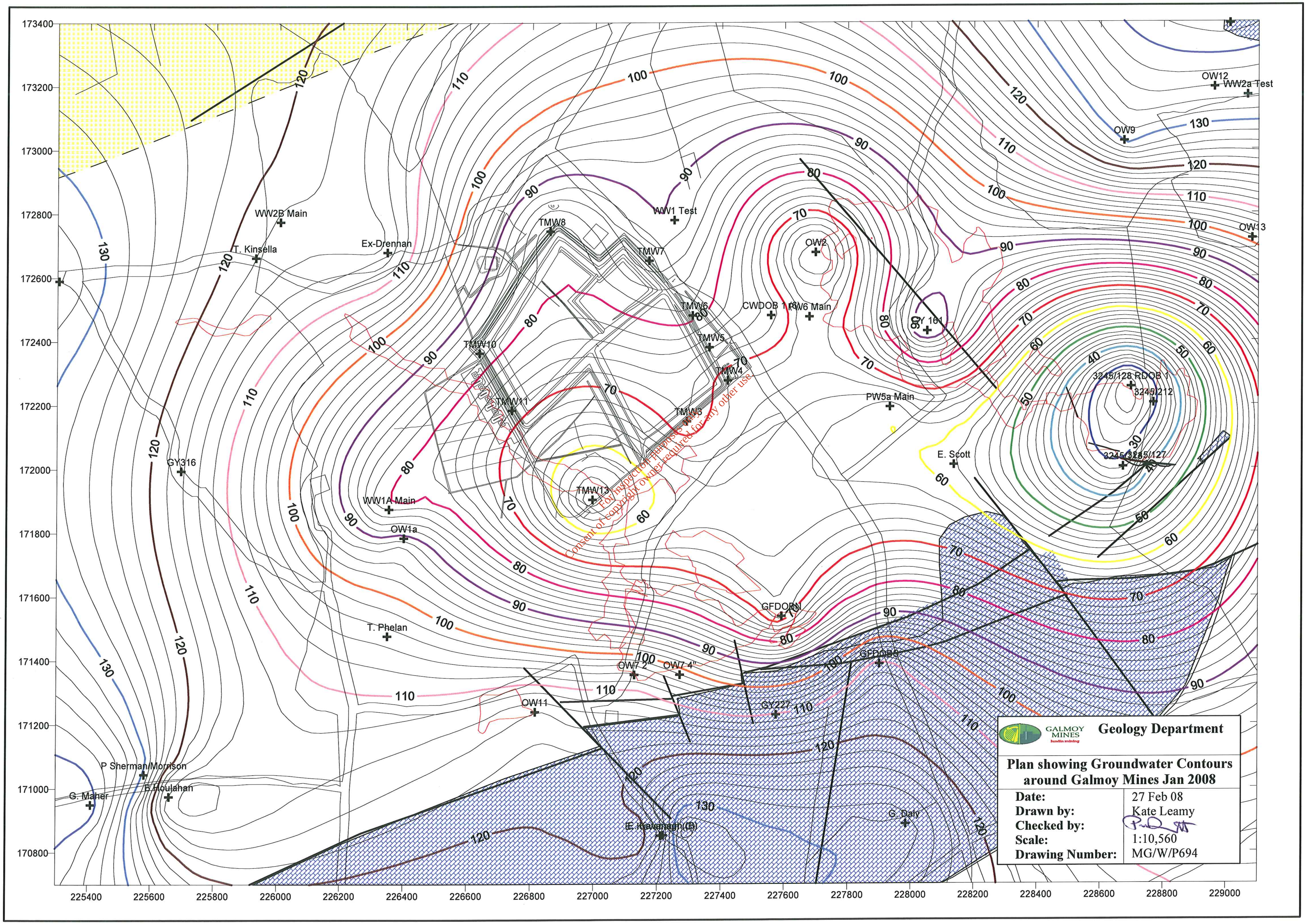
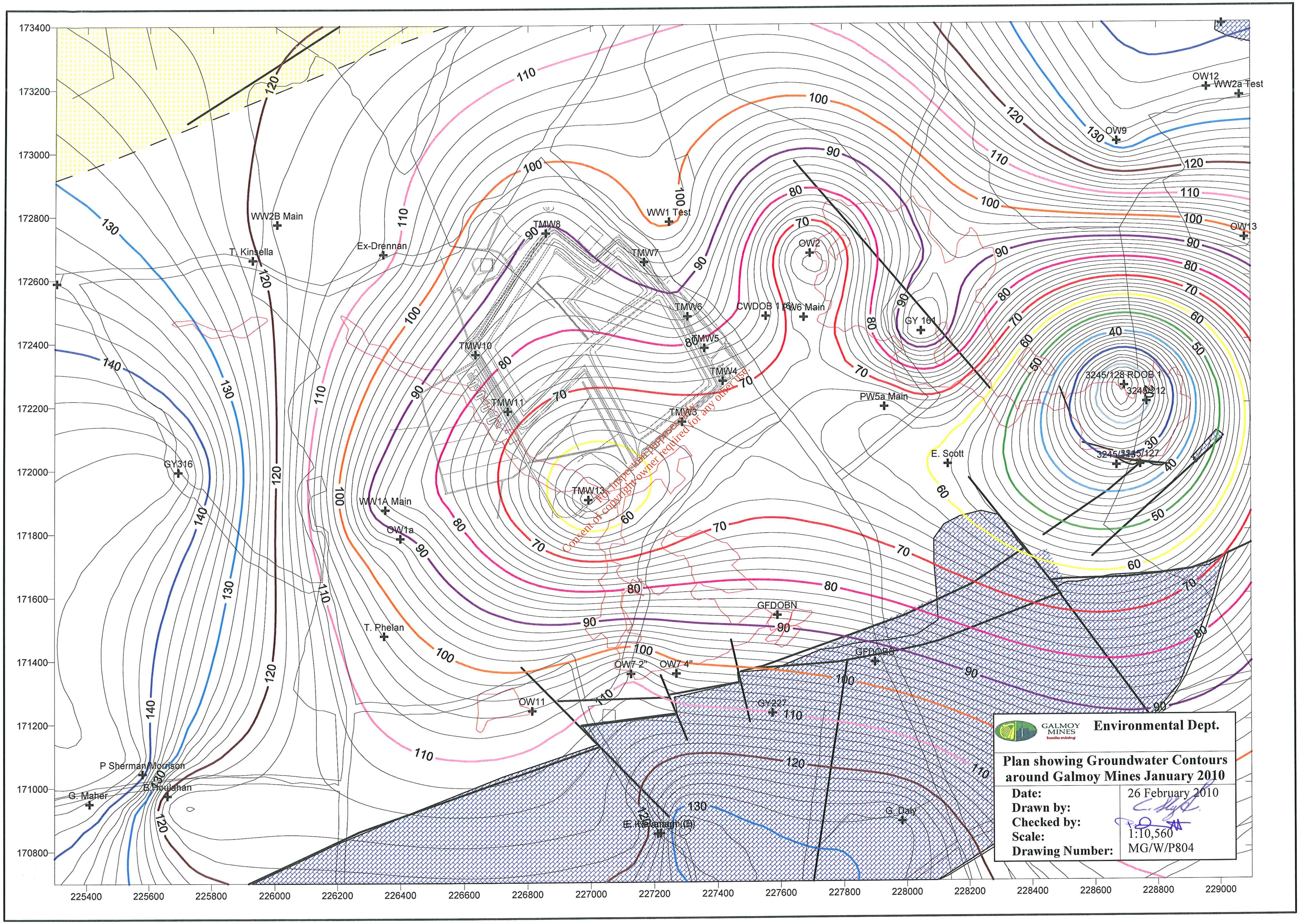
Drawn by:	Kate Leamy
Checked by:	
Scale:	1:10,560
Drawing Number:	MG/W/P579



Geology Department

Plan showing Groundwater Contours around Galmoy Mines Jan 2008

Date:	27 Feb 08
Drawn by:	Kate Leamy
Checked by:	
Scale:	1:10,560
Drawing Number:	MG/W/P694



Environmental Dept.

Plan showing Groundwater Contours around Galmoy Mines January 2010

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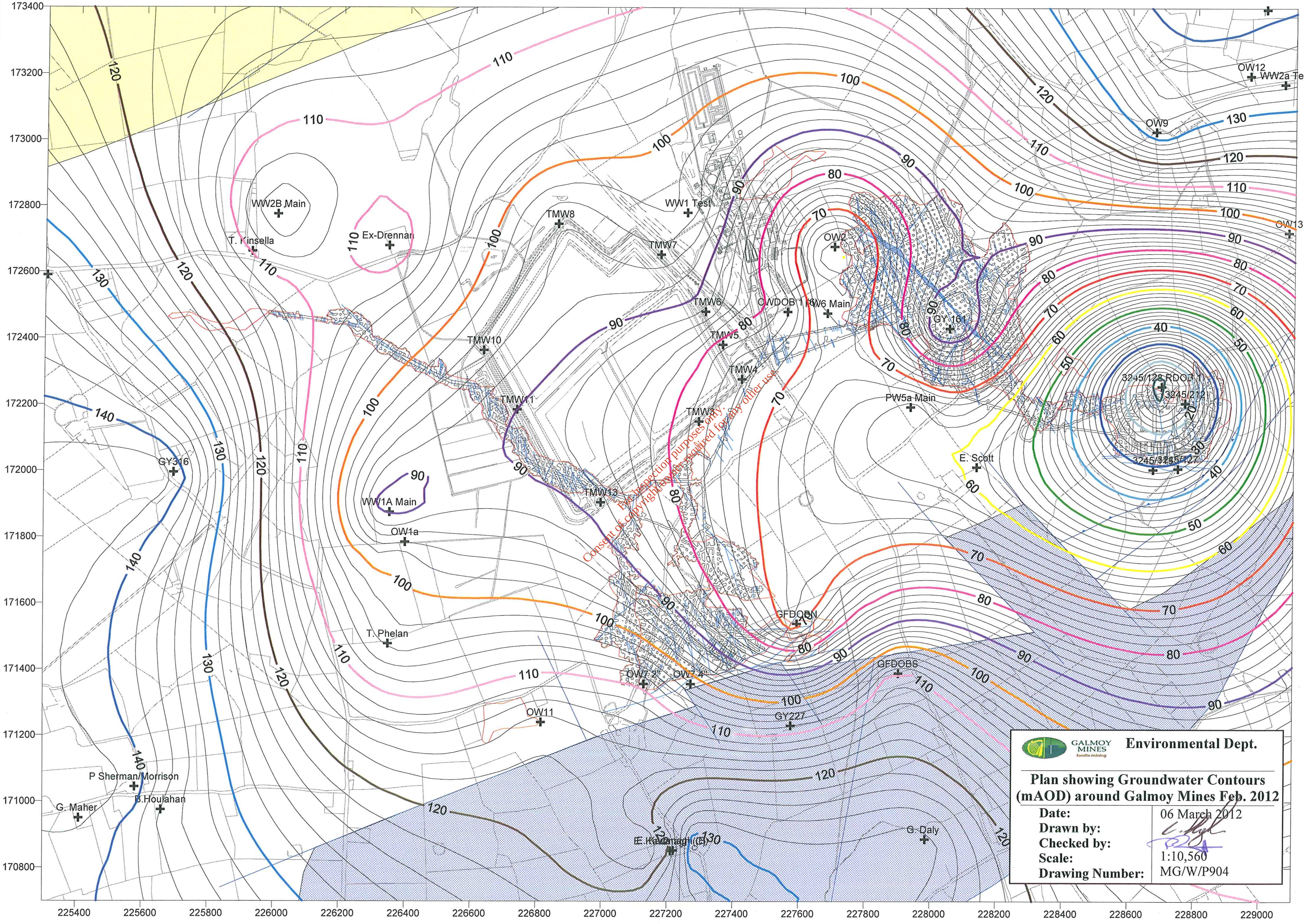
Checked by:
Scale: 1:10,560
Drawing Number: MG/W/P804

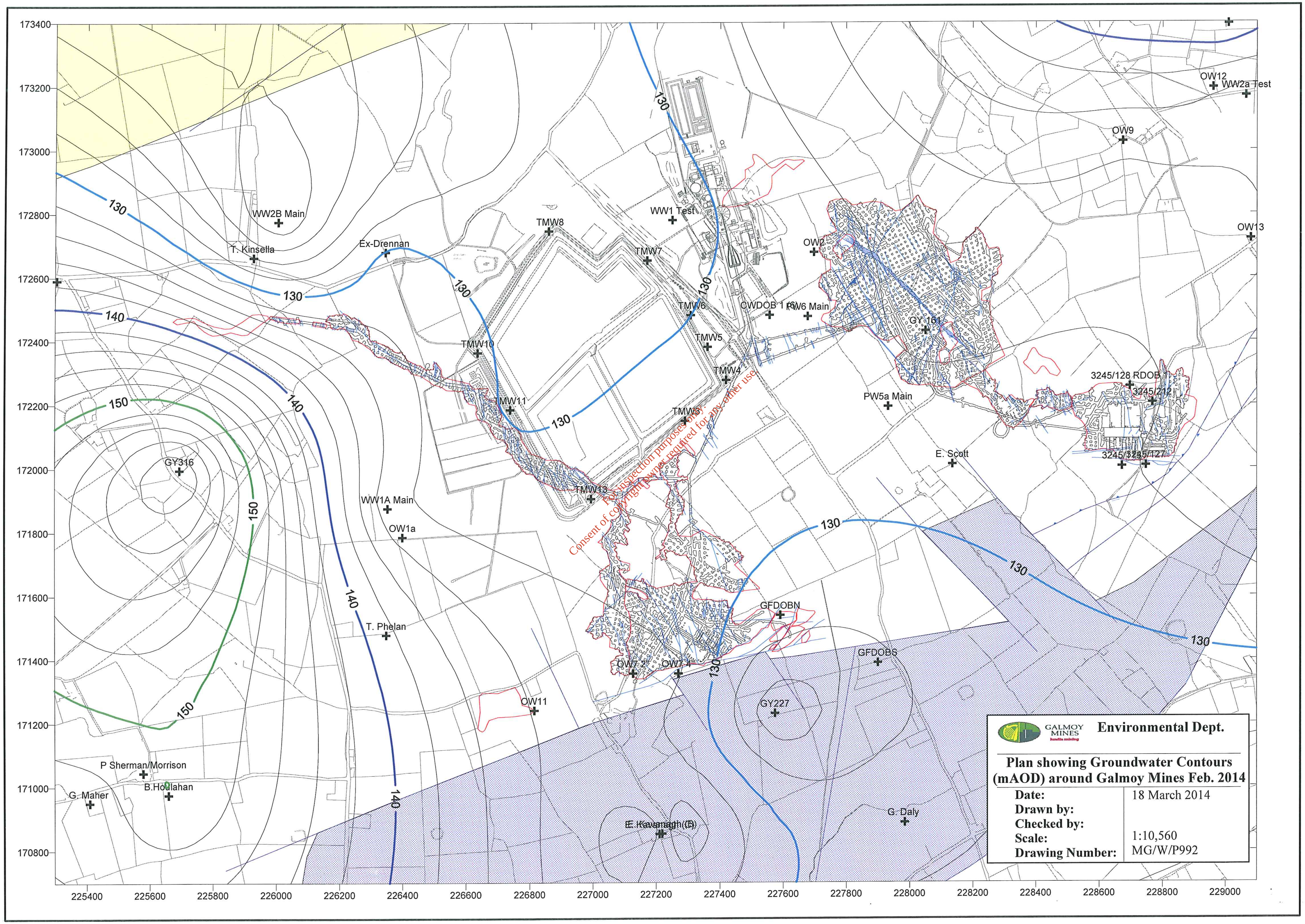


GALMOY MINES
lundin mining

Environmental Dept.

Plan showing Groundwater Contours (mAOD) around Galmoy Mines Feb. 2012

Date: 06 March 2012
Drawn by: C. Mgh
Checked by:
Scale: 1:10,560
Drawing Number: MG/W/P904



Environmental Dept.

Plan showing Groundwater Contours (mAOD) around Galmoy Mines Feb. 2014

Date:	18 March 2014
Drawn by:	
Checked by:	
Scale:	1:10,560
Drawing Number:	MG/W/P992

Appendix B

Exploration borehole logs from close to the sinkhole

GRAPHIC LOG

Page 1 of 5

HOLE NO. CN-2 GROUP ______ P.L. 586 T.D. 83.82m. CO-ORDS. ______ O.S. SHEET NO. ______

LOGGED BY I. Cowhurst STARTED ______ COMPLETED 5 June 87 ELEVATION 443.4' INCLINATION -90°

DEPTH	MINERALIZATION	SULF.	LITH.	DESCRIPTION	STRUCTURE	135-15m From	To	ASSAY RECORD Cu	Pb	Zn
Metres										
2										
4				0 - 6.10 metres. Overburden.						
6			35% Rec	6.10 - 7.62m Broken rubble pale grey dolomite.						
8			25% Rec	7.62 - 9.14m Similar broken rubbly dolomite.						
10			Cavity.	9.14 - 10.67m Recovery only fragments from above. Cavity						
12			Cavity	10.67 - 13.72m Rounded fragments etc, fell down hole? Cavity						
14				13.72 - 16.76m Few fragments of dolomite, otherwise Cavity.						
16			Cavity							
18			40% Rec	16.76 - 19.81m Broken rubbly pale grey dolomite						
20										

GRAPHIC LOG

HOLE NO. CN·2 GROUP ______ P.L. ______ T.D. ______ CO-ORDS. ______ Page 2 of ______
LOGGED BY ______ STARTED ______ COMPLETED ______ ELEVATION ______ O.S. SHEET NO. ______
INCLINATION ______

DEPTH	MINERALIZATION	SULF.	LITH.	DESCRIPTION	STRUCTURE	ASSAY RECORD From	To	Cu	Pb	Zn
			W.	19.91- 21·08 m. Brownish porous dolomite.						
22 metres			50% Rec.	21·03 - 24·08 m Broken rubbly pale gray dolomite, Not much breccia texture.	Sub vertical joints ↓					
24			60% Rec.	24.08 - 25.60m Broken pale gray rubbly dolomite.						
			cavity	25.60 - 25.91 Cavity						
26			35% Rec.	25.91 - 27.43' Rubble of pale gray dolomite.						
28				27.43 - 29.87m Broken rubbly pale gray dolomite. Minor stromatactic bands. Breccia but 500m.						
30				29.87 - 31.09m Rubble broken pale gray dolomite.						
32	Ox. pyrite		50% Rec.	31.09 - 32.00m Broken rubbly dolomite.						
34				32.00 - 35.05 Pale gray dolomite, less broken and rubbly than above. Stromatactic texture visible, minor white dol. breccia and veins	Sub vertical joints and shears.					
36				35.06 - 37.18 m. Pale gray mottled stromatactic dolomite with minor breccia bands	70° dipping planes.					
38				37.18 - 38.10 Pale gray stromatactic dolomite with minor white dolomite.						
40				38.10 - 41.16 m. Pale gray stromatactic dolomite with breccia bands	} very broken.					

GRAPHIC LOG

HOLE NO. CN. 2. GROUP ____ P.L. ____ T.D. ____ CO-ORDS. ____ Page 3 of ____
LOGGED BY ____ STARTED ____ COMPLETED ____ ELEVATION ____ O.S. SHEET NO. ____
INCLINATION ____

DEPTH	MINERALIZATION	SULF. Cu Pb Zn Ba	LITH.	DESCRIPTION	STRUCTURE	From	To	Cu	Pb	Zn	
42 metres			60% Rec.	manganese along micro fractures. 41.15 – 41.76 Broken dol. 41.76 – 43.59 m. Broken rubble.							
44			60% Rec. 50%	Dolomite, pale grey with cream blotchy appearance. Not much obvious breccia. Dark veinlets of Mn.; 43.59 - 44.20 m. Rubble pale grey dol.	very broken.						
46				44.20 - 47.24 m. mottled pale grey dolomite with cream patches. Dark veinlets of Mn still present. Some white dol. matrix							
48			50% Rec.	breccia. 47.24 - 48.16 m Broken pale grey dolomite							
50			85% Rec 60% Rec.	48.16 - 49.38 m Broken dolomite. Blotchy appearance. Mn Staining. 49.38 – 50.29' Broken rubbly dolomite Some fragments of white dol.	Several sub-vertical joints at 48.5 m. all very broken.						
52	minor oxidised pyrite.		75% Rec	matrix breccia. 50.29 – 52.73 m Solid dolomite still pale grey. white dol. matrix bx. at 51 m. Fresher and darker grey below 52.2 m.		50.29	52.73	—	—	<1	E1
54 sphalerite	? mass Zn. Fresh pyrite minor except for broken zone at end of run. Sphalerite in matrix and replacing clasts.			Dark grey dol. matrix breccia, no white dolomite below 52.2 m. 52.73 - 53.34 m. Dark grey dol. matrix bx. with slightly muddy bands. 53.34 - 55.17 m Breccia, pale clasts dark dol. matrix! minor	52.73 m broken.	52.73	53.34	—	—	6	E2
56	in matrix and disseminated in clasts. traces galena. All less than 5% py. short interval good Ab/Sp.		fault?	muddy bands. 56.17 – 55.70 Dark argillaceous lst. with calcarenite bands and crinoids, breccia texture. A. B. L. unit.	dip 35° Sheared broken zone, fault?	53.34 56.17	55.17 56.70	— —	<1 1	5 9	E3 E4
58	Bands of pale sphalerite and minor pyrite			56.70 – 59.44 m, Clean pale grey medium to fine calcarenite with crinoid debris. Breccia texture in places perhaps due to slumping. dark muddy seams at 58 - 58.4 m.		56.70	59.44	—	—	5	E5
60	Mineralisation predates muddy shears or slump planes.			59.44 - 59.9 m. Similar micrite.	? Steep 75° dips, Could be slumping.	59.44	59.9	—	—	3	E6

HOLE NO. CN.2 GROUP ______ P.L. ______ T.D. ______

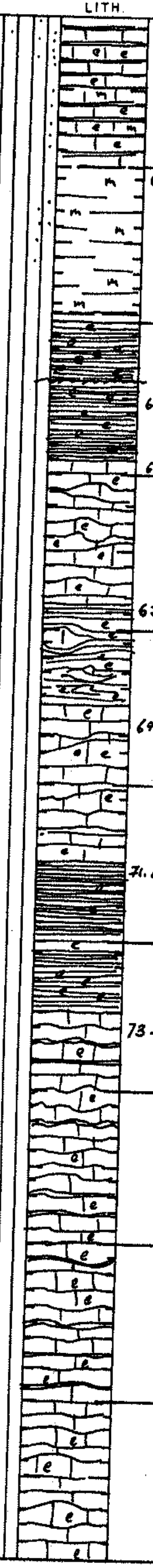
GRAPHIC LOG

Page 4 of ______

LOGGED BY ______ STARTED ______ COMPLETED ______

CO-ORDS. ______ O.S. SHEET NO. ______

ELEVATION ______ INCLINATION ______

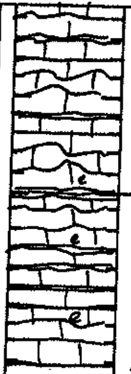


DEPTH	MINERALIZATION	SULF.	LITH.	DESCRIPTION	STRUCTURE	ASSAY RECORD				
						From	To	Cu	Pb	Zn
Metres. 62	traces Zn. minor Zn in veins.			59.9 - 60.96m. Dark muddy crinoidal lst. with calcarenite beds, 60.96 - 62.0m muddy crinoidal lst. with micrite beds.	60.8 broken.					
64	minor sphalerite along veins			62.0 - 63.9m Crinoidal micrite to fine calcarenite with shaly partings.	dip 23° calcite veins.					
66				63.9 - 64.8m Black crinoidal mudstone. minor fault.? 64.8 - 66.4 Black mdstn.	steeper dips c 55° gouge. Dip 30°					
68				66.4-67.67 m. Nodular bedded crinoidal calcarenite and black argillaceous lst.						
70				67.76 - 69.0m Black crinoidal mudstones with lenses calcarenite. Some corals and bryozoans as well as crinoids. 69.0 - 71.0 Nodular bedded crinoidal calcarenite and black argillaceous lst.	dip 40°					
72				71.0 - 73.0m Dark shaly argillaceous lst.-calc. mdstn. Scattered crinoid ossicles, abundant bryozoans // bedding.	calcite veins.					
74				73 - 83.82m Dark argillaceous limestones with nodular	dip 5°					
76				bedded calcarenites. Crinoids, corals, brachiopods and bryozoans						
78					dips c15°. dog tooth Ca vein. black specks in Ca.					
80					bitumen?					

GRAPHIC LOG

HOLE NO. CN.2 GROUP P.L. T.D. CO-ORDS. Page 5 of 5
LOGGED BY STARTED COMPLETED ELEVATION O.S. SHEET NO.
INCLINATION

DEPTH	MINERALIZATION	SULF.	LITH.	DESCRIPTION	STRUCTURE	From	To	ASSAY RECORD Cu	Pb	Zn
82										
84				E.O.H.						

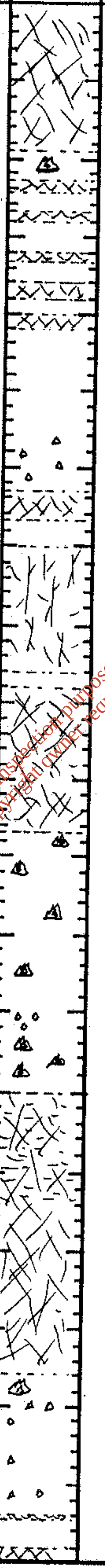


PROJECT/PL. No. Galmoy PL. 586
HOLE No. GV 119 T.D. 355'
ATTITUDE Vert.
GRID E
GRID N
ELEVATION 458·9' (139·87m
START 17th Feb 88 COMP. 22nd Feb 88
LOGGED A.A.B. DATE 2nd March 88
SCALE 1" = 10'
Page 1 of 4

DEPTH	LITHOLOGY DESCRIPTION	STRAT.		%	%	%	%	%	MINERALIZATION DESCRIPTION	ASSAY SECTIONS
10	0 – 29 Casing 0 – 25' Overburden.									
20										
29' — 30	25' – 29' Bored rock. 29'–233' Pale Buffish Gray Dolomitised									
Box 1 40	Waulsortian with ubiquitous creamy dol. veining, brecciation and briated stromatactis (In general the core is quite broken and only very broken to rubble have been noted on the graphic log.) 29'–35' 15% recovery 35–45' 80% recovery.									
49' — 50	45'–55' 65% recovery 47·5'–49' core quite brown oxidised/weathered [illegible]? with laminated contorted shaly section at 47·5'.									
2 60	55'–65' 100% recovery									
63·5' 3 70	65'–75' 100% recovery.									
75' 80	75'–85' 100% recy.									
4 88·5' 90	85'–94'(?) 100% (note tags change from being at the –5' mark to –4'; strange. is this a drillers mistake – possibly everything should be 1' deeper than recorded from this point on)									
5 99' — 100	93'–94·5' Briated stromatactis with bryozoan fronds very prominent darker grey than normal. 94'–104' 90% recovery. 94·5–104·5 very rubbly.									

CONROY PETROLEUM AND NATURAL RESOURCES P.l.c.
DIAMOND DRILL LOG

PROJECT/P.L. No. ____________ GRID E ____________ START ________ COMP. ______
HOLE No. CY 119 T.D. ________ GRID N ____________ LOGGED ________ DATE ______
ATTITUDE ____________ ELEVATION ____________ SCALE ________ Page 2 of 4

DEPTH	LITHOLOGY				MINERALIZATION						ASSAY
100'	DESCRIPTION	STRAT.			%	%	%	%	%	DESCRIPTION	SECTIONS
6 109.5 110	104'–114' 100% recovery ?										
7 120	110.5' Briated Stromatactis with prominent primary cavity sets. 114'–124' 100% recovery.										
121 8 130	124'–134' 95% recovery.										
135.5 140	134'–144' 90% recovery. 135'–143' Broken around sub vert joints.										
9 149 150	144'–154' 80% recovery. 144'–153.5' very rubbly stained yellow, limonite and some rusty surfaces.										
10 160	1535–170 Briated stromatactis with quite prominent briated other primary cavity sets. esp. 164–170 154–164 100% recovery										
162' 11 170											
173 12 180	170 – 188 very broken with top 7' covered in brown clay.										
184.5 190											
13 197.5 2 100											

CONROY PETROLEUM AND NATURAL RESOURCES P.l.c.
DIAMOND DRILL LOG

PROJECT/P.L. No. ____________ GRID E ____________ START ________ COMP ________
HOLE No. CY 19 T.D. ________ GRID N ____________ LOGGED ________ DATE ________
ATTITUDE ____________ ELEVATION ____________ SCALE ________ Page 3 of 4

DEPTH 200'	LITHOLOGY DESCRIPTION	STRAT.		MINERALIZATION DESCRIPTION	ASSAY SECTIONS
14					
210 210					
15	214.5 - 216 rusty joint surface at top of broken section. 217.5 - 223 darker gray section with prominent				
220					
-223' -	223 - 223.5 minor rock matrix bx			rusty pyrite specks in bryozoan bx.	
16 230					
	230-233 bx with creamy dol matrix + minor buff r.m. some darker clasts derived from primary cavity seds. 233-270 The creamy dol. veining decreases and is not as common or prominent as above. The bx tends to flow less distinct and blending into buff r.m.b. 234-235 rusty joint.				
-237' -					
240					
17					
250 249.5 -	250-253 Slightly darker gray than usual very fine bx possibly broken up bryozoans.				
18					
260 260					
19					
270				rusty pyrite in sub vert irreg joint.	
	270'-279.5' Generally oxidised tan r.m.b originally quite muddy but with only minor rusty pyrite.			270-279.5 numerous specks of rusty pyrite throughout but not of much significance in quantity.	
-274 -					
	279.5-285 V. broken but fragments of partly oxidised and partly grey dol. with r.m.b. 291.5-284.5 4' cavity reported.			6" leached slight oxidised but mainly fresh pyrite and grey dol.	
280					
20	285-294.5 Cavity Filled sand consisting of rusty disintegrated sulphide probably mainly massive pyrite.			285-294.5 Disintegrated sulphide probably mainly pyrite. Note sample is a grab sample	285 0863 294.5
290					
	294.5 -355 ABL. 294.5 -303 Wavy bedded to nodular pale micrite in black calc' mudstone with hints of chert.		thin gouge greenish along bedding Dip 15°		
-298 -					
300					

CONROY PETROLEUM AND NATURAL RESOURCES P.l.c.
DIAMOND DRILL LOG

PROJECT/P.L. No. ____________ GRID E ____________ START ________ COMP. ________
HOLE No. GY119 T.D. ________ GRID N ____________ LOGGED ________ DATE ________
ATTITUDE ____________ ELEVATION ____________ SCALE ________ Page 4 of 4

DEPTH	LITHOLOGY DESCRIPTION	STRAT.			MINERALIZATION %	%	%	%	%	DESCRIPTION	ASSAY SECTIONS
300'											
21 -305- 310	303-320.4 Crinoidal (larg) micrites in dark calc. mudstones. 305-307 almost conglomeratic rounded nodule clasts of micrite with mudstone partings and large crinoids		Dip 15°								
22 320	212 black gouge 213.5 slightly gougy disintegrated hard black mudstone.		black gouge at 40° Dip 5°								
23 330	320.5-355 Nodular to wavy bedded micrites set in dark calc. mudstone (predominant and increasingly so downwards). The black mudstone contains scattered crinoids, and diffuse laminae of comminuted bioclastic debris, calcarenite or bryozoa. Single corals are rare.										
-334- 340	332 minor gouge at base of pinkish calcite vein 333.5 ditto. 335 minor gouge along bedding. 336 ditto. 339.5-341 very gougy. pink calcite, poss minor fault.										
24 -348'- 350	348.5-350 very broken sub-vert gouge + pink calcite very minor faults.		Dip<5°								
25 -355- 360	352'-353 broken core mainly pink calcite End of hole.										
70											
80											
90											
100											

CONROY PETROLEUM AND NATURAL RESOURCES P.l.c.
DIAMOND DRILL LOG

PROJECT/P.L. No. Galmoy PL 586 GRID E ______ START 11-3-88 COMP 22-3-88
HOLE No. G/130 T.D. 314 GRID N ______ LOGGED A.A.B. DATE 7-4-88
ATTITUDE Vert. ELEVATION 449.58' (137.03 m) SCALE 1" = 10' Page 1 of 4

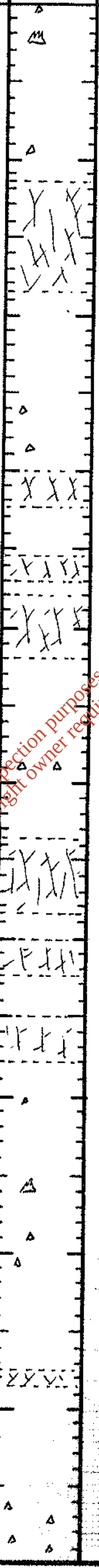
DEPTH	LITHOLOGY			MINERALIZATION						ASSAY
	DESCRIPTION	STRAT.		%	%	%	%	%	DESCRIPTION	SECTIONS
10	0-30 Casing.									
20										
30 30										
1 40	30 - 218.5 Pale buffish grey dolomitised Waulsortian with creamy dol. veining, bx and bxiated stromatactis. However, bxiation not very developed in this hole. 34'-44' 90% recovery. 35-36 Minor bx with final fill of Ferroan									
-44- 50	dol. & calcite. 44'-54' 10% recovery although no recorded cavities.									
2 60	54-64 30% recovery									
70	64-74 100% recovery.									
-75- 80	74-84 50% recovery.									
3 90	84-94 100% recovery. 89-90 Well preserved Waulsortian fabric									
-93- 4 100	94-104 100% recovery. 95 pinkish rhombs of dol. in vugs. 99' bxiated stromatactis with prom. dk primary cavity sed Surrounding rock sugary.									

CONROY PETROLEUM AND NATURAL RESOURCES P.l.c.
DIAMOND DRILL LOG

PROJECT/P.L. No. ____________ GRID E ____________ START ________ COMP ________

HOLE No. GY 130 T.D. ________ GRID N ____________ LOGGED ________ DATE ________

ATTITUDE ____________ ELEVATION ____________ SCALE ________ Page 2 of 4



DEPTH	LITHOLOGY		MINERALIZATION						ASSAY
100	DESCRIPTION	STRAT.	%	%	%	%	%	DESCRIPTION	SECTIONS
4 - 107 - 10	102.5 Waulsortian Fabric 104 - 114 100 % recovery. 108.5 thin grey dol. vein at 35° to l.c.a.								
5 - 119 - 20	111.5 - 118.5 Quite broken around sub-vert. joints some slightly rusty. 114 - 124 100% recovery.								
6 - 124 - 30	124 - 134 100 % recovery.								
7 - 137 - 40	134 - 144 100 % recovery 137 rather diffuse brixated stromatactis with diffuse dark primary cavity sed.								
8 50	144 - 154 100 % recovery.								
- 151.4 - 9 60	154 - 164 100 % recovery.								
- 165 - 70	164 - 174 100 % recovery. 168 - 184 small patches of brown weathering pos. picking out muddier mottles								
10 - 177 - 80	172.5 rusty joint at 20° to l.c.a. 174 - 184 100 % recovery. 176 rather diffuse stromatactis but unbriated though infilled with creamy dol.							rust in joint may be rusty pyrite.? small blob of rusty pyrite.	
11 90	184 - 194 100 % recovery. 186 - 197 vertical joint. 187.5 - 188.5 Broken around sub-vert. joint with rusty staining.								
- 191 - 12 100	194 - 204 100 % recovery. 196 - 225 Comparatively well developed bx								

CONROY PETROLEUM AND NATURAL RESOURCES P.l.c.

DIAMOND DRILL LOG

PROJECT/P.L. No. ____________ GRID E ____________ START ________ COMP. ______

HOLE No. GY 130 T.D. ________ GRID N ____________ LOGGED ________ DATE ______

ATTITUDE ____________ ELEVATION ____________ SCALE ________ Page 3 of 4

DEPTH	LITHOLOGY DESCRIPTION	STRAT.	%	%	%	%	%	MINERALIZATION DESCRIPTION	ASSAY SECTIONS
12 206 10	204 - 214 100 % recovery							speck of rusty pyrite	
13 20 220	214 - 224 100 % recovery. 216·5 - 217·5 Bxiated stromatactis 218·5 - 279 Predominantly buffish to tan (oxidised) but with patches of grey dol.							specks rusty and fresh pyrite specks of rusty pyrite in trains lining bx. rusty pyrite. fresh pyrite in grey patch rusty and fresh pyrite.	
14 NQ 30 230	traces of r.m.b esp. towards base of section 220-229 bxiated stromatactis breaking into tan bx 224-234 90% recovery. At 230' rods became stuck-no obvious reason							rusty pyrite speck rusty pyrite in thin creamy dol. vein.	
BQ 15 40	from core. Reduced to BQ 232·5 Grey dol. with darker prom. bryozoa 234 - 244 80% recovery. 236 - 237 Bx with x cutting thin dol vein crossing bxiated stromatactis.								
246 50	244-254 75% recovery.							rusty pyrite	
16 60 260	254 - 264 90 % recovery. 259 - 260 prominant dk primary sed. in bx								
17 70	264 - 274 100 % recovery. 267 - 268 very dark grey with bx and Waulsortian fabric.							speck of rusty pyrite.	
80	274 - 284 90 % recovery. 279 - 296 Mainly Grey dol. Waulsortian							rusty pyrite specks 279 - 294 pyrite in	
280·5 18 90	with r.m.b. (slight oxidation in some patches and minor creamy to pinkish dol. veining with bx slightly more angular, more crackle, than usual. Pyrite in rock matrix common. 284 - 294 90 % recovery.							rock matrix common though not massive.	
100	292 - 294 Bx with pinkish dol aswell as r.m. 294 - 204 75 % recovery. 296 - 314 ABL. (wavy bedded micrite in dk. calc. mudstone) 296' - 300' Very broken only 1' of core recovered.							294 - 296 Mainly pyrite with some pink dol.	

CONROY PETROLEUM AND NATURAL RESOURCES P.l.c.

DIAMOND DRILL LOG

PROJECT/P.L. No. ____________ GRID E ____________ START ________ COMP ______
HOLE No. CY 130 T.D. ________ GRID N ____________ LOGGED ________ DATE ______
ATTITUDE ____________ ELEVATION ____________ SCALE ________ Page 4 of 4

DEPTH	LITHOLOGY DESCRIPTION	STRAT.			MINERALIZATION %	%	%	%	%	DESCRIPTION	ASSAY SECTIONS
300'											
303.5 19 10	303½-314' 100% recovery. 305-306 large cavities packed with soft nodules of micrite. 308.5 pinkish white calcite vein at 45° pos. some movement		Dip 5°								
314	End of hole.		Dip 10°								
20											
30											
40											
50											
60											
70											
80											
90											
100											

CONROY PETROLEUM AND NATURAL RESOURCES P.l.c.
DIAMOND DRILL LOG

PROJECT/PL No. Galmoy PL586 GRID E 227757.75 START 1-6-88 COMP 3-6-88
HOLE No. GY171 T.D. 320' GRID N 172648 LOGGED A.A.B. DATE 20-6-88
ATTITUDE Vert. ELEVATION 464.5' (141.57m) SCALE 1"=10' Page 1 of 4

DEPTH	LITHOLOGY DESCRIPTION	STRAT.	%	%	%	%	%	MINERALIZATION DESCRIPTION	ASSAY SECTIONS
10	0-28' Casing.								
20									
28 30	28'-294.5' Mainly Pale Buffish								
Box 1 40	Grey Dolomitised Waulsortian with creamy dol. veining bx and bxiated stromatactis. Bx quite well developed. Core generally quite broken. 28-55 generally with little bx.								
47 50	28-34 80% recovery 30.5-33.5 rubbly 34-44 40% recovery 37'-43' Clay filled cavity recorded. 44'-54' 100% recovery.								
2 60	55' bxiation increase downwards.								
62 3 70									
76 4 80									
83 5 90	86-91 slightly broken due mainly to sub-vert irreg. joints.								
97 100	97-109.5 Extremely broken almost rubbly but fragments tend to be sharp angular and therefore probably highly jointed in situ.								

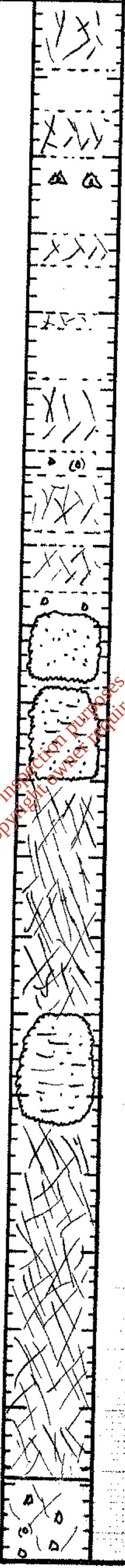
CONROY PETROLEUM AND NATURAL RESOURCES P.l.c.
DIAMOND DRILL LOG

PROJECT/P.L. No. ____________ GRID E ____________ START ________ COMP. ______
HOLE No. CY171 T.D. ________ GRID N ____________ LOGGED ________ DATE ______
ATTITUDE ____________ ELEVATION ____________ SCALE ________ Page 2 of 4

DEPTH 100'	LITHOLOGY DESCRIPTION	STRAT.		%	%	%	%	%	MINERALIZATION DESCRIPTION	ASSAY SECTIONS
6 10	109.5 minor sand recoved possibly small cavity none recorded.									
111 7 20	112-114 minor brecciated stromatactis with thin but prominent primary cavity sed. 115.5 - 126.5 Slightly broken									
124 8 30									small single blebs of rusty pyrite.	
136 40										
9 149 50	146 - 197.5 well developed bxs.									
10 60									speck of rusty pyrite	
162 11 70	162 - 164 Bx with quite large grey dol. clasts with matrix tending to be creamyish, i.e. prob. a fine mixture of creamy dol and fine r.m. 168 - 169.5 buff dol. with diffuse bx.								very minor speck of rusty pyrite	
176 80	171.5 - 174 Bx with grey dol. clasts. 177 - 180 slightly broken									
12 189 90									minor rusty pyrite lining edge of bx.	
13 100	192 - 194 limonitic sub.vert joints 197 - 204.5 quite broken slightly limonitic.									

CONROY PETROLEUM AND NATURAL RESOURCES P.l.c.
DIAMOND DRILL LOG

PROJECT/P.L. No. ____________
HOLE No. GY 171 T.D. ________
ATTITUDE ________________
GRID E ____________
GRID N ____________
ELEVATION ____________
START ________ COMP ______
LOGGED ________ DATE ______
SCALE ________ Page 3 of 4



DEPTH	LITHOLOGY DESCRIPTION	STRAT.	%	%	%	%	%	MINERALIZATION DESCRIPTION	ASSAY SECTIONS
200									
—202— 14 10	204.5-224 Dolomitized Waulsortian appears to be more tan coloured almost pink in places than above.								
—215— 20	217-220 pink dolomite.							specks of rusty pyrite	
15 —227— 30									
16 40	234-244 60% recovery. 239.5'-243.5' Sand filled cavity recorded								
—244— 50	244-294 Generally rubbly cavernous 244-250 Sand/clay filled cavity recorded. 244-254 30% recovery.								
60	254-264 30% recovery.								
17 70	264-274 15% recovery. 265(approx) 7' clay and sand filled cavity recorded.								
80	274-284 10% recovery rubble includes very oxidised r.m.b. and pebbles of rusty pyrite.							274-284 pebbles of rusty massive pyrite included in section exact location unknown.	
90	284-294 15% recovery.								
100	294-304 50% recovery. 294.5-302.5 (Note poor recovery ∴ this could be 299-302.5) Bx with pink dol. matrix and grey dol. clasts with some r.m. The clast could be ABL.							specks of rusty pyrite in 1cm thick clast or part band of fresh pyrite in pink dol.	

CONROY PETROLEUM AND NATURAL RESOURCES P.l.c.
DIAMOND DRILL LOG

PROJECT/P.L. No. ____________
HOLE No. GY171 T.D. ________
ATTITUDE ________________
GRID E ____________
GRID N ____________
ELEVATION ____________
START ________ COMP. ________
LOGGED ________ DATE ________
SCALE ________ Page 4 of 4

DEPTH	LITHOLOGY DESCRIPTION	STRAT.			%	%	%	%	%	MINERALIZATION DESCRIPTION	ASSAY SECTIONS
300'											
–301'–	302·5 gougy leached dol. with sub.vert. movement. 302·5–320 ABL.		//								
18	302·5–303·5 Broken gougy dolomitized ABL. micrite with pink dol. vein. Also at 302·5 minor pinkish dol. bx with white calcite. 303·5–309 wavy bedded to nodular unfossiliferous micrites with wispy laminae of calc. mudstone.		Dip20°?								
10	305 – minor gouge with clasts of micrite + calcite. 304–317 Mainly pale micrites some of which are internally 'soft' nodules with large crinoids. Only minor interlude of black calc. mudstone.										
– 316 –	317' 2" gouge		Dip15°								
19	317–320' Mainly fine grained unfossiliferous calcarenite with minor bands of black calc. mudstone.										
20 320	End of Hole.		Dip10°								
30											
40											
50											
60											
70											
80											
90											
100											

CONROY PETROLEUM AND NATURAL RESOURCES P.l.c.
DIAMOND DRILL LOG

PROJECT/P.L. No.
HOLE No. GY403 T.D. 324'
ATTITUDE Vert.

GRID E
GRID N
ELEVATION 454·2'

START 15-11-88 COMP 21-11-88
LOGGED A.A.B. DATE Jan '89
SCALE 1": 10' Page 1 of 4

DEPTH	LITHOLOGY DESCRIPTION	STRAT.			MINERALIZATION %	%	%	%	%	DESCRIPTION	ASSAY SECTIONS
10	0 – 5' Overburden 0 – 20' Casing										
20 20											
Box 1 30	20-261 Predominantly Pale buffish grey dolomitised Waulsortian with creamy dol. veining, bx and bxiated stromatactis (often with dk primary cavity sediment). 20'-34' 50% recovery.										
40	20'-52' Generally very broken only a few pieces up to 6" but mainly small angular fragmts probably due to intense irregular jointing. 34'-44' 70% recovery.										
42·5 2 50	44-54 90% recovery.										
54·5 60	54-64 90% recovery. 55-58 Quite broken sub-vert. jointing stained slightly limonitically.									thin veinlet of rusty pyrite	
3 70 69	64-74 95% recovery.										
4 80 79	70'-77' mainly very broken but part. intersecting sub-vert joints. 74-84 100% recovery. 79-81·5 Slightly broken-sub-vert joints.										
5 90 90	84-94 100% recovery. 86-88 Slightly broken. 88-90 rather diffuse bx.										
6 100	92-94 Slightly broken sub-vert joint 94-104 100% recovery. 98-101·5 Slightly broken -sub-vert. joints									very small black dots along bryozoan fronds pos. rusty pyrite.	

CONROY PETROLEUM AND NATURAL RESOURCES P.l.c.
DIAMOND DRILL LOG

PROJECT/P.L. No. ______________ GRID E ______________ START ______________ COMP. ______________
HOLE No. GY 403 T.D. ______________ GRID N ______________ LOGGED ______________ DATE ______________
ATTITUDE ______________ ELEVATION ______________ SCALE ______________ Page 2 of 4

DEPTH	LITHOLOGY			MINERALIZATION						ASSAY SECTIONS
100'	DESCRIPTION	STRAT.		%	%	%	%	%	DESCRIPTION	
-104'- 7 10	103–107 quite broken. 107-108 Slightly darker grey than usual.									
-116- 20	112 Bx with dk grey clasts pel. fragmts cavity sed 115 – 118 Slightly to well broken beginning with strong jointing at 60° 119-120 Slightly broken									
8 -128'- 30	129.5-131 Slightly broken									
9 40	133 dk grey patch with very dk. bryozoan fronds 135-138 Slightly broken								specks of rusty pyrite	
-141- 10 50	137.25 - 138.25 well broken								prominant bleb of rusty pyrite bleb of rusty pyrite veinlets (discontinuous) of rusty pyrite.	
-154.5- 11 60	151 – 152 Prominant bxiated stromatactis with primary cavity sed. 155 – 163 Generally broken, some slightly - some well due to joints some sub-vert some at 60°. About 155 there is a slight colour change with rock below being slightly more grey less buff.									
-166.5- 70	165.5 – 172.75 Slightly broken mainly due to irreg. jointing.								bleb of rusty pyrite.	
12 179- 80	176.5 prominant bxiated stromatactis with dk primary cavity sed.									
13 90	186.5 – 188.5 Very slightly broken horizontally with vuggy bxiated stromatactis 189 – 190 Generally broken - some very broken.									
-192- 14 100	191 – 192 approx. 1' cavity rounded. 192 very vuggy bxiated stromatactis.									

CONROY PETROLEUM AND NATURAL RESOURCES P.l.c.
DIAMOND DRILL LOG

PROJECT/P.L. No. ____________
HOLE No. GY 403 T.D. ________
ATTITUDE ____________
GRID E ____________
GRID N ____________
ELEVATION ____________
START ________ COMP. ________
LOGGED ________ DATE ________
SCALE ________ Page 3 of 4

DEPTH	LITHOLOGY DESCRIPTION	STRAT.	Zn %	Pb %	Py %	%	%	DESCRIPTION	ASSAY SECTIONS
200' -204·5- 10 15	201' brxiated stromatactis vuggy 206 vuggy brxiated stromatactis 207·5-211 Slightly broken								
-216·5- 20	214-224 80% recovery (no cavity recorded) 216-227 Slightly broken but including some core loss. below 220 the joints tend to be horizontal. The loss is probably between 218-220.								
16 -227·5- 30	227 very prominent bx with dk grey clasts 228 dk bryozoan fronds								
17 40	237·5-243 Predominantly Grey Waulsortian with white dol. veining.							pyrite bleb (fresh)	
-241- 18 50	243-244·5 Buff dolomitised Waulsortian as before. 244·5-246 Grey dolomitised Waulsortian 246-255 Buff dolomitised Waulsortian as before.								
-255- 60	255-259 Grey dolomitised Waulsortian with white to pinkish white dol. veining etc. 259-261 Buff dolomite as before.							speck of rusty pyrite bleb of pyrite (fresh) speck of pyrite (fresh)	
19 -269- 70	261-275 Grey Dolomitised Waulsortian with white crystaline dolomite infilling bxs with many clasts of dk primary cavity sed. (but no other stromatactis features discernible) Also							veinlets of pyrite veinlets of pyrite bleb of pyrite 266-271·5 numerous blebs and thin discontinuous veinlets of pyrite.	
20 80	traces of light grey diffuse r.m. 262 large prominent grey clast with bryozoa. 271-291·5 slightly broken jointing. Surfaces are yellow, oxidised but rock unoxidised. 275-291·5 Grey Dolomitised Waulsortian with r.m.b. At top it is diffuse but becomes darker, muddier more definite downwards.		–	–	<1%			275-289·5 Some specks and blebs of pyrite.	275 1248
-282·5-	Minerlised from 289·5 but especially below 282. 282·5-284 Slightly broken		3%	–	5%			289·5-282 Small rounded clots of pyrite in matrix minor dissemi ZnS.	289·5 1249
			8%	–	3%			282-284 similar though more ZnS	282 1250
21			25%	1%	3%			284-285·5 Almost massive ZnS passing down into dissemi 285·5-291·5 Dissemi ZnS in clasts and some late ZnS with pyrite in matrix.	284 1251
90			10%	1%	8%				287·5 1252
	291·5-298·5 Almost Massive Pyrite with diffuse partly replaced clasts of dol and minor pinkish late crystaline dol. infills.	minor gouge	–	–	80%			291·5-298·5 almost massive pyrite no discernible ZnS or PbS	291·5 1253
-295-	298·5-324 A.B.L.	grey gouge	–	–	80%				295 1254
100	298·5 2" grey gouge.	Dip 10°	2%	–	–			298·5-300 Dissem ZnS in patches in calc' mudstone.	298·5 1255 300

CONROY PETROLEUM AND NATURAL RESOURCES P.l.c.
DIAMOND DRILL LOG

PROJECT/P.L. No. ____________
HOLE No. GY 403 T.D. ________
ATTITUDE ________________
GRID E ________________
GRID N ________________
ELEVATION ________________
START ________ COMP. ______
LOGGED ________ DATE ______
SCALE ________ Page 4 of 4

DEPTH	LITHOLOGY			MINERALIZATION						ASSAY
300	DESCRIPTION	STRAT.		%	%	%	%	%	DESCRIPTION	SECTIONS
22 -304- 10	298·5-300' Mainly black calc' mudstone 300-305·5 Mainly nodular wavy bedded micrites with traces of chert. 301-302 irregular calcite veining. 305·5-324 Thick beds (than above c.6"-12") of pale crinoidal micrite some crinoids large and some micrites as nodules interbedded with dk calc' mudstone 50:50		Dip 10°						trace pyrite assoc' with calcite trace ZnS in mud band ditto.	
23 -318- 20	313 pink calcite veining. 314 irreg. calcite veining. 315 minor bedding slip gouge									
24 -324-	323 white calcite vein associated with bedding slip. End of hole		Dip 10°							
30										
40										
50										
60										
70										
80										
90										
100										

CONROY PETROLEUM AND NATURAL RESOURCES P.l.c.
DIAMOND DRILL LOG

APPENDIX B

APEX Geoservices Report

AGL 14045_4

REPORT
ON THE
GPR INVESTIGATION
OF
THE FIELD SURROUNDING THE SINKHOLE
AT
GALMOY MINE
COUNTY KILKENNY
FOR

9TH MAY 2014

APEX Geoservices Limited
6 Knockmullen Business Park
Gorey
Co. Wexford

T: 0402 21842
F: 0402 21843
E: info@apexgeoservices.ie
W: www.apexgeoservices.com

PRIVATE AND CONFIDENTIAL

THE FINDINGS OF THIS REPORT ARE THE RESULT OF A GEOPHYSICAL SURVEY USING NON-INVASIVE SURVEY TECHNIQUES CARRIED OUT ON THE GROUND SURFACE. INTERPRETATIONS CONTAINED IN THIS REPORT ARE DERIVED FROM A KNOWLEDGE OF THE GROUND CONDITIONS, THE GEOPHYSICAL RESPONSES OF GROUND MATERIALS AND THE EXPERIENCE OF THE AUTHOR. APEX GEOSERVICES LTD. HAS PREPARED THIS REPORT IN LINE WITH BEST CURRENT PRACTICE AND WITH ALL REASONABLE SKILL, CARE AND DILIGENCE IN CONSIDERATION OF THE LIMITS IMPOSED BY THE SURVEY TECHNIQUES USED AND THE RESOURCES DEVOTED TO IT BY AGREEMENT WITH THE CLIENT. THE INTERPRETATIVE BASIS OF THE CONCLUSIONS CONTAINED IN THIS REPORT SHOULD BE TAKEN INTO ACCOUNT IN ANY FUTURE USE OF THIS REPORT.

PROJECT NUMBER	AGL14045_01		
AUTHOR	**CHECKED**	**REPORT STATUS**	**DATE**
HUGH POWER B.SC. (EARTH SCI., HONS)	EURGEOL PETER O`CONNOR P.GEO., M.SC. (GEOPHYSICS)	VERSION 4	9TH MAY 2014

1. EXECUTIVE SUMMARY

A sinkhole has recently developed in a field at Castletown, near Galmoy, Co. Kilkenny. APEX Geoservices Limited was requested by Golder Associates Ireland to carry out a geophysical investigation in the vicinity of the sinkhole in order to identify the presence of any further potential cavities.

The investigation consisted of Ground Penetrating Radar (GPR). GPR was collected in the field in which the sinkhole developed. GPR was also collected on a nearby road which passes over a marked fault (the Main Fissure). Under suitable conditions GPR can give detailed information on the near surface and in the area of the investigation provided data down to 8m below ground level (bgl), and was considered a suitable method to screen for any cavities under development that might be susceptible to sinkhole in the short term.

In this report any reflections that potentially show an underground feature are generally termed an anomaly. These could be due to buried pipes or other objects or changes in materials, such as sand lenses or cavities, which could be sand filled or not.

A total of 540 GPR profiles were collected across the site. GPR profiles were recorded at 2m spacing in the designated grids in the grass field surrounding the sinkhole. Two GPR profiles (815m length) were carried out on the road adjacent to the field in which the sinkhole occurred and 4 profiles at 2m intervals were also collected parallel to the road, with the first profile 2m inside the field boundary.

There were no obvious reflectors indicative of possible cavities on the road or parallel field profiles, where the Main Fissure crosses the road.

A surface depression to the south-east of the existing sinkhole was evident at the time of survey. This depression was surveyed and showed up as a large area of anomalous reflections on the GPR data, indicative of previous subsidence and infill. A similar reflection pattern occurs at location A8 but only occurs on one profile. These features could be further investigated by probing.

There are three clusters of reflections to the south of the existing sinkhole and these are labelled as Anomalies A16, A17 and A26 on Drawing AGL14045_01. These features could be further investigated by probing.

There is a cluster of reflections in the southern part of the southern field and immediately south of the fissure zone, A3, A4 and A32. These may be due to rock pinnacles but could be investigated given their proximity to the fissure zone and the road.

The critical roof thickness/diameter threshold for an open cavity that can be arched by the inherent stiffness of the typical glacial till that is present on site, should be estimated to within an acceptable factor of safety. Any reflections indicating possible cavities below this ratio should be investigated by probing.

Anomalies A21, A22 and A23 occur along the county road at between 195-220m from the northern end of the road GPR profiles. There are also similar reflections along the road profile at 720-730m. Consideration could be given to investigating by probing.

2. INTRODUCTION

A solution feature (sinkhole) has recently developed in a field at Castletown, near Galmoy, Co. Kilkenny. APEX Geoservices Limited was requested by Golder Associates Ireland to carry out a geophysical investigation in the vicinity of the sinkhole in order to identify the presence of any further potential cavities.

The investigation consisted of Ground Penetrating Radar (GPR). GPR was collected in the field in which the sinkhole developed. GPR was also collected on a nearby road which passes over a marked fault (the Main Fissure).

2.1 Survey Objectives

The objectives of the survey were:

- To screen the site for near surface cavities that could be susceptible to further sinkhole development.

2.2 Site Background

The sinkhole (diameter c. 8m) is located in a grass field to the east of Galmoy Mine Plant with approximate coordinates of ING 227836 172698 (Fig. 2.1). From an AutoCAD map of the mine infrastructure, provided by the client, the sinkhole is seen to be located above an area of backfilled mine and above the Main Fissure with a width of up to 8m. It is understood that the Main Fissure zone was mapped during the development of the mine.

Over 70 mineral exploration boreholes were drilled during the 1980's in the field containing the sinkhole and in the field immediately to the north. From borehole data which has been supplied by Golder, overburden thicknesses range from 0.9m to 32.6m with an average thickness of 5.9m. The summary borehole logs show numerous cavities of up to 10m vertical extent. It is understood that these cavities are usually sand filled.

Electrical Resistivity Tomography (ERT) profiling has been carried out by Golder in the fields and along the county road. Depth to bedrock varies from 0 to 15m with an average depth of around 8m. Overburden resistivity ranges from 100 to 400 ohm-m which is typical of a sandy gravelly clay till. The bedrock topography is irregular and bedrock resistivity values vary from 500 ohm-m upwards, both of which are indicative of variably weathered bedrock and the presence of palaeo-karst features.

2.2.1 Topography

The topography of the site ranges from approximately 130mOD to 150mOD (Fig. 2.2) with an undulating surface that appears to be related to variations in bedrock topography, especially in the north-eastern part of the survey area.

Fig. 2.1 Existing sinkhole

Fig. 2.2 Field in which sinkhole occurred

2.2.2 Soils

The GSI online quaternary map describes soils across the site as tills derived from limestone (Fig. 2.3)

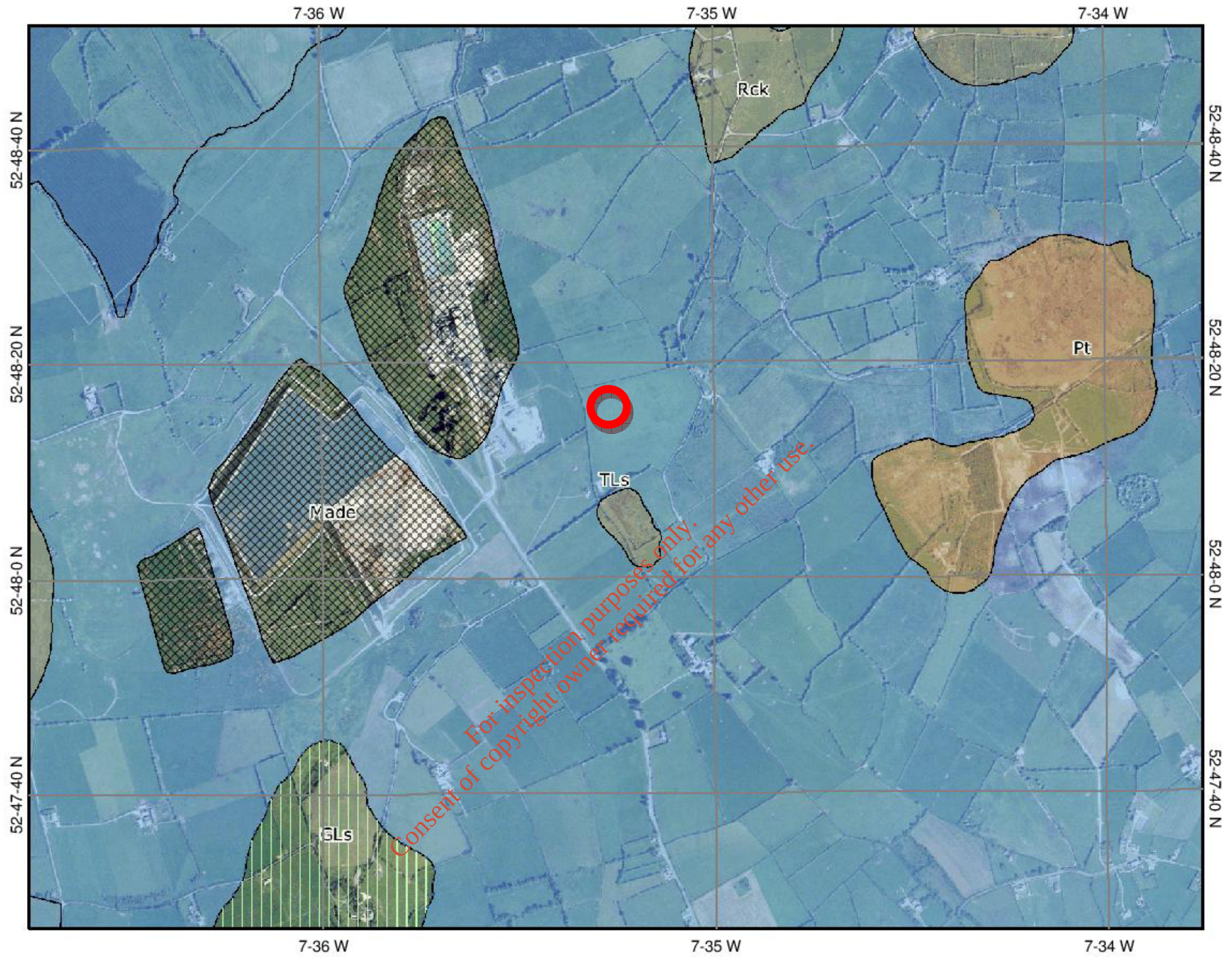


Fig. 2.3 GSI Soils Map

(Made=made ground, Rck=rock, Pt=Peat, TLs=Limestone Till, GLs=Limestone Gravel).

2.2.3 Geology

The GSI online bedrock map indicates that the site is underlain by Waulsortian Limestone described as a dolomitised massive fine-grained limestone (Fig.2.4).

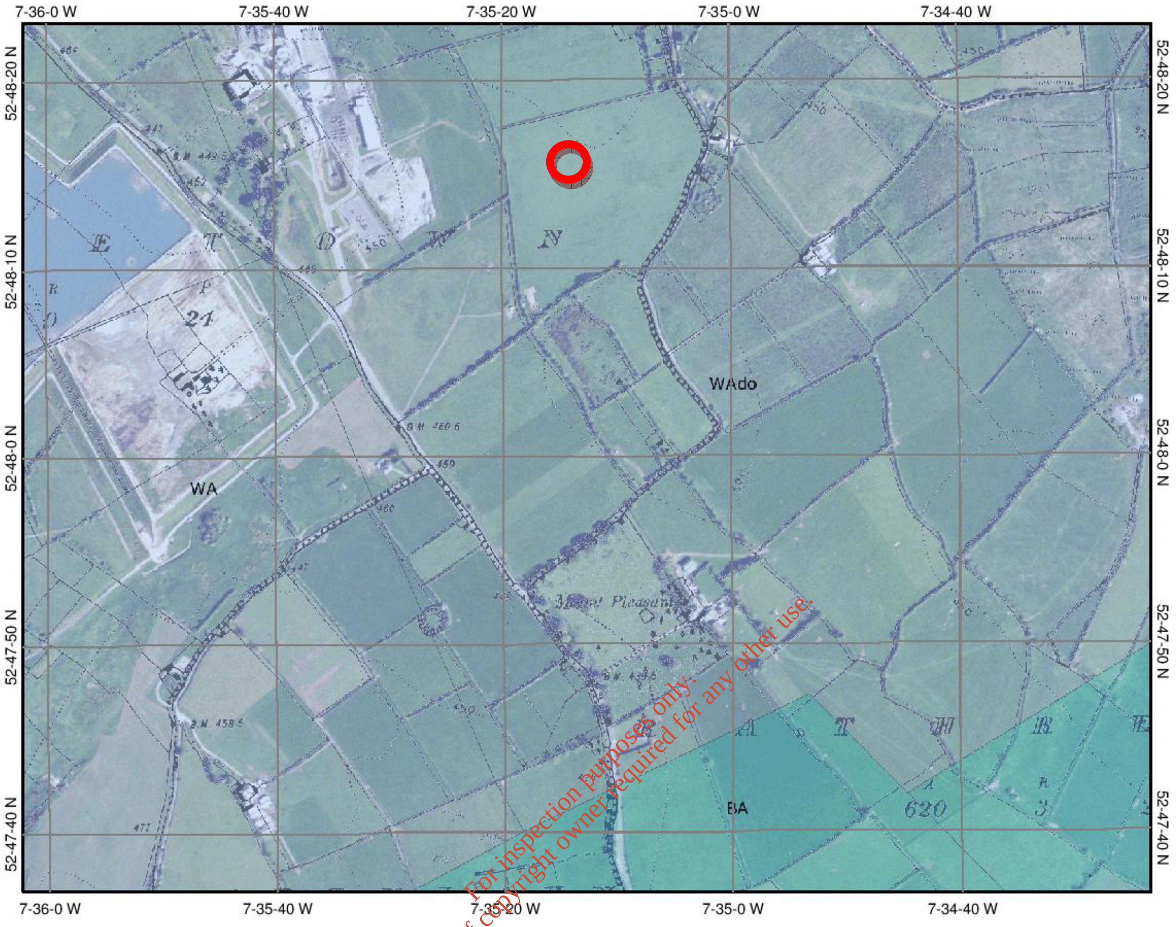


Fig. 2.4 Bedrock Geology (WA=Waulsortian, WAdo=Waulsortian(dolomitised), BA=Ballysteen).

2.3 Survey Rationale

Under suitable conditions GPR can give detailed information on the near surface and in the area of the investigation provided data down to 8m below ground level (bgl), and was considered a suitable method to screen for any cavities under development that might be susceptible to sinkhole in the short term.

GPR works by sending radio waves into the ground and measuring the time of the reflected wave. Reflections occur where different material properties exist. Features such as cavities can be outlined if good penetration of the GPR signal is achieved. The velocity and depth of penetration of the GPR signal varies depending on the electrical properties of the sub-soil, with highly conductive materials such as clays showing low penetration due to high absorption rates.

The absence of features associated with cavitation is not conclusive proof of the absence of these features in the ground as they may lie outside the range or resolution of the GPR signal, lie between survey profiles or may be masked by shallower features or poor ground conditions.

Further information on the methodology is given in **APPENDIX B: DETAILED METHODOLOGY**.

3. SURVEY AND RESULTS

The survey was carried out on the 19th, 25th, 26th, 27th of February and on the 11th March 2014. GPR profiles were collected in the two fields surrounding the sinkhole, as well as on the road to the east of the sinkhole.

Additional surveying was carried out on the 2nd April in the southern part of the southern field.

A total of 540 GPR profiles were collected across the site. GPR profiles were recorded at 2m spacing in the designated grids in the grass field surrounding the sinkhole (see Drawing AGL14045_01 & 02). Two GPR profiles (815m length) were carried out on the road adjacent to the field in which the sinkhole occurred (see Drawing AGL14045_03), and 4 profiles at 2m interval were also collected parallel to the road, with the first line 2m inside the field boundary.

The profiles were recorded using a 100MHz frequency antenna to provide the required resolution as well as depth of penetration. An average depth penetration of c. 6-8m was achieved with the GPR. This higher than average penetration rate for Irish glacial material is related to the sand and gravel content of the till. The GPR profiles start and end points were surveyed with an RTK DGPS to accurately relocate the data.

All GPR profiles were processed to enhance the reflected signal and then visually screened for reflections typical of cavitation. All strong reflector locations and depths are presented in Drawings AGL14045_01, AGL14045_02 and AGL14045_03 and are divided into **probable (red)** and **possible (blue)** features. A list of the probable features is supplied in Table 3.1 with coordinates. These are also displayed on extracts from the GPR profiles in **APPENDIX C: GPR PROFILES.**

Two types of reflections indicative of infilled cavities have been observed**. Single point** reflectors with a hyperbolic diffraction pattern are usually associated with relatively narrow diameter (1-2m) single point air or sand filled cavities. Wider **linear reflectors** have also been observed which could be associated with larger diameter (> 3m) features but which can also arise from a stratigraphic change such as the transition to a sand or gravel lens within the overburden. Reflections are classified as probable or possible depending on the strength and clarity of the reflected signal.

Reflections from the top of the bedrock are also visible on some profiles, and in these cases the probable and possible cavities can be classified as occurring within the overburden or within bedrock.

Southern and Northern Fields

A surface depression to the south-east of the existing sinkhole was evident at the time of survey. (This depression is outlined on the original OSI 6'' sheet from c. 1850). This depression was surveyed and showed up as a large area of anomalous reflections on the GPR data, indicative of previous subsidence and infilling (Fig. 3.1). A similar reflection pattern occurs at location A8 but only occurs on one profile. This feature could be further investigated by probing.

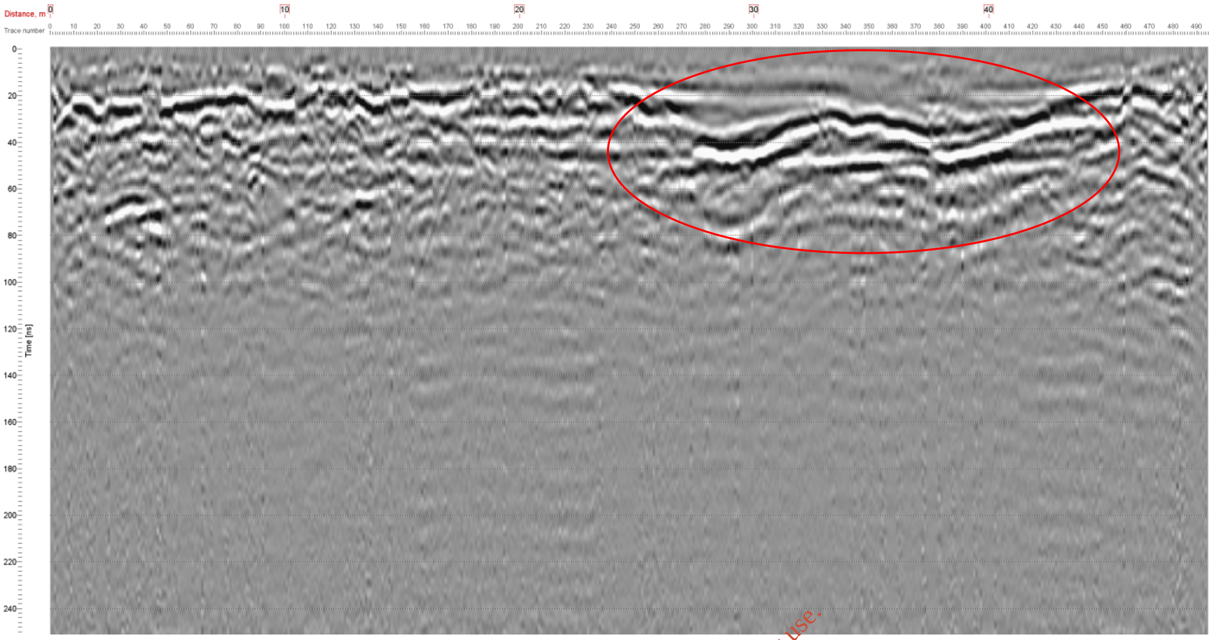


Fig. 3.1 Shallow reflections from 25-45m at surface depression south-east of sinkhole.

There are three clusters of reflections to the south of the existing sinkhole and these are labelled as Anomalies A16, A17 and A26 on Drawing AGL14045_01. These features could be further investigated by probing.

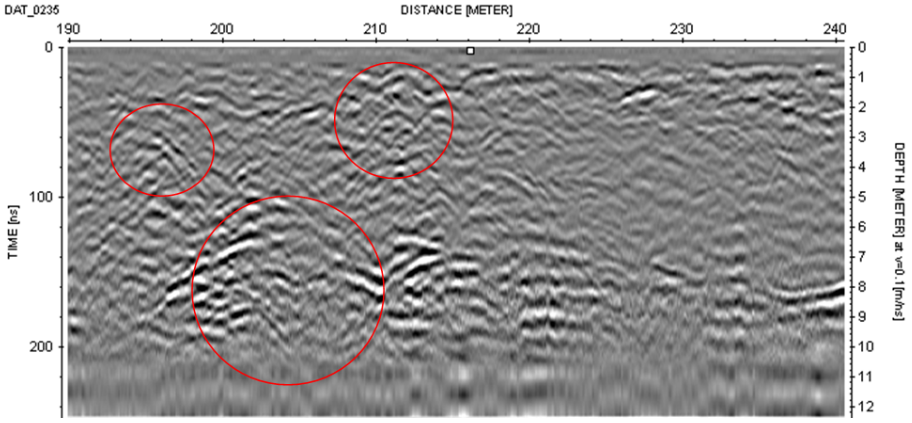
There is a cluster of reflections in the southern part of the southern field and immediately south of the fissure zone, A3, A4 and A32. These may be due to rock pinnacles but could be investigated given their proximity to the fissure zone and the road.

The critical roof thickness/diameter threshold for an open cavity that can be arched by the inherent stiffness of the typical glacial till present on site, should be estimated to within an acceptable factor of safety. Any anomalous reflections indicating possible feature depth and dimensions below this ratio could be investigated by probing.

County Road

There were no obvious reflectors indicative of probable or possible cavities on the road or parallel field profiles where the Main Fissure crosses the road. However a number of anomalies were identified at other locations,

Anomaly A22 occurs along the county road between 195-220m from the northern end of the road GPR profiles (Fig. 3.2), and there are also a number of other possible anomalies in the immediate vicinity (Fig. 3.2). This correlates with an area where some underground settlement was known to have previously occurred within the mine area. There are also similar reflections (Anomaly A2) along the road profile at 720-730m and at 800m (Anomaly A1). Consideration could be given to investigating by probing in the vicinity of these anomalies.



Anomaly No. A22

Fig. 3.2 Deep and shallow reflections from area between 195-220m along county road profile.

Buried Pipeline

A number of strong shallow reflections were also observed on the road and in the field at the northern end of the survey area. A typical example is shown below in Fig. 3.3

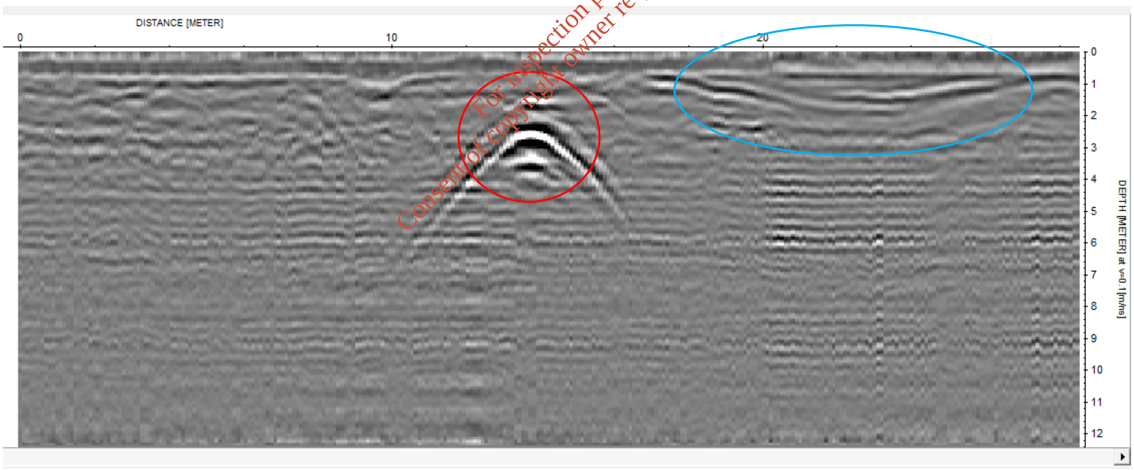
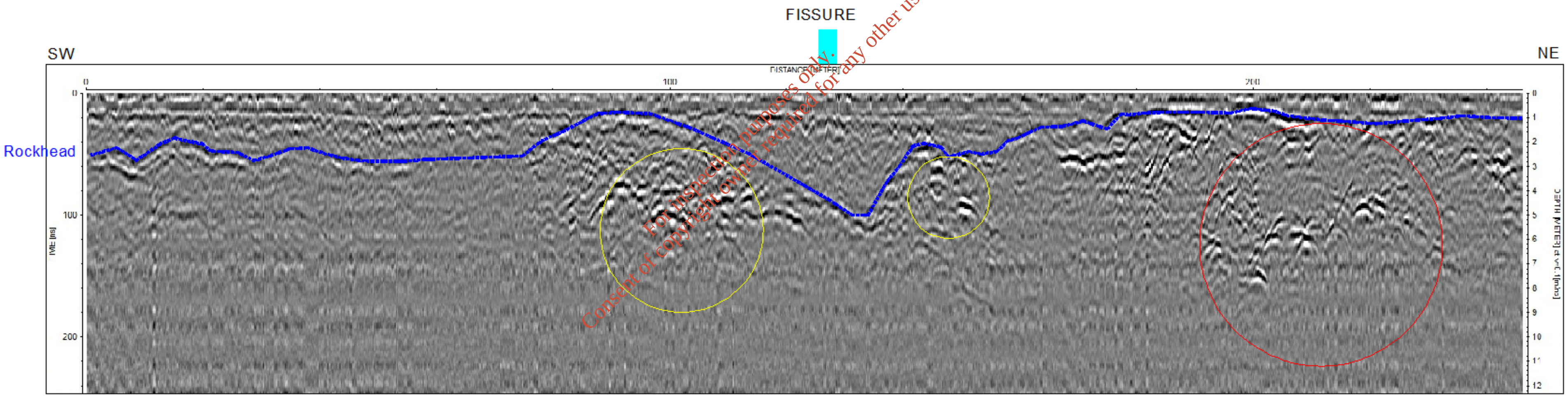


Fig. 3.3 Reflection from buried 400mm diameter pipe in northern field. Record 560 crossing pipe at 13.9m, 1.4m deep. Also noted infilled surface depression (blue) between 17.0-28.0m, possibly related to construction.

These reflections occur consistently in two linear patterns and are related to two 400mm diameter steel lined pipes or culverts running in a NNW direction in this area (Drawing AGL14045_01-03). This has been confirmed by the client.

A 250m long SW-NE trending profile was recorded through the southern field (Fig. 3.4) and clearly shows the thickening of overburden in the vicinity of the fissure. Deep point reflectors indicative of possible cavities or changes in material within the bedrock can be seen at the north-eastern end of the profile(red circle).



SW **NE**

Fig. 3.4 Profile running SW-NE though the centre of the southern field. Depth penetration of up to 8m has been achieved. The main fissure zone intersects the profile at 128m. The increase in depth to bedrock in the vicinity of the fissure is clearly visible. Point reflections on either side of the fissure indicate possible sand filled cavities (yellow). To the NE deeper reflectors (red)within the rock can be seen around chainage 200m.

Anomaly Number	Easting	Northing	Anomaly Depth (m)	Comment
A1	228054.4	172207.2	4.8	Located along the road
A2	228066.8	172260.9	4.2	Located along the road
A3	227979.2	172551.7	3.6	
A4	227972.8	172559.4	3.6	
A5	227901.6	172572.7	1.1	
A6	228008.3	172578.9	2.2	
A7	227983.8	172579.4	2.9	
A8	227889.7	172612.4	0.9	Similar to surface depression to SE
A9	227941.8	172630.8	2.1	
A10	227938.6	172636.0	5.2	
A11	227874.4	172645.5	0.5	Close to surface probable drain/service
A12	227880.3	172648.2	2.2	
A13	227881.2	172652.3	0.5	Close to surface probable drain/service
A14	228026.5	172645.8	0.9	Close to surface probable drain/service
A15	227943.2	172671.8	4.8	
A16	227801.3	172667.9	2.7	Cluster of anomalies across profiles
A17	227843.8	172673.0	2.2	Cluster of anomalies across profiles
A18	228039.6	172674.6	1.5	In field beside road
A19	227891.4	172682.3	1.5	
A20	227895.0	172688.6	4.2	
A21	228059.1	172686.6	5.8	Located along the road
A22	228057.5	172727.1	6.3	Located along the road
A23	228041.9	172740.1	0.9	Close to surface probable drain/service
A24	227923.3	172735.7	4.8	
A25	227876.5	172746.9	3.9	
A26	227826.8	172669.6	2.4	Cluster of anomalies across profiles
A27	227924.9	172828.4	3.1	
A28	227905	172911.5	1.4	
A29	227769.8	172739.8	1.4	
A30	227709.6	172769.1	1.3	
A31	227884.8	172537.2	4.8	
A32	227941.9	172554	5.1	
A33	227974.2	172544.5	4.3	

Table 3.1. Probable (red) GPR features.

4. RECOMMENDATIONS

It is recommended that a selected number of the probable anomalies from A1 to A33 (see Table 3.1) be investigated with use of dynamic probing on a 2m grid.

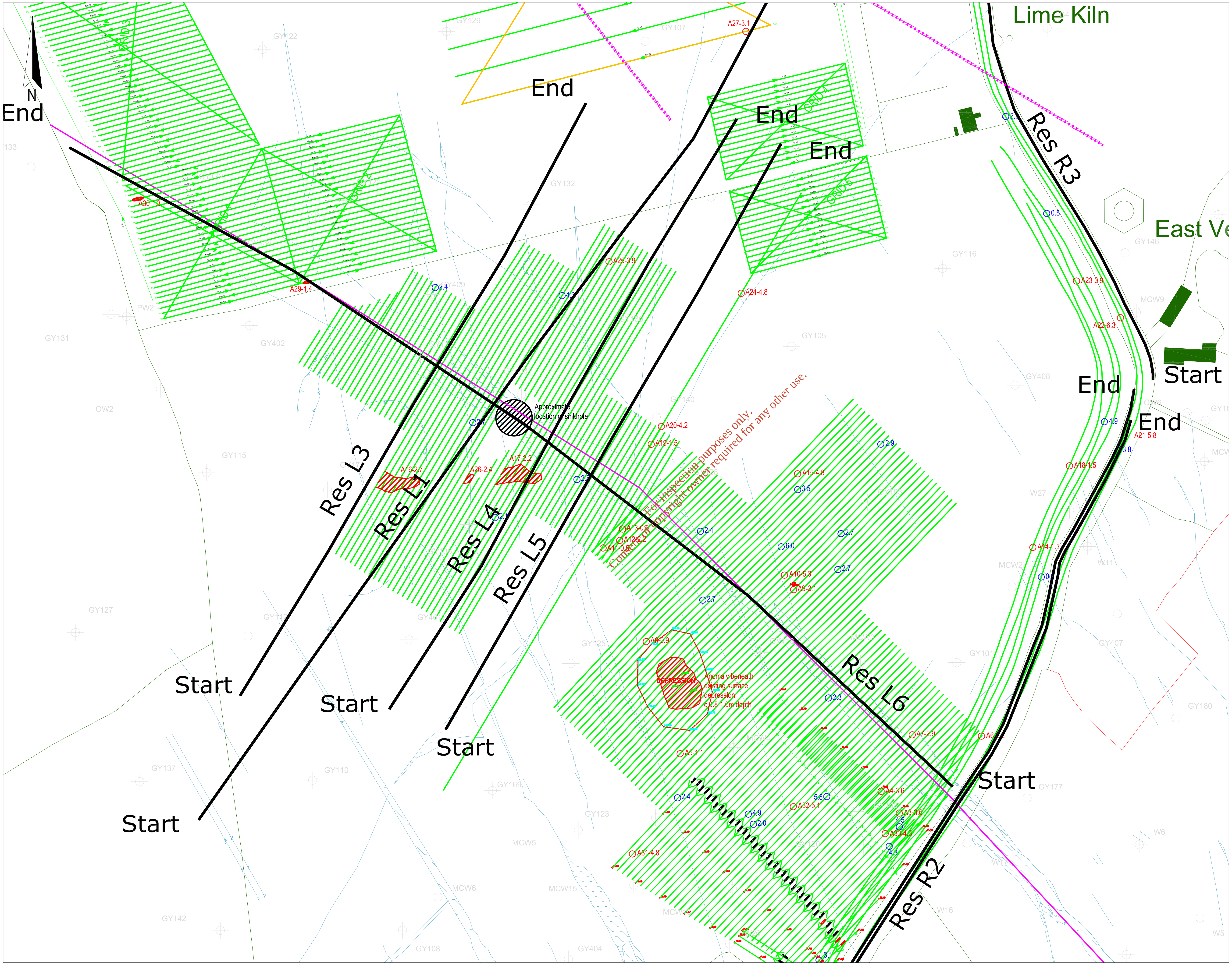
The critical roof thickness/diameter threshold for an open cavity that can be arched by the inherent stiffness of the typical glacial till that is present on site, should be estimated to within an acceptable factor of safety. Any anomalous reflections indicating possible cavities with depth and dimensions below this ratio should be investigated by probing.

A local grid of GPR should be used to accurately locate the centre of the selected anomalies before probing commences. The geophysical interpretation should be reviewed after completion of the dynamic probing.

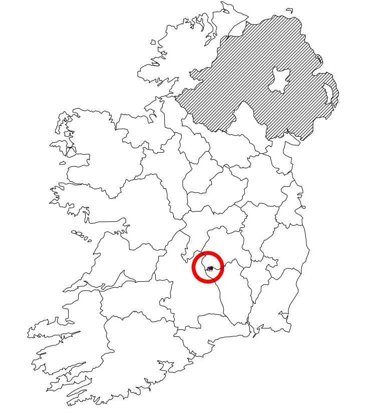
APPENDIX A: DRAWINGS

GPR PROFILE AND INTERPRETED VOID LOCATIONS (SOUTHERN FIELD)

SCALE 1:1000



INDEX MAP:



LEGEND:

━	GPR Survey Profile
○ A1-2.1	Probable cavity Anomaly Number-Depth (m)
○ 2.7	Possible cavity Depth (m)
▨ c.2.7	Area of probable cavity Depth (m)
▨	Main Fissure
┅	Pipeline
▭	Infill

apex geoservices

6 Knockmullen Business Park
Gorey
Co. Wexford
Ireland.
T +353 (0)402-21842
F +353 (0)402-21843
E info@apexgeoservices.ie
www.apexgeoservices.ie

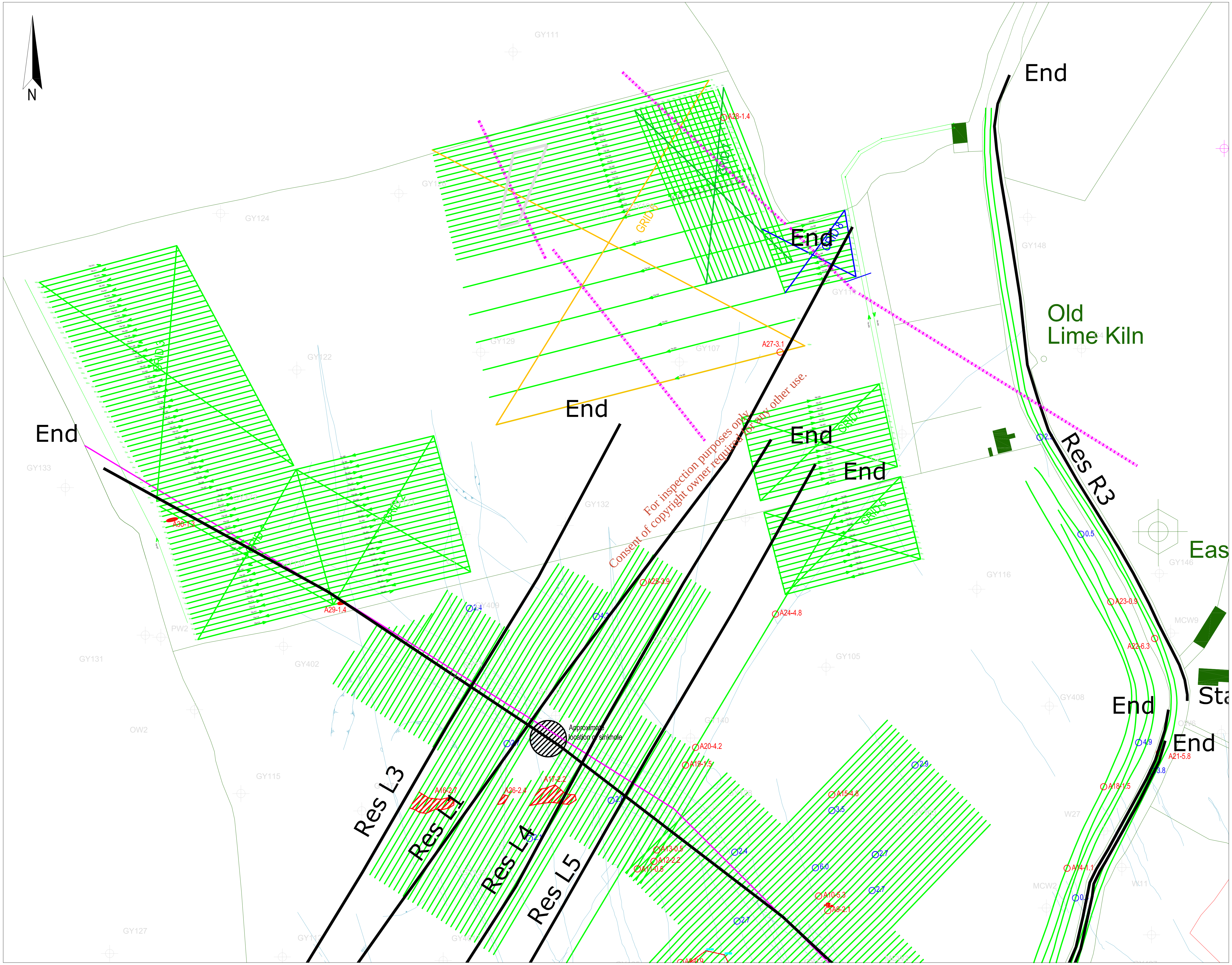
Regus House, Herald Way
Pegasus Business Park
Castle Donington
Derby DE74 2TZ
UK
T +44 (0)844 8700 692
E info@apexgeoservices.co.uk
www.apexgeoservices.co.uk

PROJECT:	GALMOY SINKHOLE GEOPHYSICAL SURVEY
CLIENT:	GOLDER LIMITED
DRAWING NO:	AGL14045_01
SCALE:	AS INDICATED @ A3
DATE:	6th March 2014

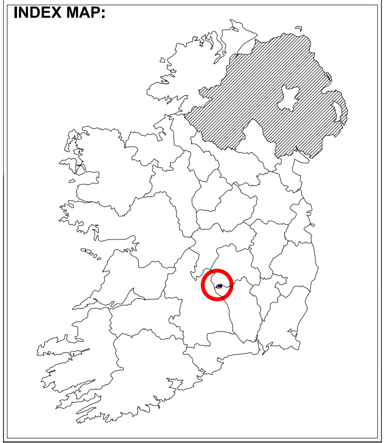
Version:	Date:	Drawn By:	Checked:
1	6/03/2014	HP	POC
2	9/04/2014	POC	HP
3	6/05/2014	POC	HP

BACKGROUND MAP - GPR PROFILE AND INTERPRETED VOID LOCATIONS(NORTHERN FIELD)

SCALE 1:1000



INDEX MAP:



LEGEND:

━	GPR Survey Profile
○A1-2.1	Probable cavity Anomaly Number-Depth (m)
○2.7	Possible cavity Depth (m)
▨ c.2.7	Area of probable cavity Depth (m)
▨	Main Fissure
┅	Pipeline
▱	Infill

apex geoservices

6 Knockmullen Business Park
Gorey
Co. Wexford
Ireland.
T +353 (0)402-21842
F +353 (0)402-21843
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www.apexgeoservices.ie

Regus House, Herald Way
Pegasus Business Park
Castle Donington
Derby DE74 2TZ
UK
T +44 (0)844 8700 692
E info@apexgeoservices.co.uk
www.apexgeoservices.co.uk

PROJECT: GALMOY SINKHOLE GEOPHYSICAL SURVEY

CLIENT.: GOLDER LIMITED

DRAWING NO: AGL14045_02

SCALE: AS INDICATED @ A3

DATE: 6th March 2014

Version:	Date:	Drawn By:	Checked:
1	6/03/2014	HP	POC
2	9/04/2014	POC	HP
3	6/05/2014	POC	HP

FIGURE 1: NORTH ROAD SECTION

SCALE 1:1000

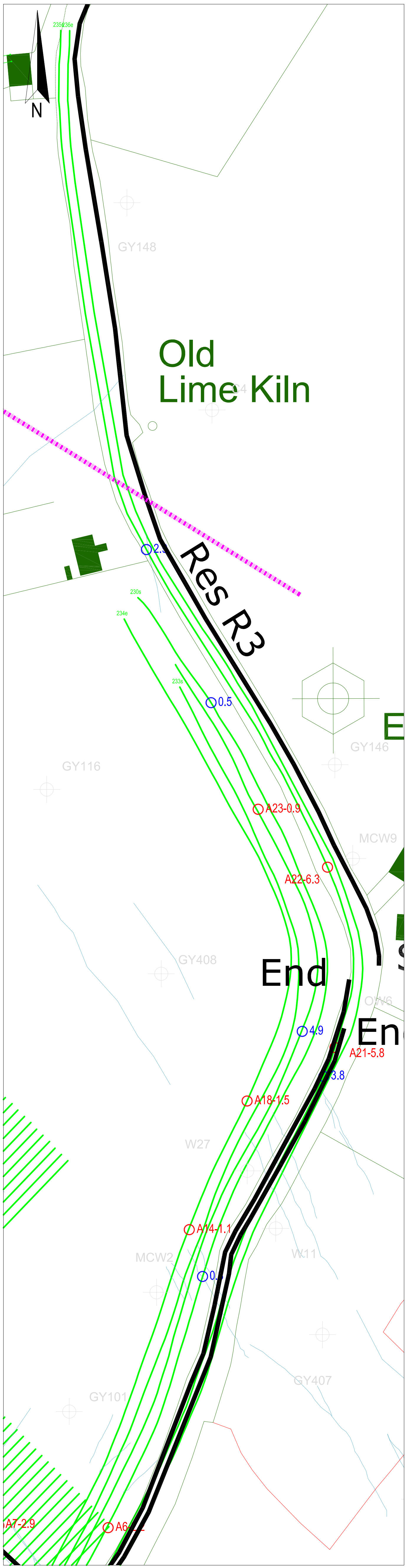


FIGURE 2: CENTRAL ROAD SECTION

SCALE 1:1000

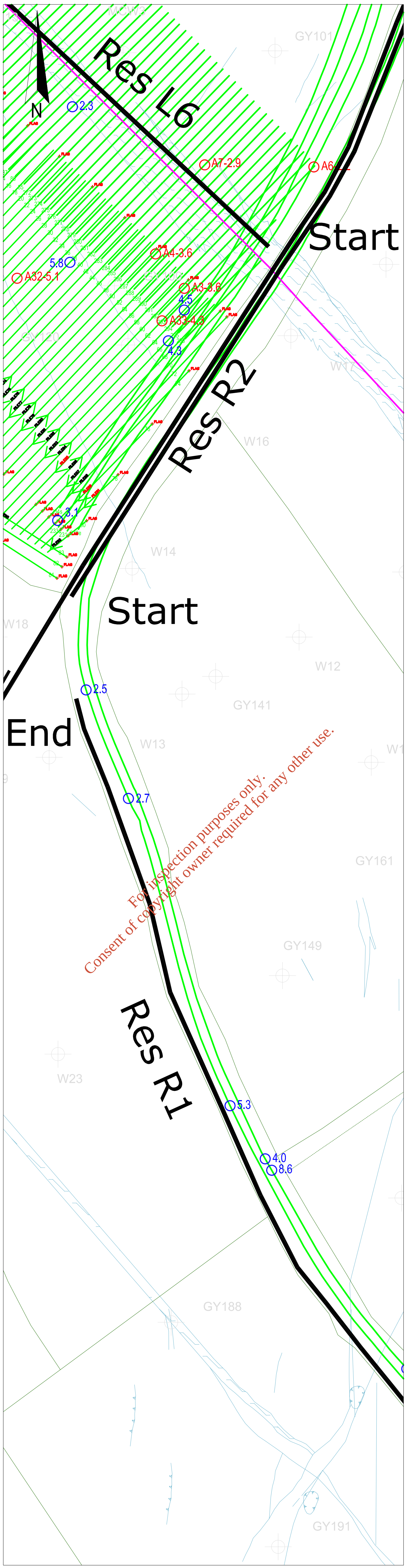


FIGURE 3: SOUTH ROAD SECTION

SCALE 1:1000

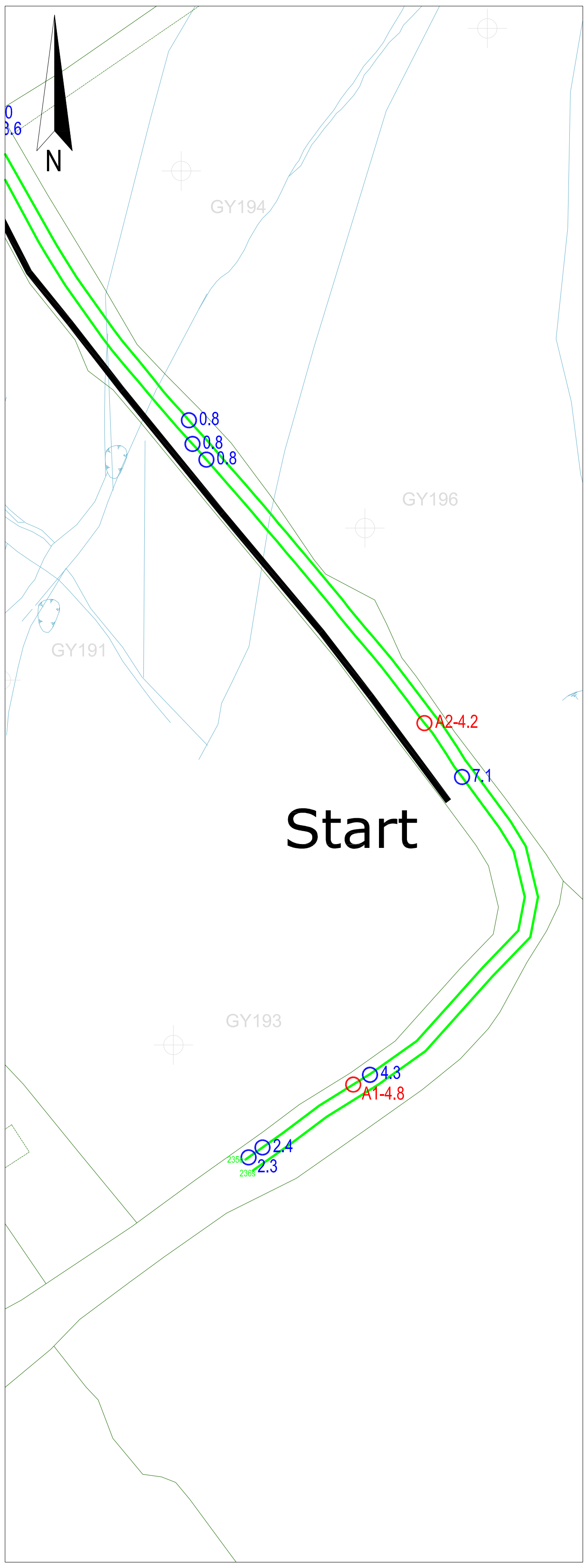
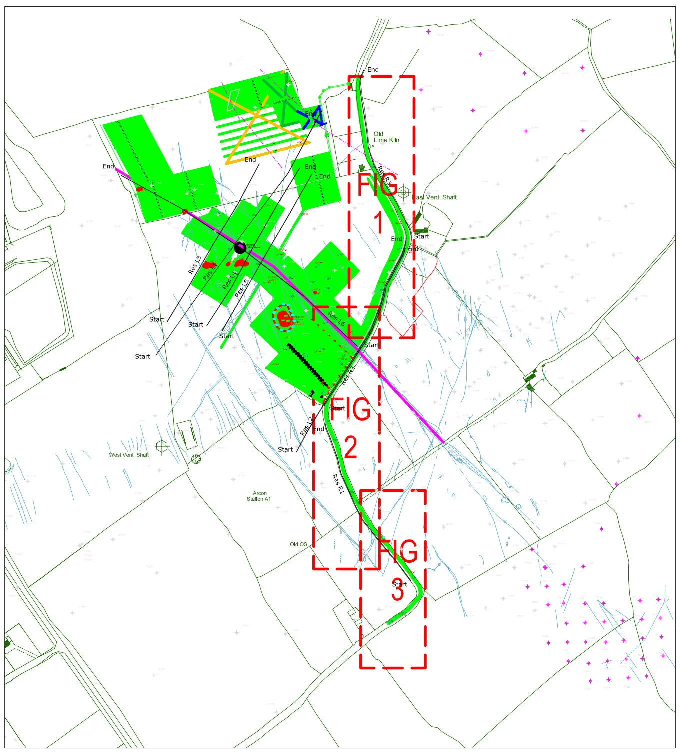


FIGURE 4: LOCATION MAP

SCALE 1:10000



apex geoservices

6 Knockmullen Business Park
Gorey
Co. Wexford
Ireland.
T +353 (0)402-21842
F +353 (0)402-21843
E info@apexgeoservices.ie
www.apexgeoservices.ie

Regus House, Herald Way
Pegasus Business Park
Castle Donington
Derby DE74 2TZ
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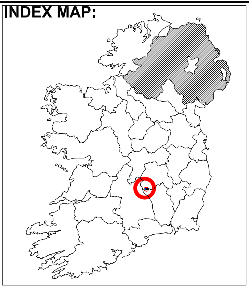
T +44 (0)844 8700 692
E info@apexgeoservices.co.uk
www.apexgeoservices.co.uk

INDEX MAP:



LEGEND:

🟩	GPR Survey Profile	c.2.7 ▨	Area of probable cavity Depth (m)
○A1-2.1	Probable cavity Anomaly Number-Depth (m)		Main Fissure
○2.7	Possible cavity Depth (m)		Pipeline

NOTES:

PROJECT: GALMOY SINKHOLE
GEOPHYSICAL SURVEY
DRAWING No.: GOLDER LIMITED
DATE: AGL14045_03
CLIENT: AS INDICATED @ A3
SCALE: 6th March 2014

Version:	Date:	Drawn By:	Checked:
1	6/03/2014	HP	POC
2	9/04/2014	POC	HP
3	6/05/2014	POC	HP

APPENDIX B: DETAILED METHODOLOGY

GPR Principles

Ground Probing Radar (GPR) involves the measurement of the amplitude versus traveltime (Two-Way-Time in Nanoseconds [ns]) of a high frequency pulse of electromagnetic energy from the ground surface to a subsurface layer. These pulses are transmitted with a high repetition rate as the antenna is towed along the ground and the reflected pulses build up a picture of the subsurface structure. Partial reflections of the electromagnetic pulse occur at the boundaries of materials with different geo-electric properties.

The penetration of the GPR signal depends on the nature of the subsurface material. Clay-rich and water saturated soils have a lower penetration than gravelly and dry soils. Subsurface air-filled cavities and medium-large diameter buried services usually have a good geo-electric contrast with the surrounding material and can be seen on the upper 1-8 m of the GPR record. Continuous boundaries such as the bedrock interface or changes in soil type may also be visible.

Signal penetration and resolution limits are also governed by the centre frequency of the transmitted electromagnetic pulse. High frequencies give good resolution and shallow penetration. Lower frequencies give lower resolution and deeper penetration.

GPR Data Collection

The GPR survey was carried out using a MALA system, with a towed antennae with built-in odometer. The data was recorded on the hard disk in the operating console and later transferred to a computer for processing and printing. Each grid line was recorded with a 100 MHz antenna. The distance along each profile was recorded in the GPR record header by the odometer.

A total of 540 no. profiles were recorded at a spacing of 2m. Notes were taken of any surface features that were likely to interfere with the recorded GPR signal.

GPR Data Processing

The processing of GPR data was carried out using proprietary processing software (ReflexWin V.6.0). The following processing was applied to the data:

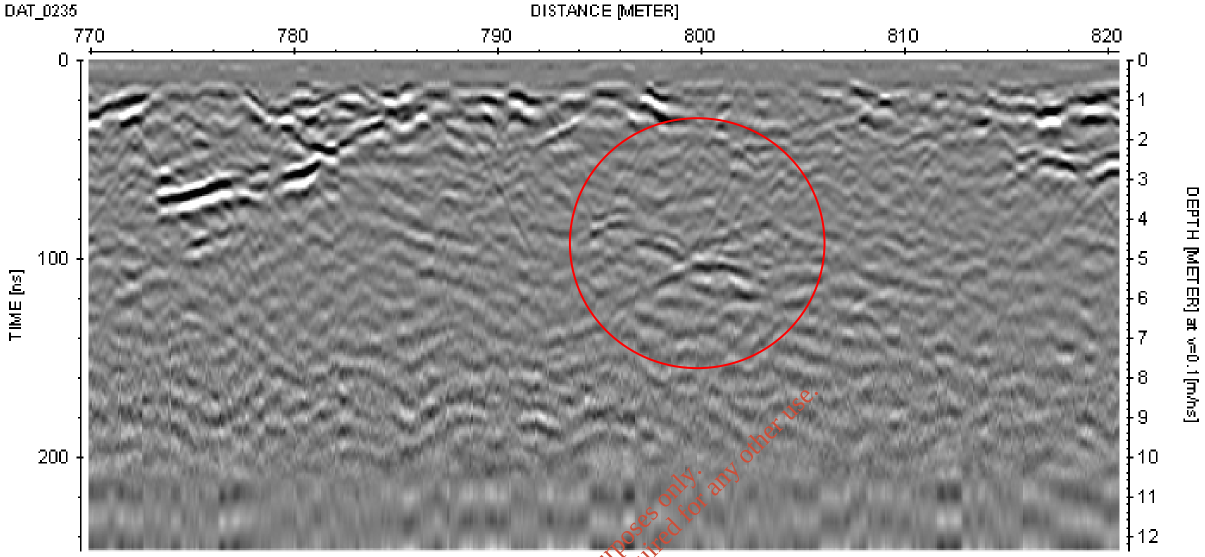
Temporal relocation (depth correction)
Maximum phase correction
Amplitude recovery gain (time dependant)
Background removal
Frequency bandpass filtering

GPR Relocation

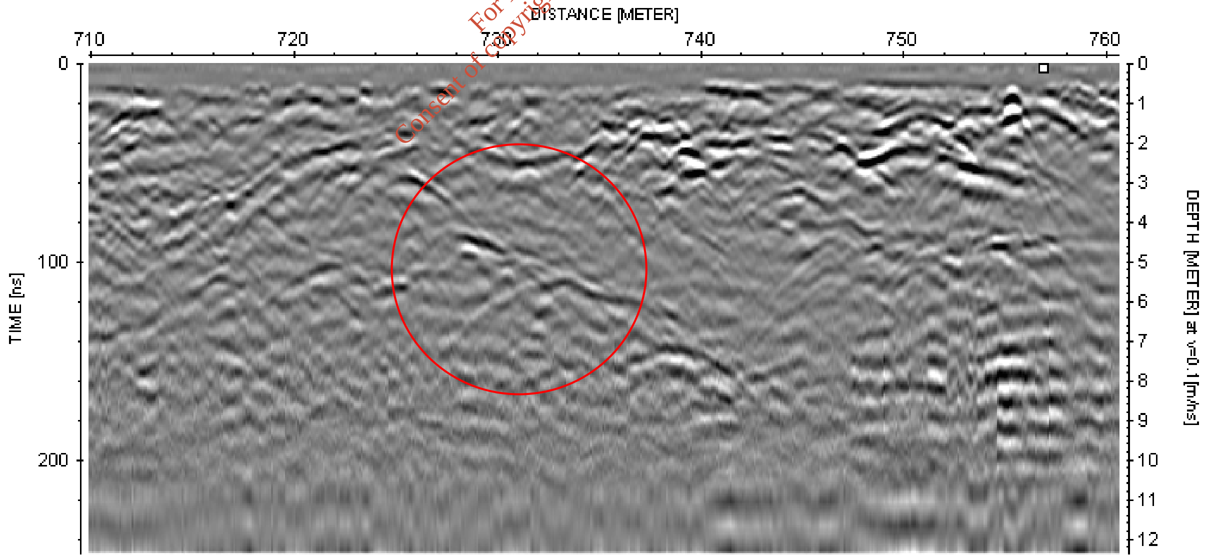
All data were referenced using an RTK Differential GPS system with c.20mm accuracy. All positions within this report are given in Irish National Grid coordinates.

APPENDIX C: GPR PROFILES – Probable Anomalies

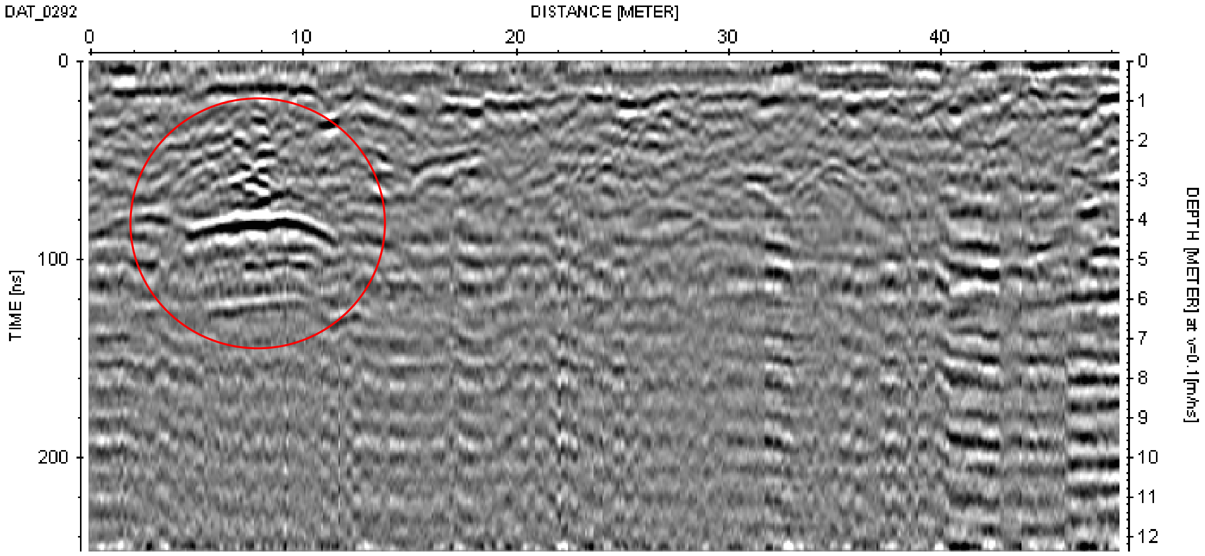
The following images are of the GPR profiles which contain the most likely void locations (i.e probable anomalies).



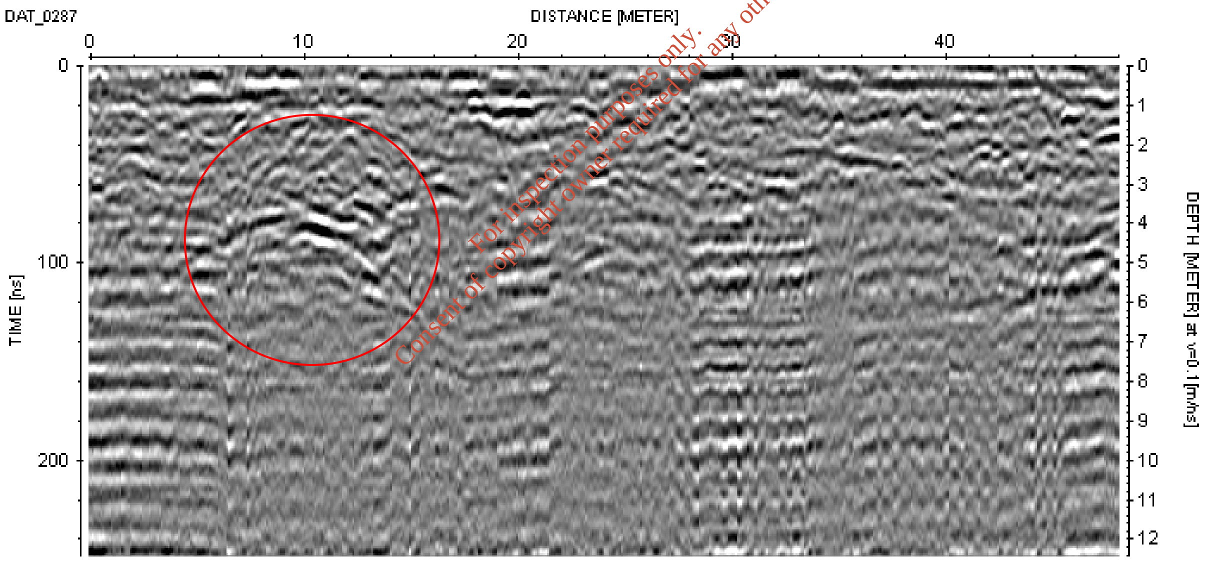
Anomaly No. A1



Anomaly No. A2



Anomaly No. A3



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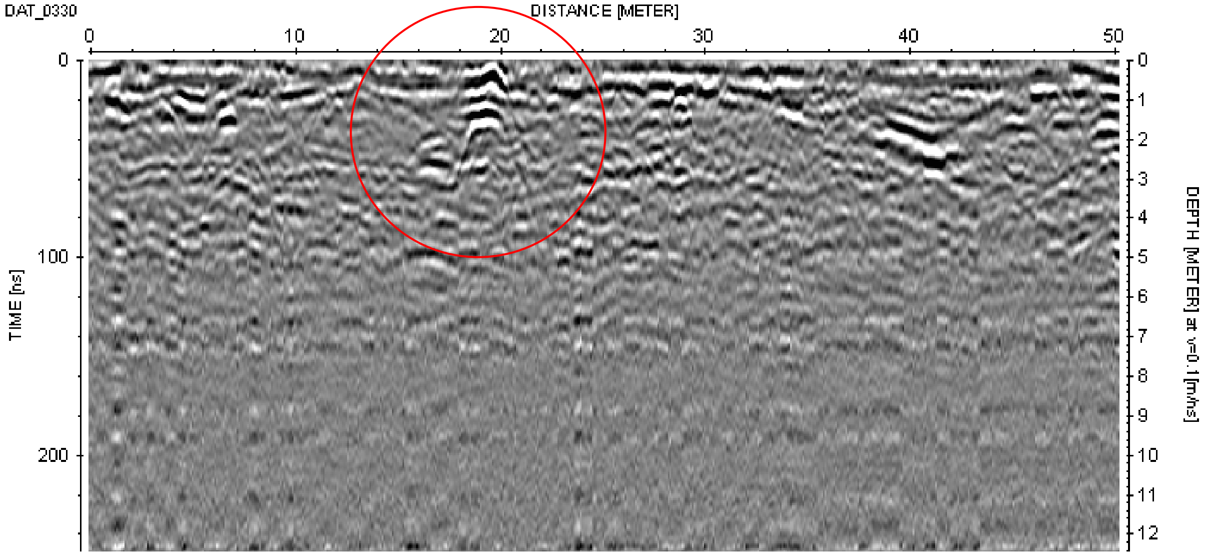

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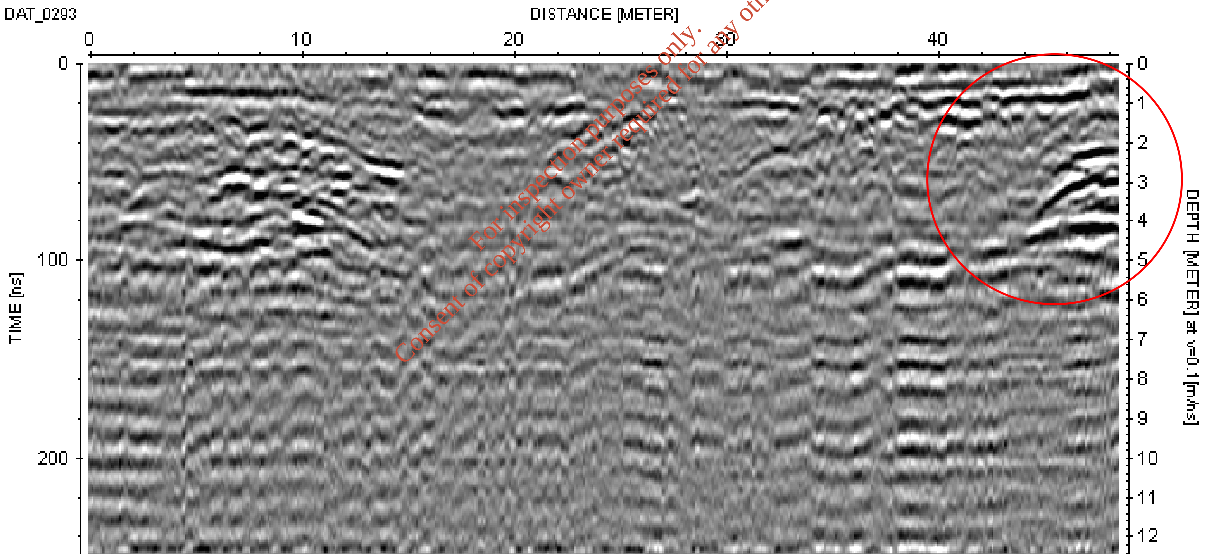

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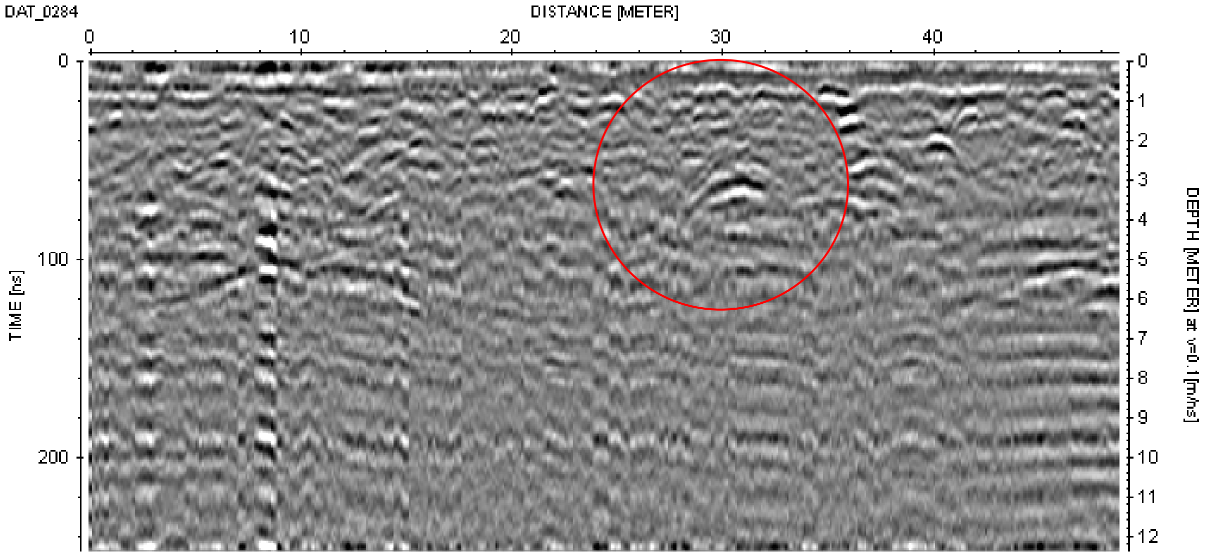

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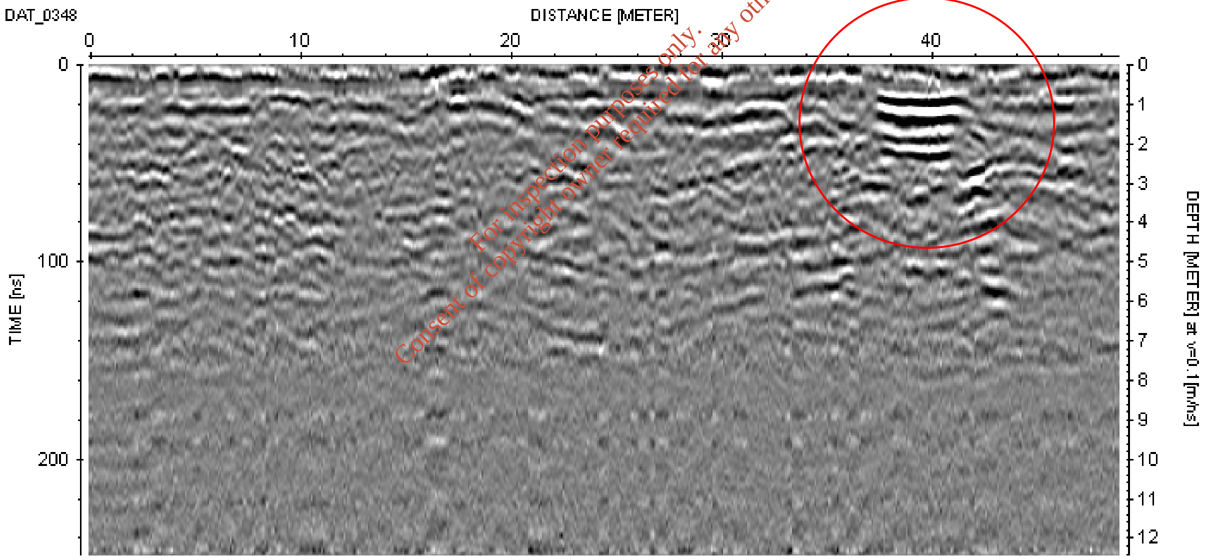

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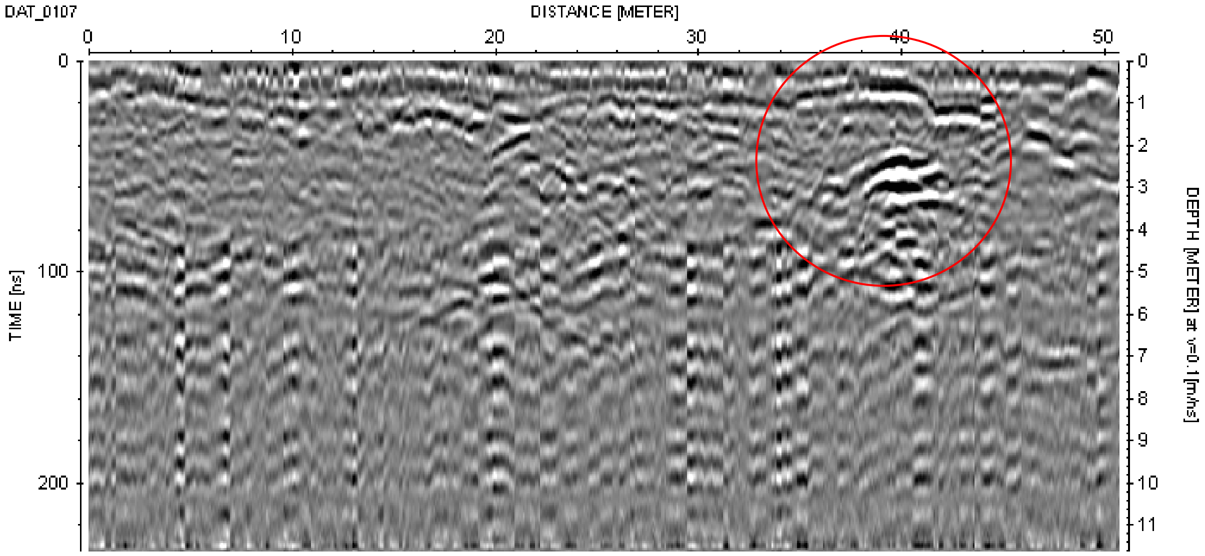

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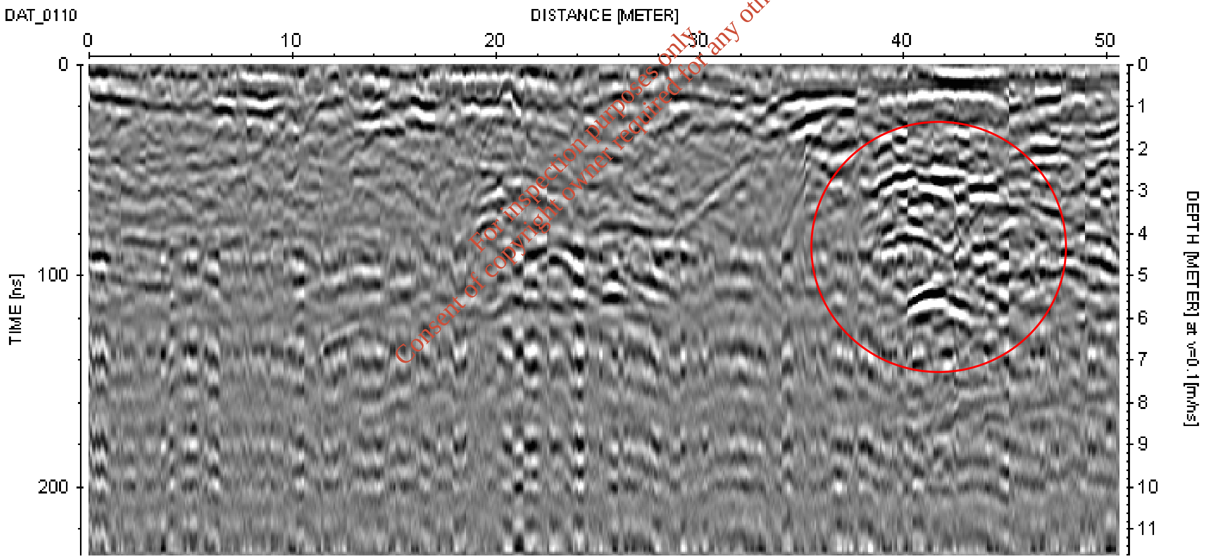

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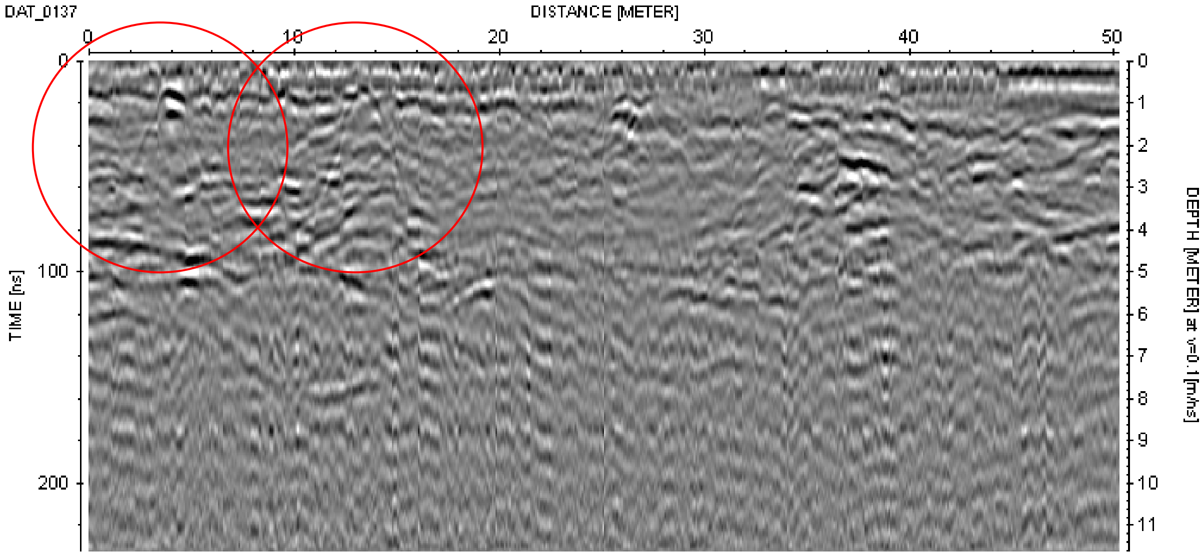

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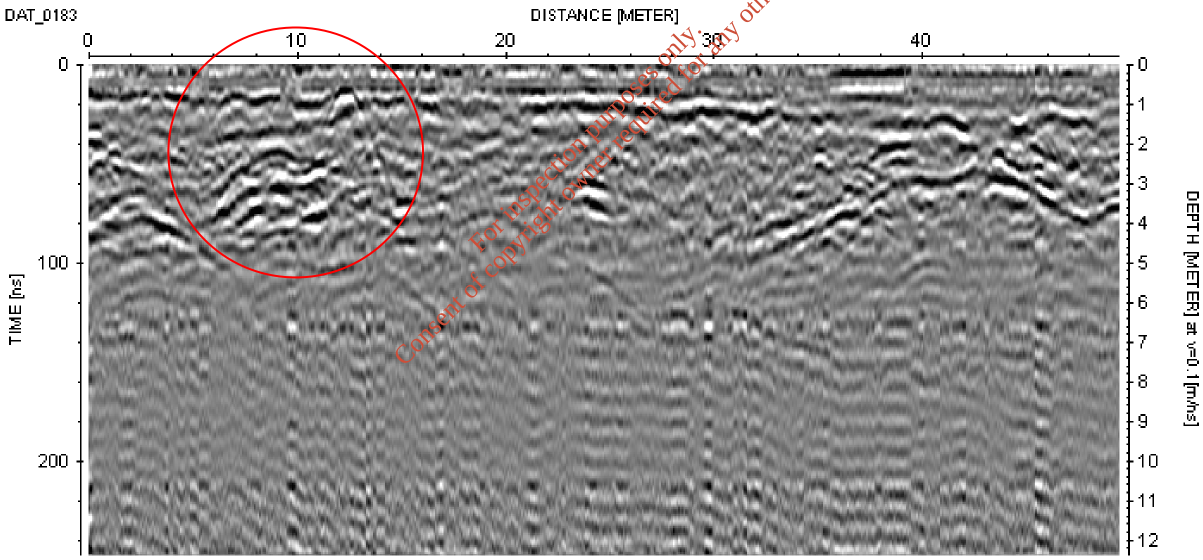

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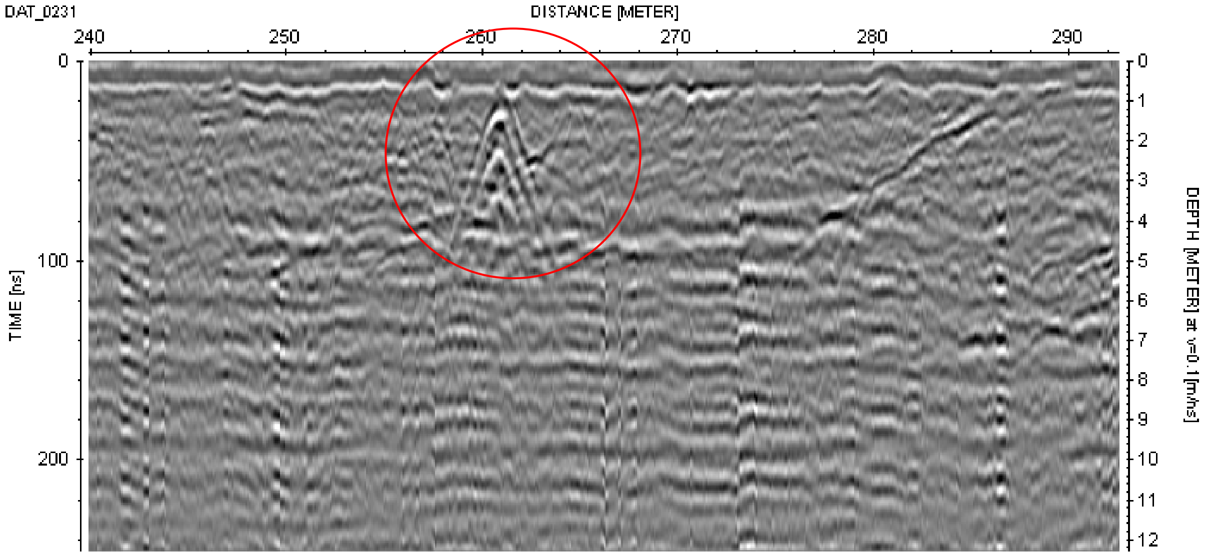

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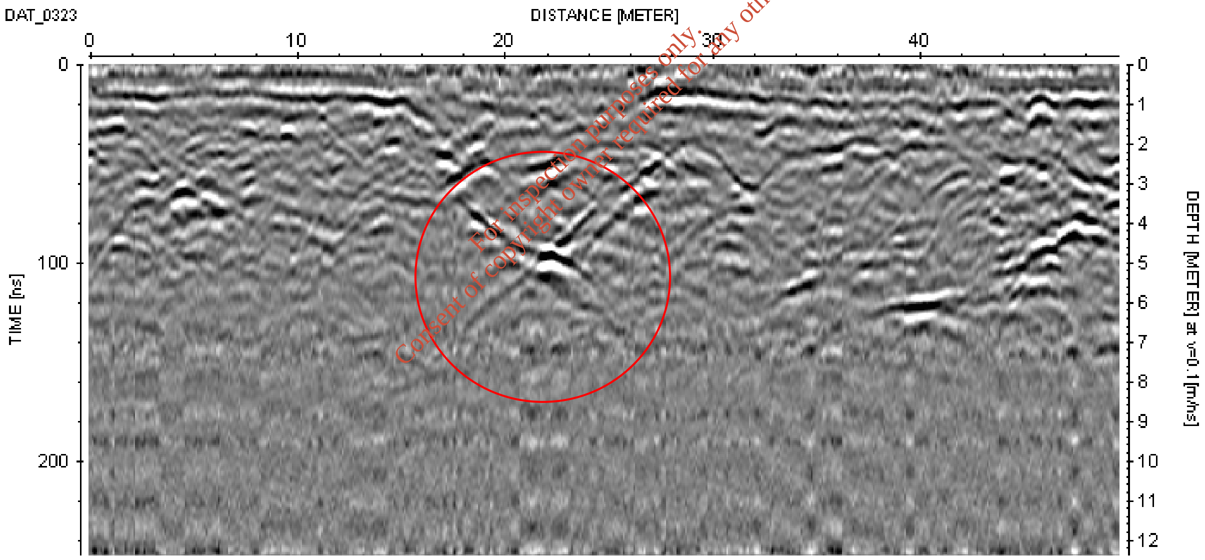

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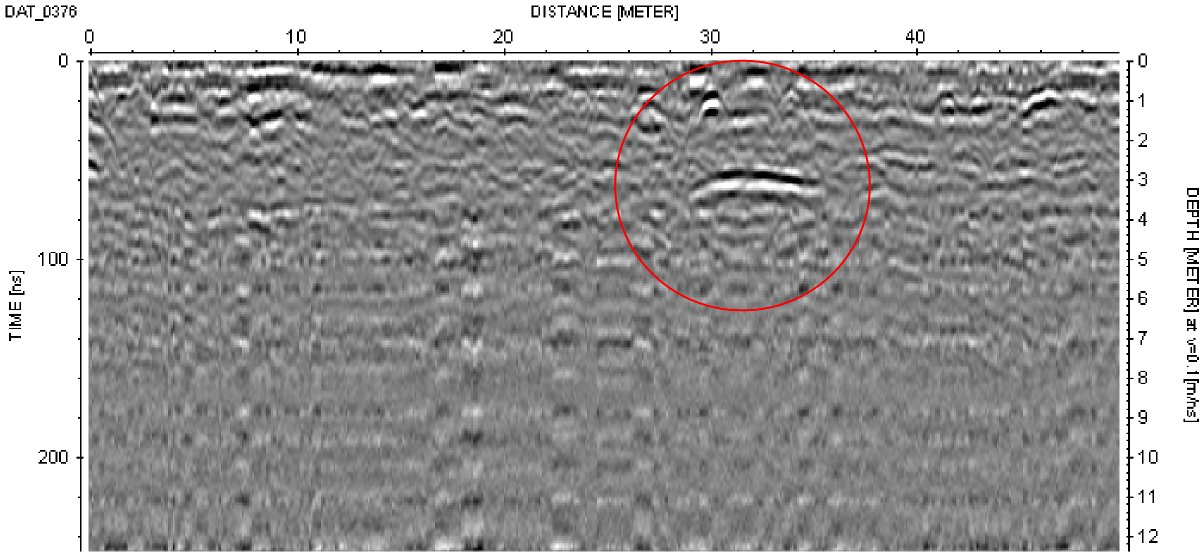

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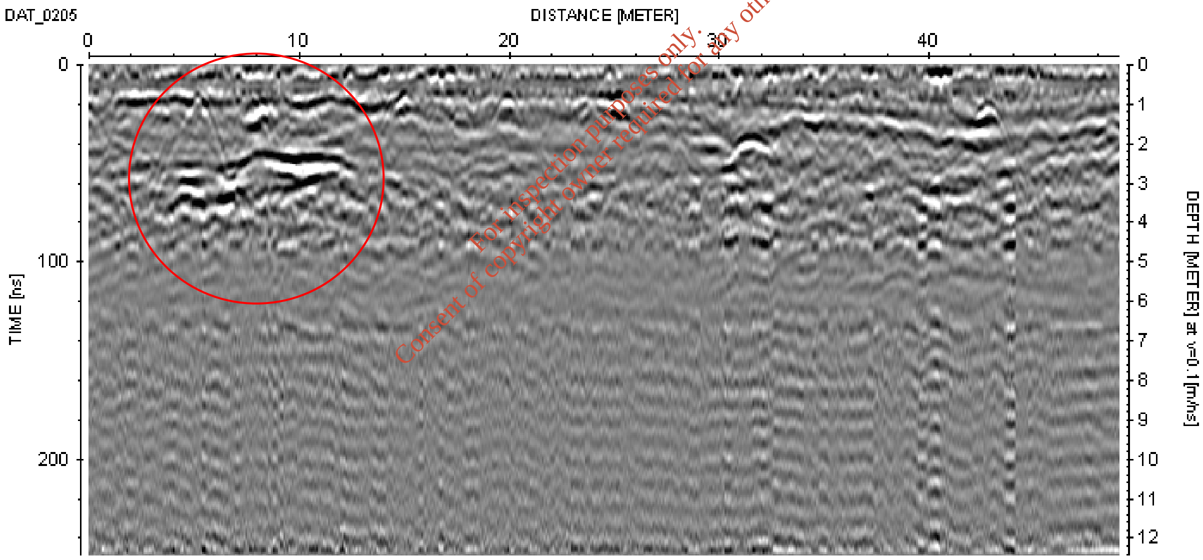

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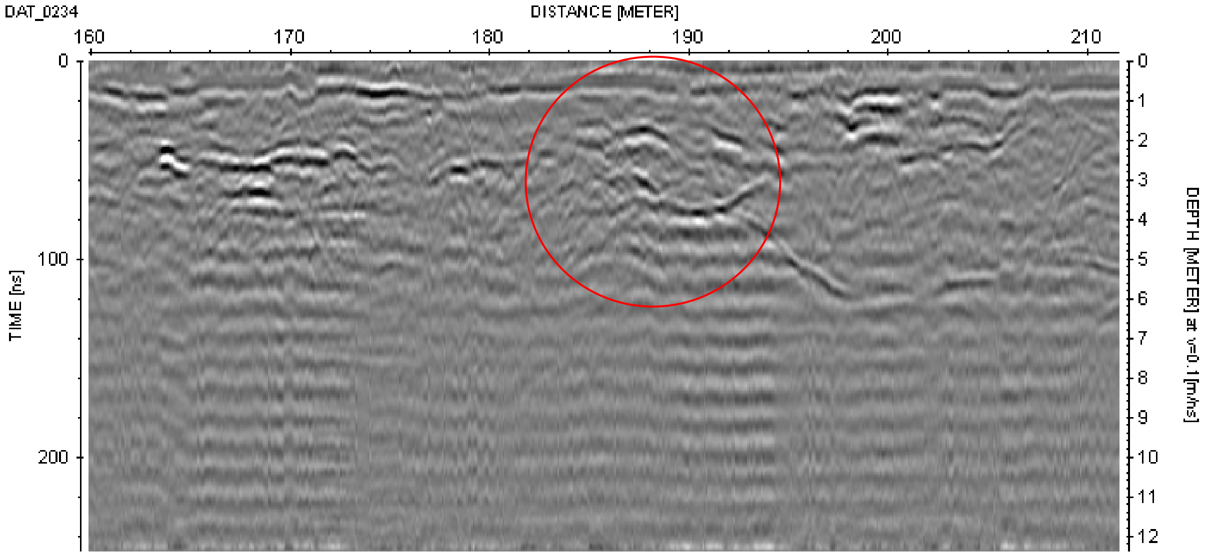

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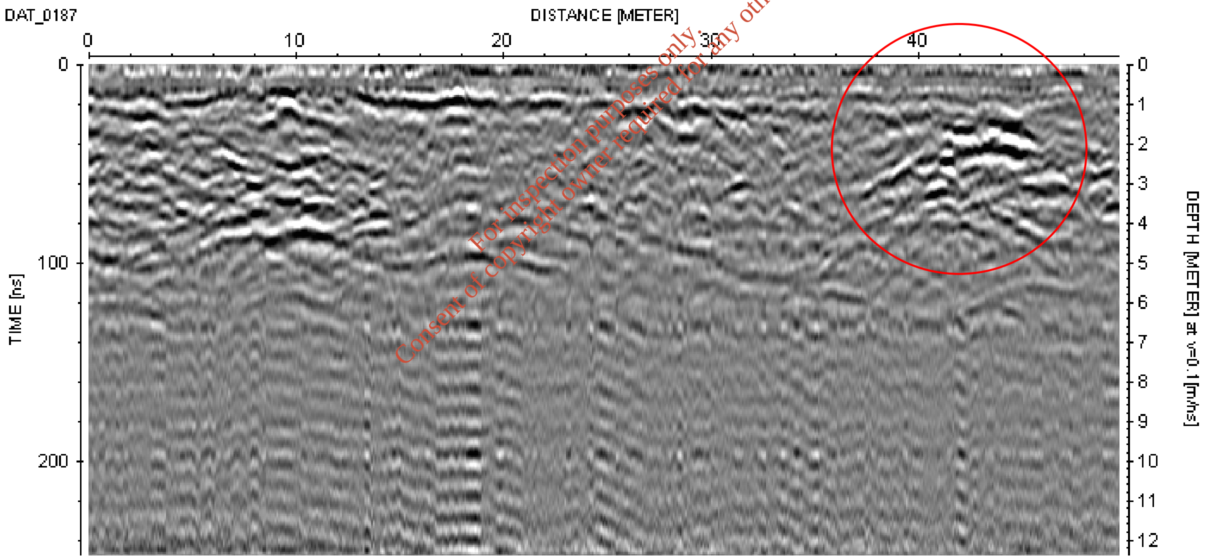

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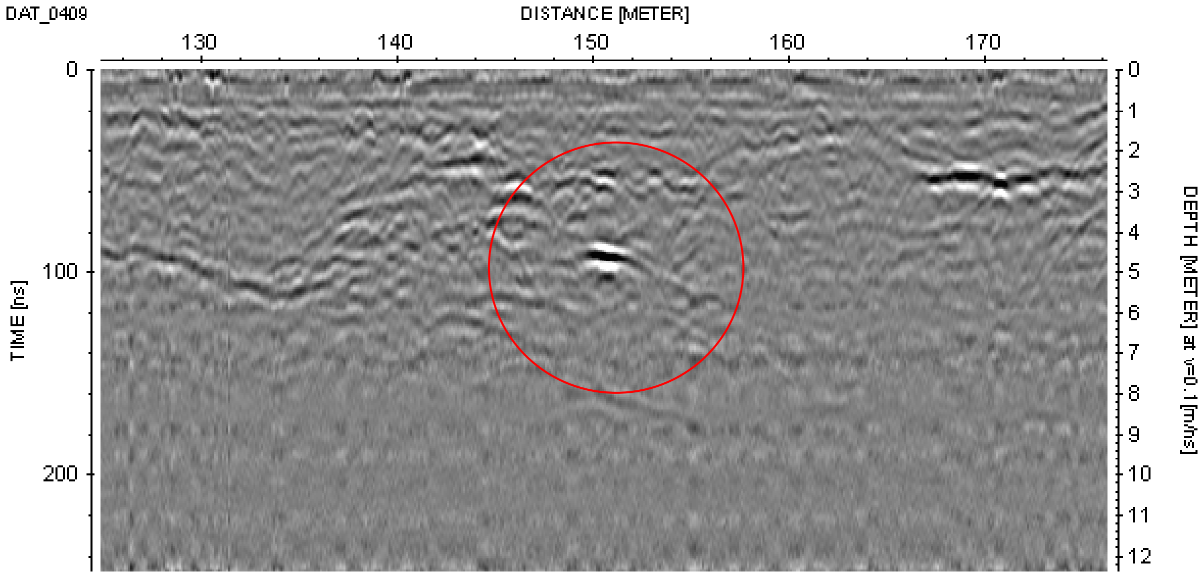

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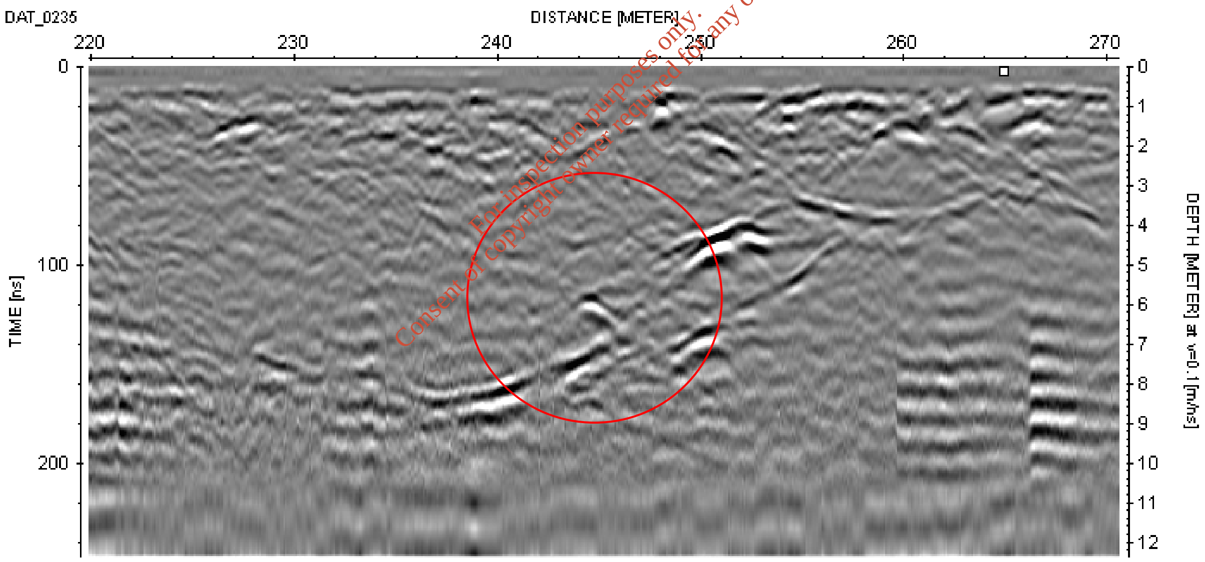

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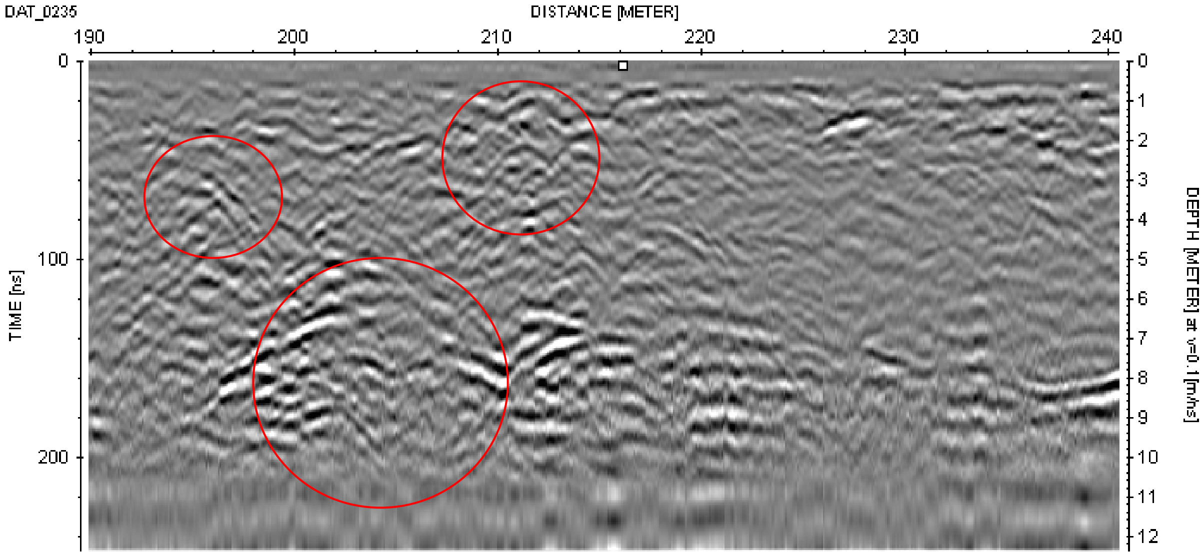

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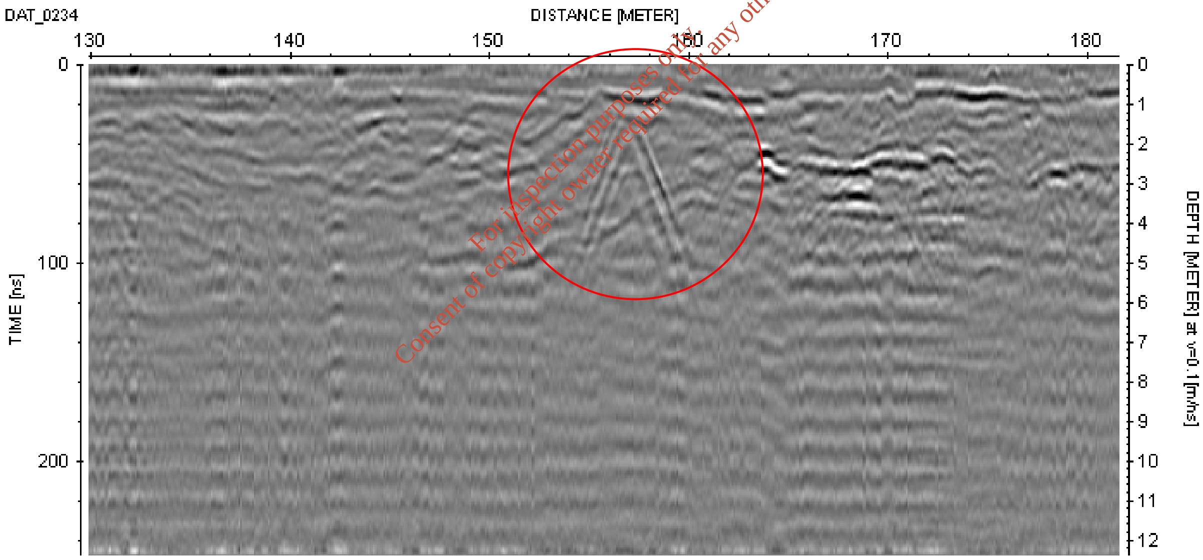

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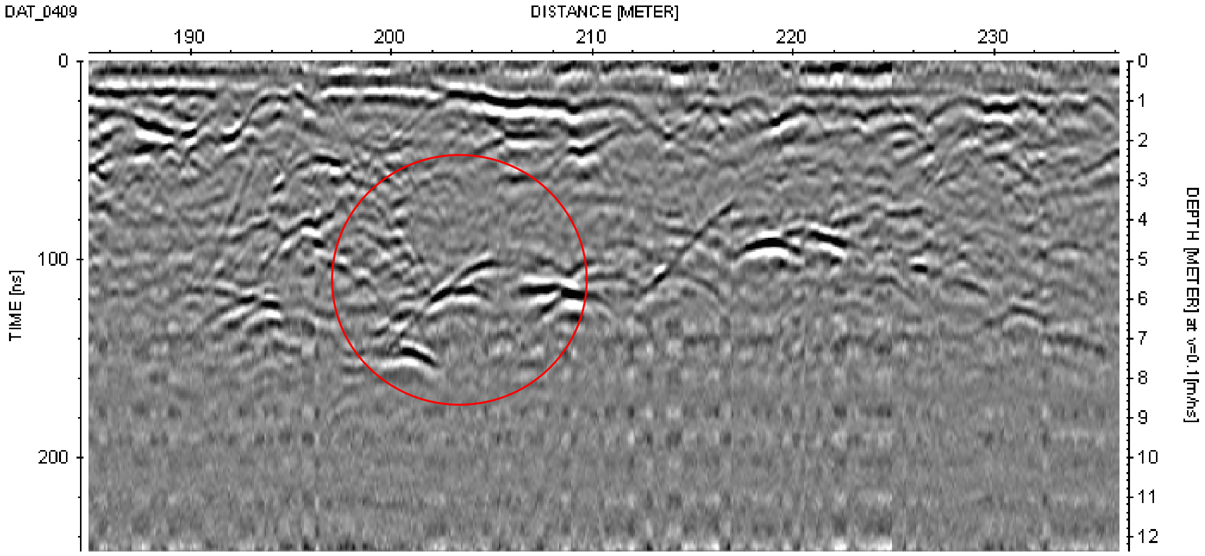

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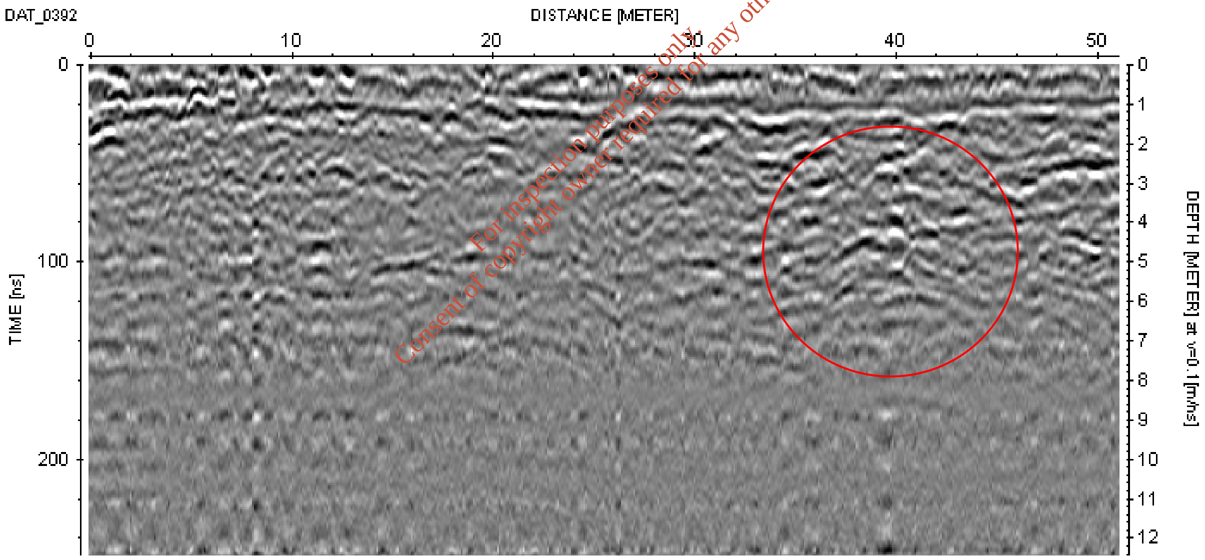

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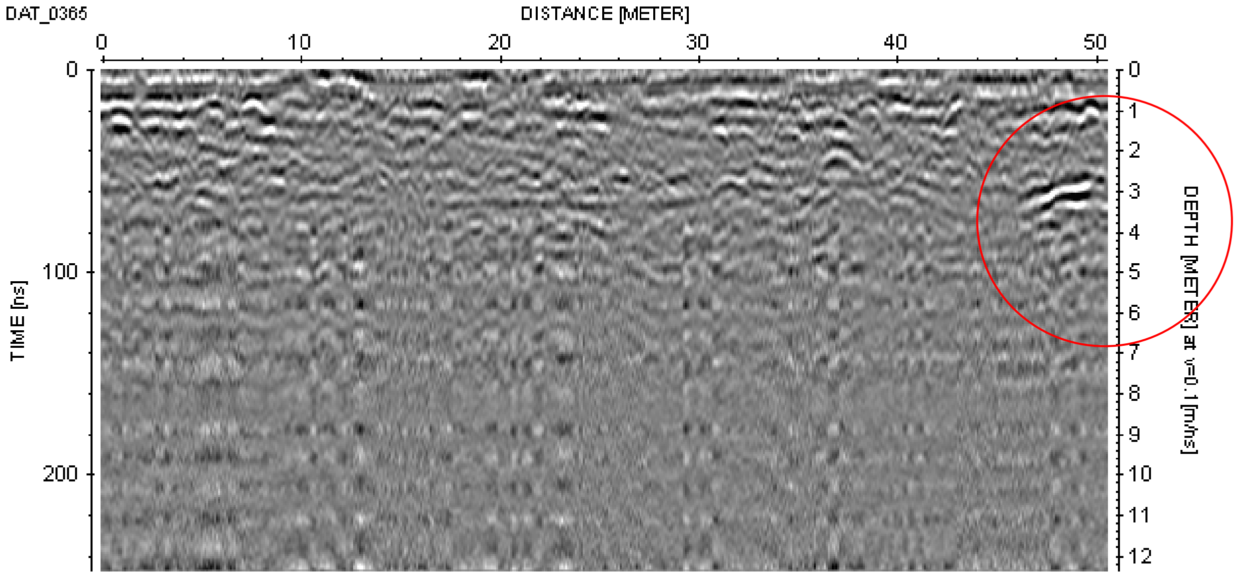

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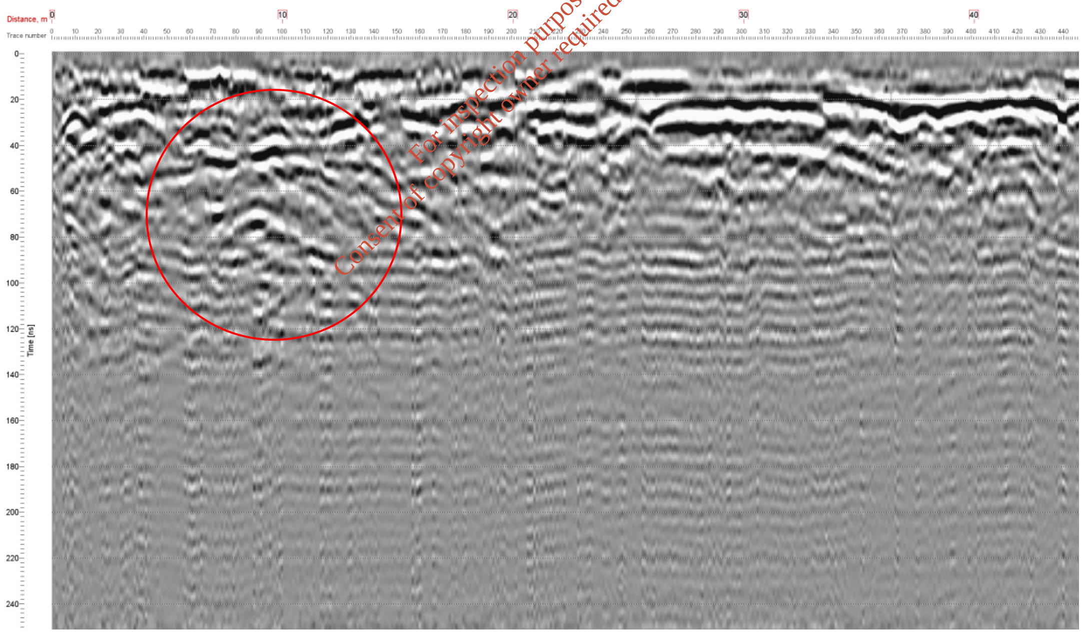

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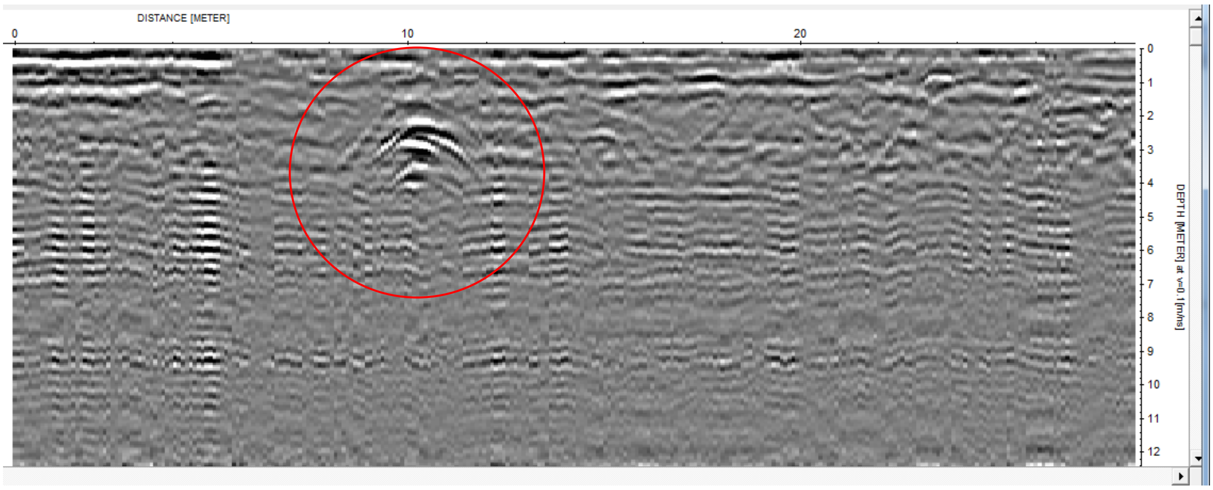
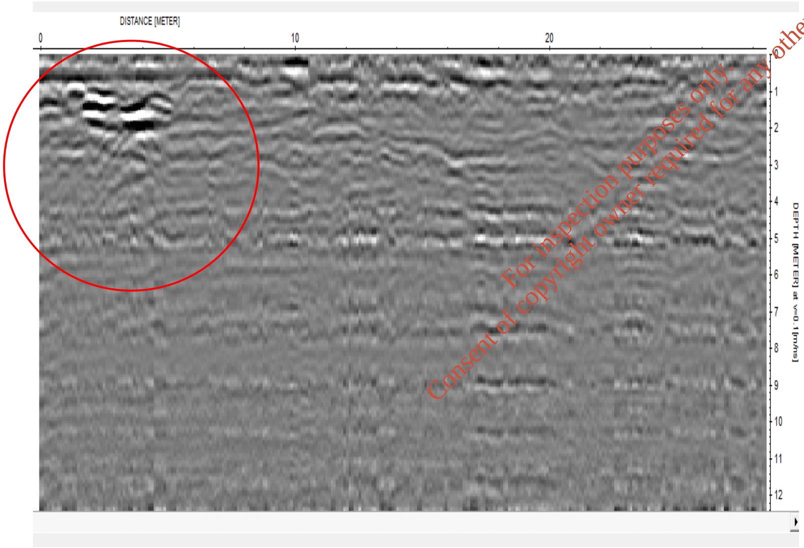
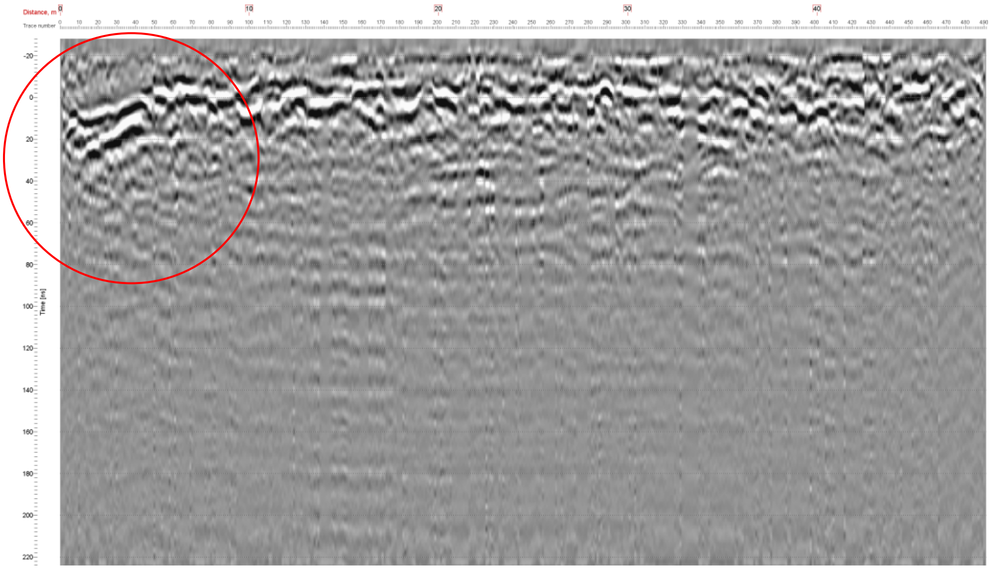


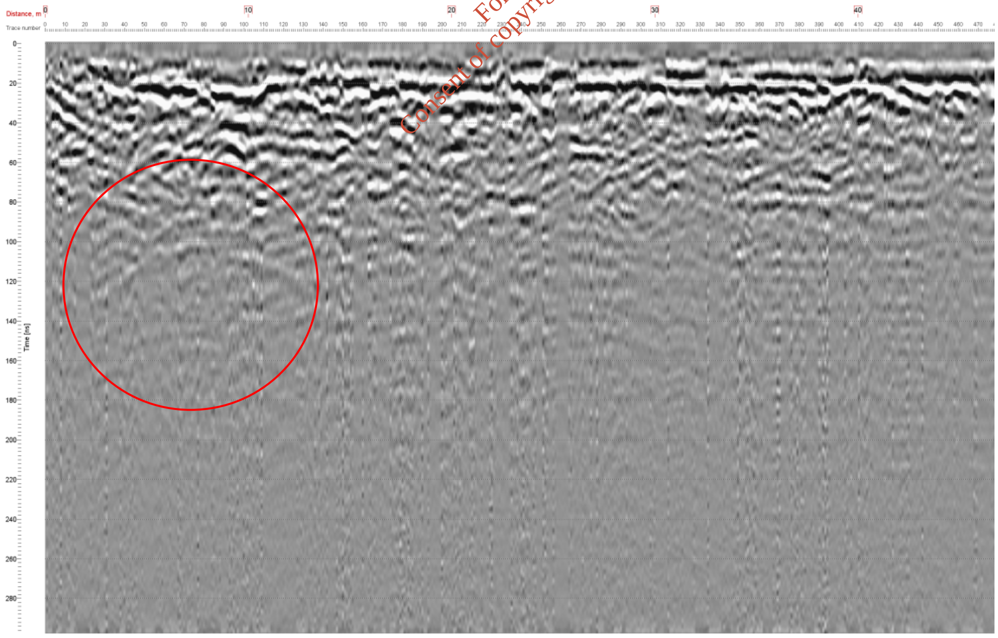
Anomaly A28 Record 578 showing point reflector at 10.2m at depth of 1.4m.



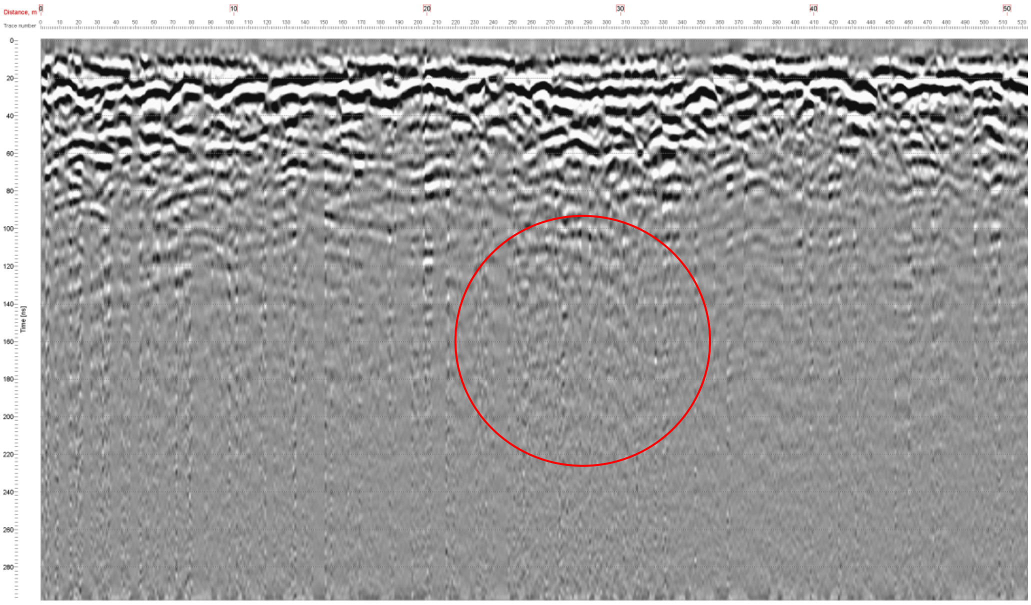
Anomaly A29. Record 441 showing flat reflector between 1.6-4.2m at depth of 1.4m. Located over Main Fissure.



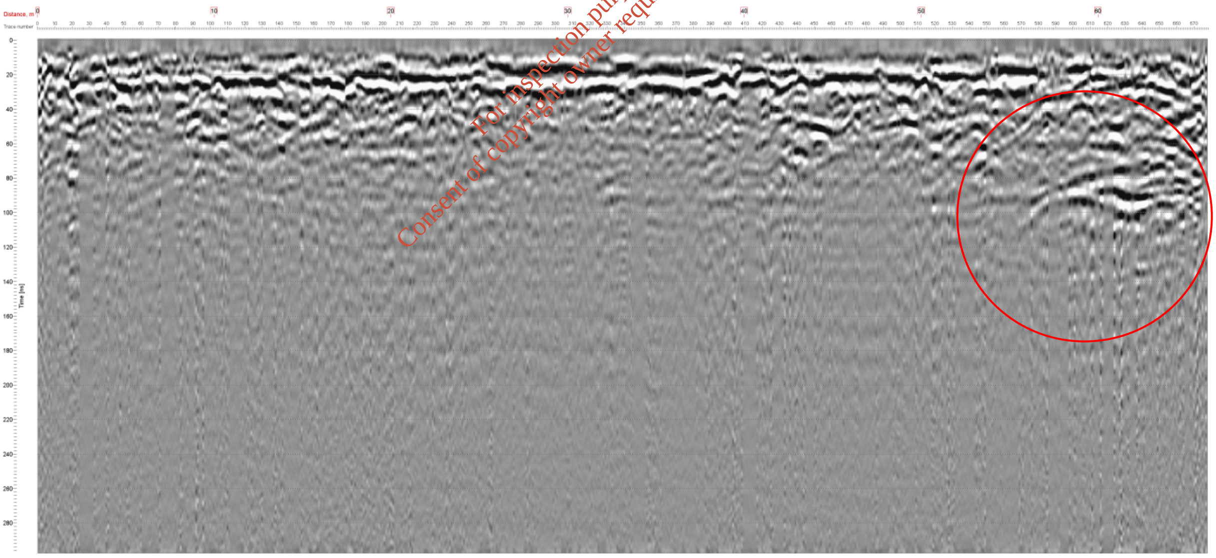
Anomaly A30. Record 437 showing weak reflector between 1.0-5.0m at depth of 1.3m.



Anomaly A31. Very weak but large anomaly centred at 8m along the profile.



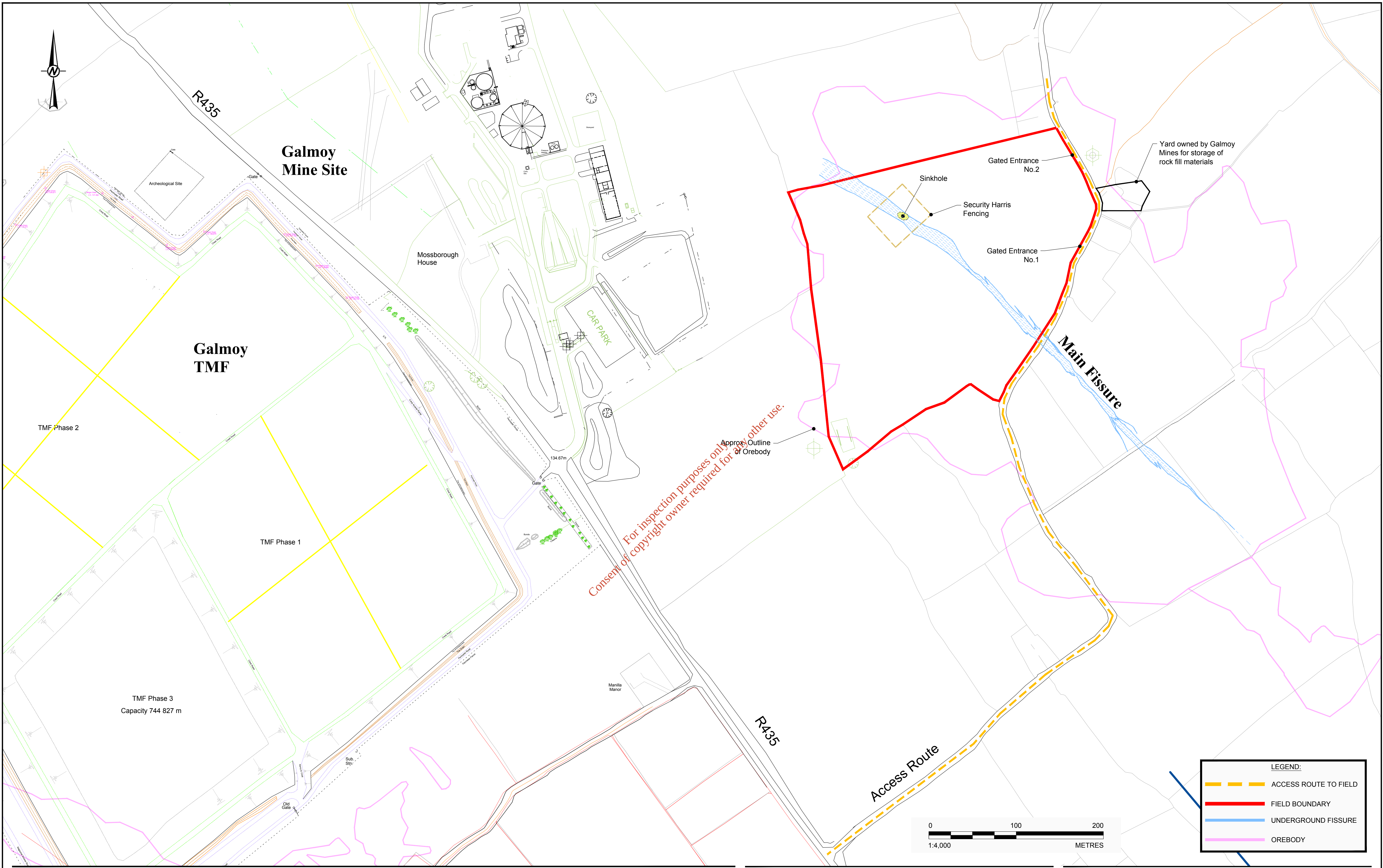
Anomaly A32. Very weak but large anomaly centred at 26m along the profile.



Anomaly A33. Anomaly centred at 58.7m along the profile.

APPENDIX C

Remediation Diagrams



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A	2014-03-06	Original Drawing	BK	BK	BB	BB	2014-04-03

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GALMOY SINKHOLE REVIEW AND REMEDIATION

TITLE

LOCATION PLAN

PROJECT No.	Size	Rev.		DRAWING
14 5071 50031	A3	B	1 of 5	1

Path: \\naa1-s-main01\Company\PROJECTS\5. MINING\GALMOY MINES\14 5071 5 0031 - Galmoy Mines Limited - Sinkhole Review\11. GRAPHICS\5. WORKING DRAWINGS\Sinkhole Remediation\ | File Name: Drawings 1 and 2 revB.dwg

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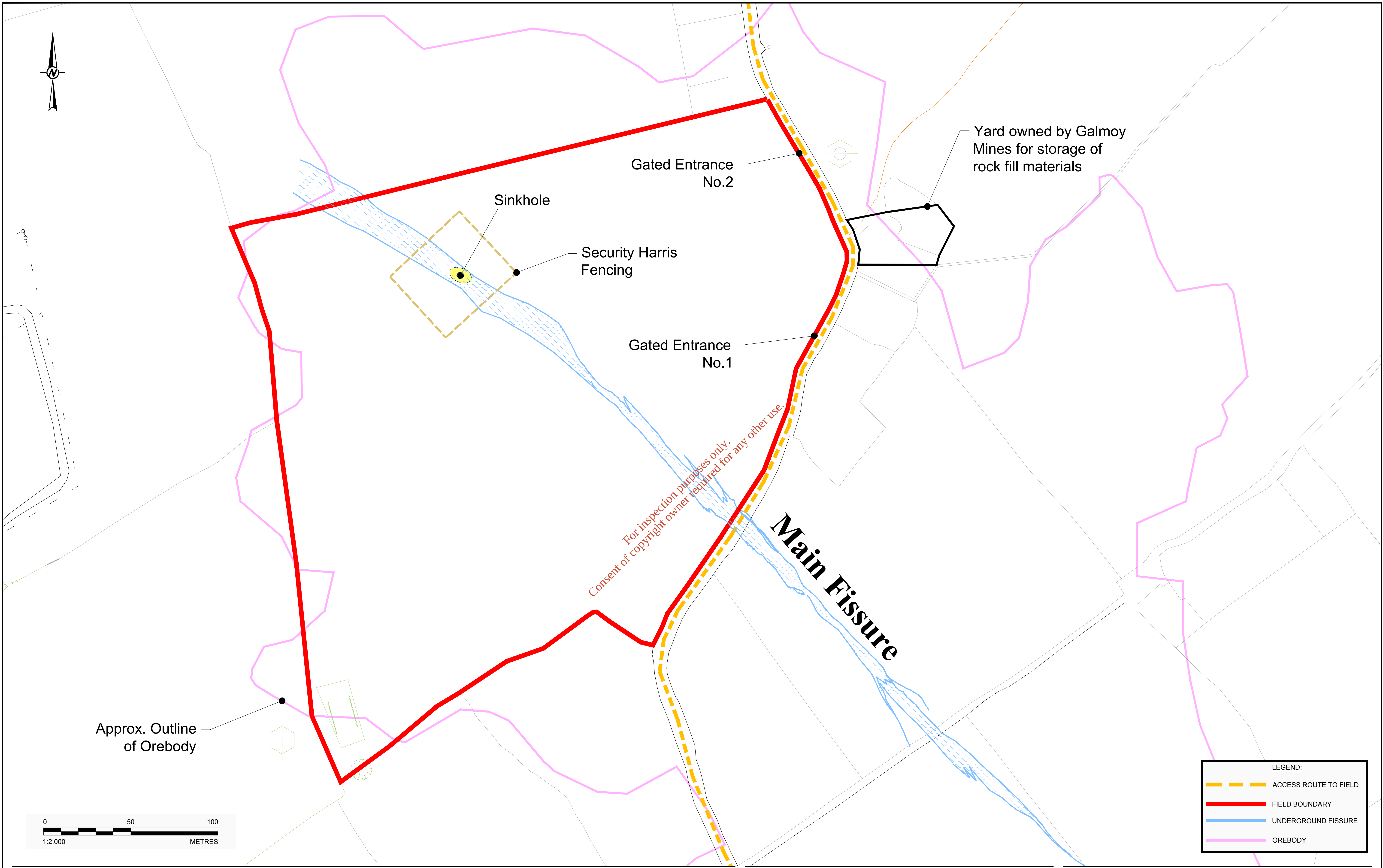

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PLAN OF SINKHOLE

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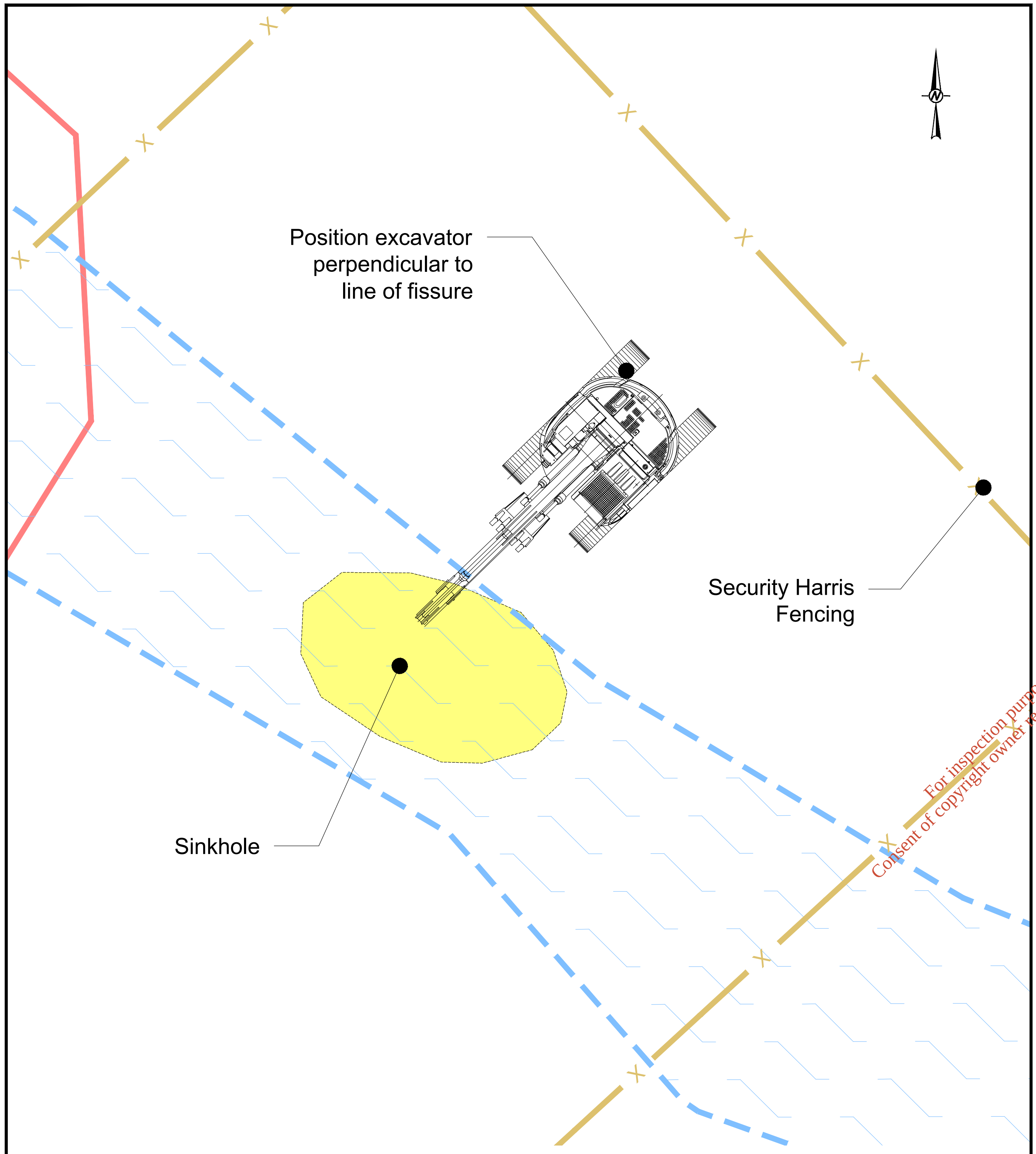
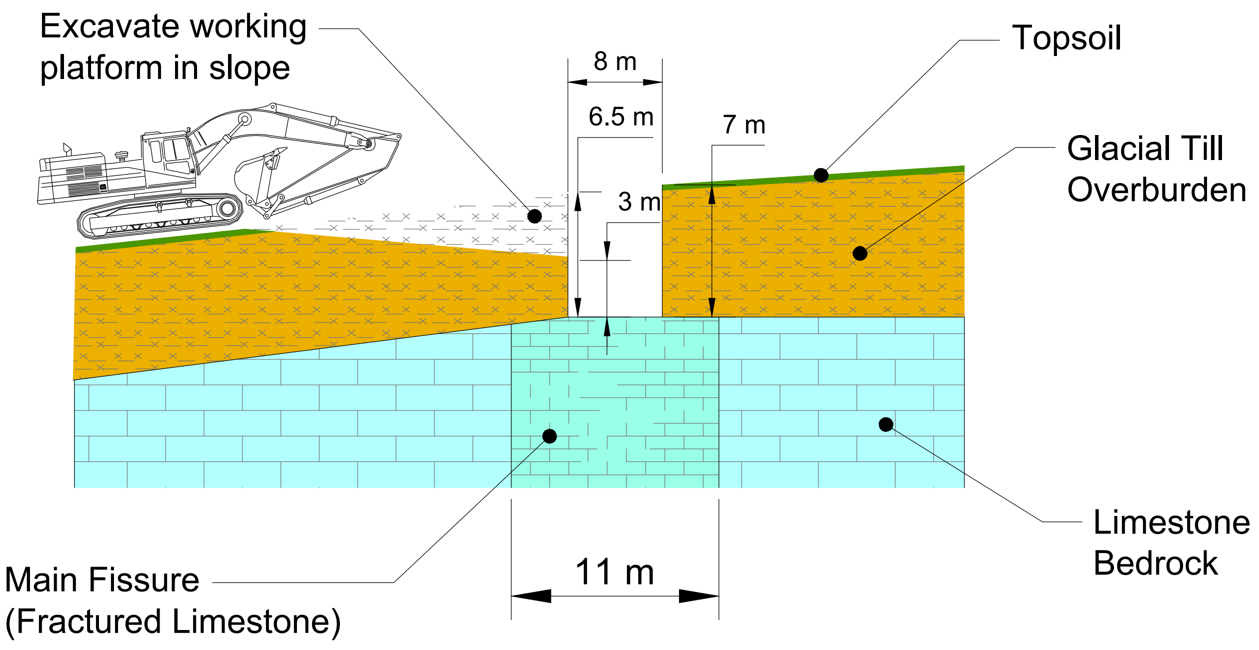
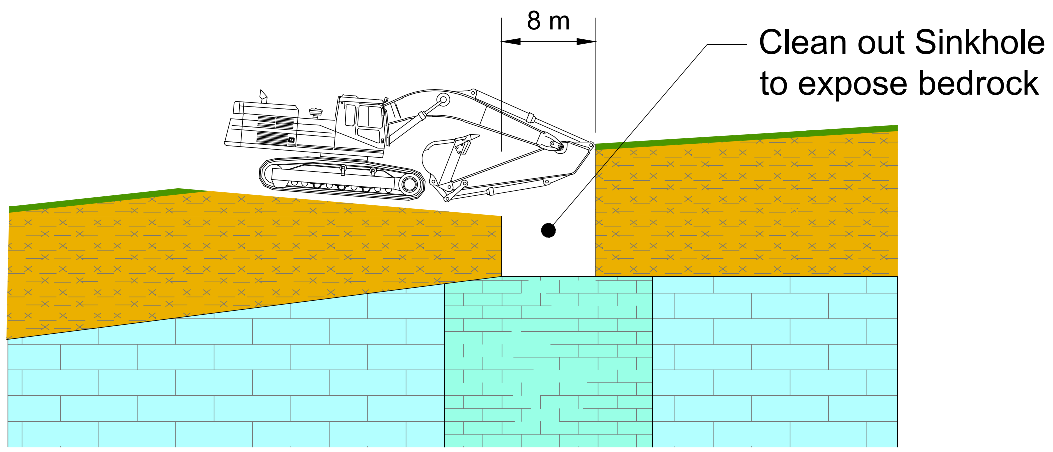


STEP 1: POSITION EXCAVATOR PERPENDICULAR TO FISSURE AND DOWNHILL OF THE SINKHOLE

0 5 10
1:250 METRES



STEP 2: EXCAVATE WORKING PLATFORM BY REMOVING SECTION OF SLOPE TO APPROX. 3m FROM BASE OF SINKHOLE



STEP 3: CLEAN OUT BASE OF SINKHOLE TO BEDROCK AND SHAPE SIDES FOR REPAIR PLUG

0 10 20
1:400 METRES

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B	2015	B	POB	POB	BB	BB	2014-05-09
A	2014-03-06	Original Drawing	BK	BK	BB	BB	2014-04-03

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TITLE

SINKHOLE REMEDIATION: SHEET 1 OF 3

PROJECT No.	Size	Rev.	3 of 5	DRAWING
14 5071 50031	A3	B		3

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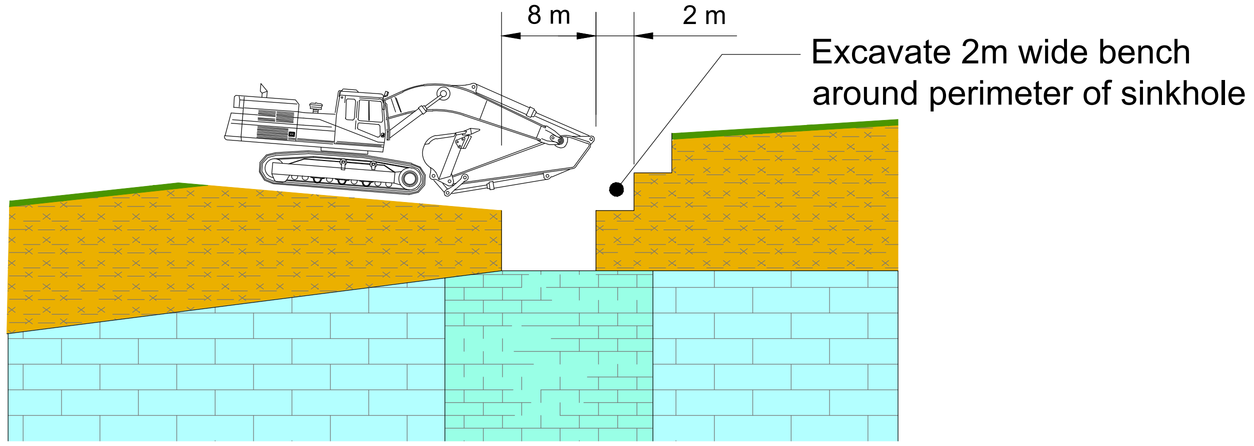
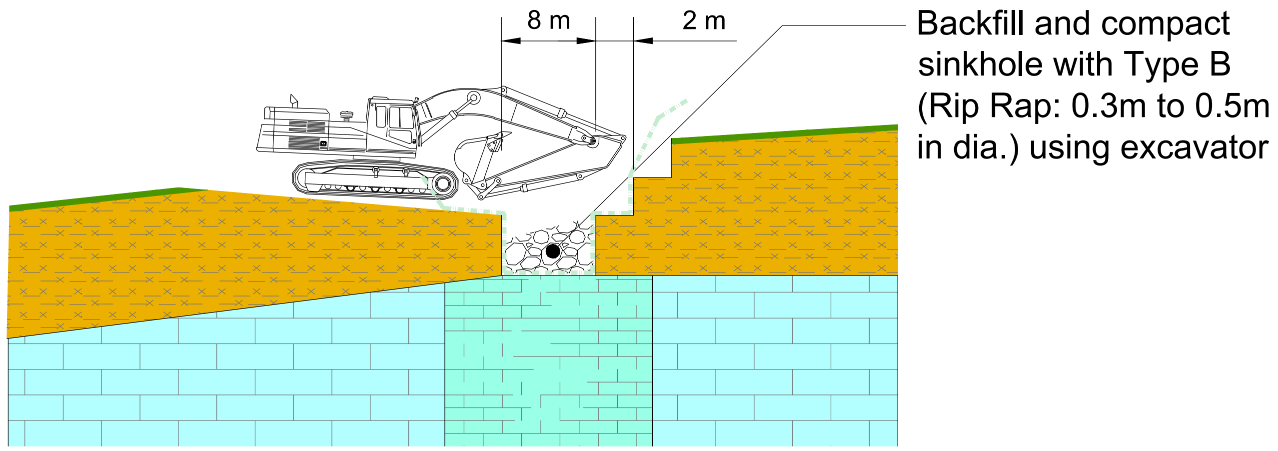
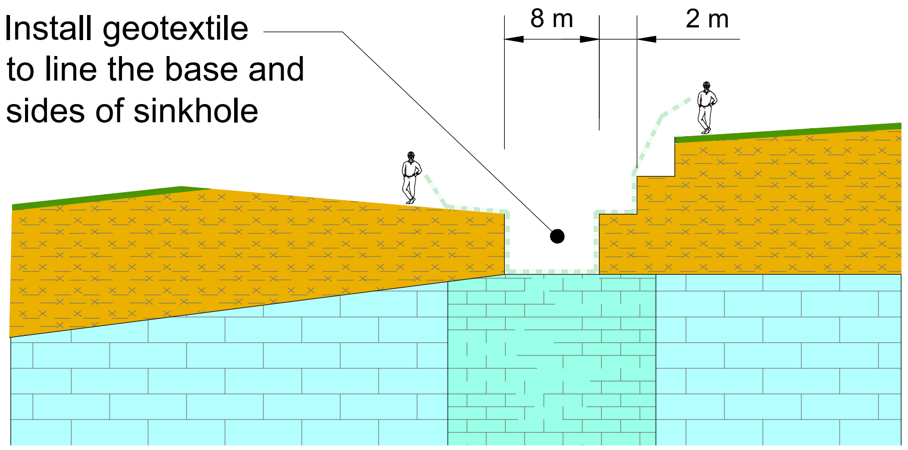


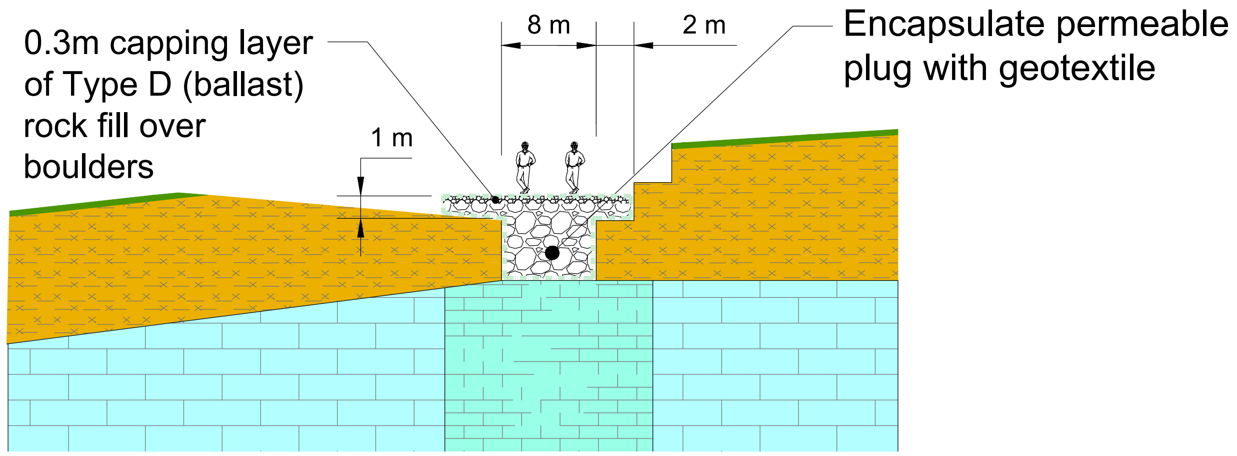
STEP 4: EXCAVATE A 2m WIDE BENCH AROUND THE PERIMETER OF THE SINKHOLE AT THE 3m ELEVATION



STEP 6: BACKFILL SINKHOLE BY PLACING TYPE B (RIP RAP) AND COMPACT INTO PLACE USING THE EXCAVATOR BUCKET



STEP 5: DRAPE GEOTEXTILE ALONG BASE AND SIDES OF SINKHOLE ALLOWING 1m OVERLAP BETWEEN ROLLS AND ENSURE SUFFICIENT LENGTH TO ENCAPSULATE PLUG



STEP 7: PLACE 0.3m LAYER OF TYPE D (BALLAST) ROCK FILL OVER BOULDERS AND FOLD OVER GEOTEXTILE WRAP

0 10 20
1:400 METRES

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SINKHOLE REMEDIATION: SHEET 2 OF 3

PROJECT No. 14 5071 50031
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Rev. B
4 of 5
DRAWING 4

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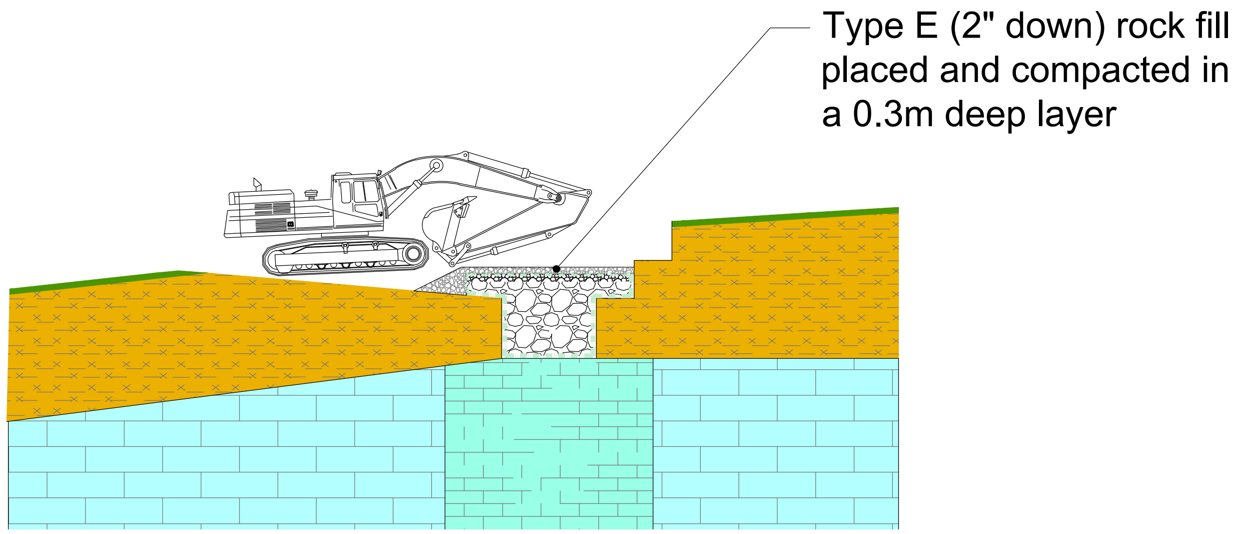
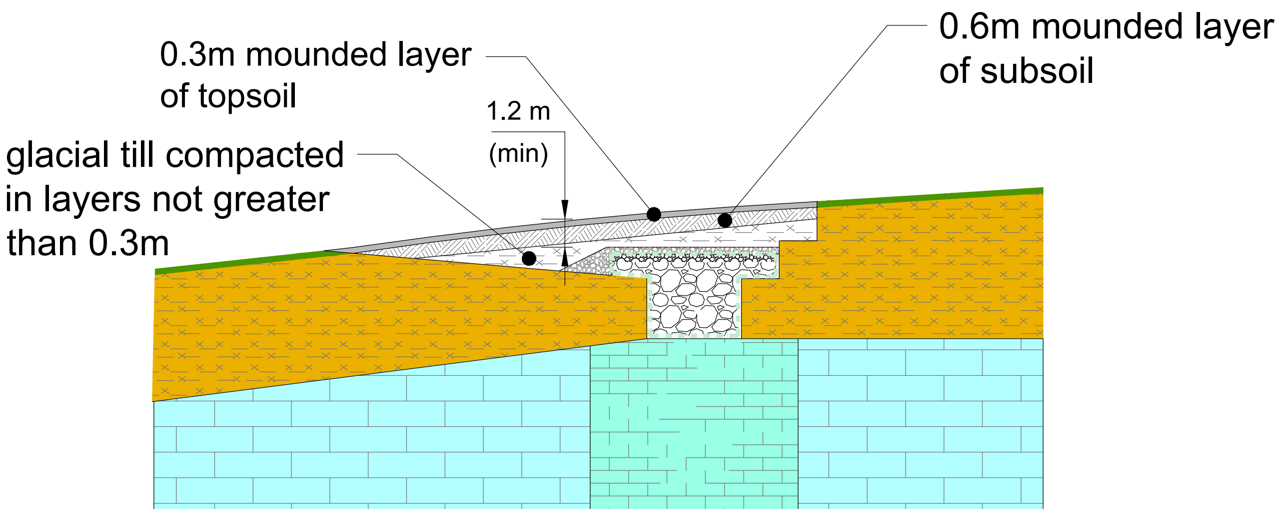
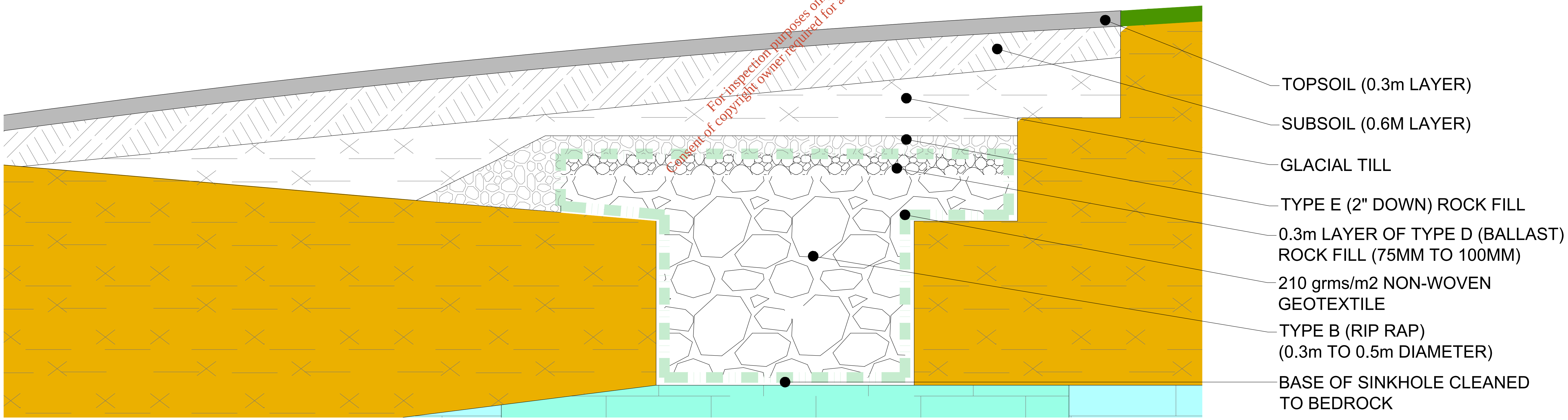


STEP 8: PLACE TYPE E (2" DOWN) IN A SINGLE 0.3m LAYER
AND COMPACT USING THE TRENCH-WHACKER
FITTED TO EXCAVATOR



STEP 9: PLACE AND COMPACT GLACIAL TILL IN LAYERS NOT GREATER
THAN 0.3m TO WITHIN 0.8m OF THE FINAL SURFACE. CAP WITH
0.6m LAYER OF COMPACTED SUBSOIL AND 0.3m LAYER OF TOPSOIL

0 10 20
1:400 METRES



DETAIL SECTION OF SINKHOLE REMEDIATION WITH PERMEABLE PLUG

0 2 4
1:80 METRES

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SINKHOLE REMEDIATION: SHEET 3 OF 3

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solutions@golder.com
www.golder.com

Golder Associates Ireland Limited
Town Centre House
Dublin Road
Naas
Co. Kildare
Ireland
T: +353 45 87 4411