Figure 2.23 Rathcore Quarry eastern margin - weathered limestone epikarst and residual karst orange clays overlain by dark boulder clay

the clay was not transported and deposited by ice or water. The irregular small and large boulders in the clay appear to be remnants of partially decomposed limestone in situ. The problem with the classic in situ weathering origin is the colour of the clay. The orange and rich yellow colour indicates a significant content of iron oxides in the clay. These may have come from the Waulsortian limestone, but the evidence from the rock beneath the clay is that there is very little iron sulphide (pyrites) or iron oxide in the limestone. It is a very pure limestone. Therefore, to create a thick layer of residual iron rich clay would require the solution weathering of a great volume of pure limestone. It is possible but it would take a long time.

However, there is a possible alternative origin for the clay, suggested to me by Colin Bunce. When an ice sheet melted and retreated, the land surface was left covered with loose detritus ranging in grain size from very fine rock flour to large boulders. For many years there would have been no soil or vegetation to bind the fine material left behind by the ice. During dry periods, winds could pick up the fine material, creating swirling dust storms over a barren stony landscape. The dark grey limestones and black shales rocks to the south and east of Rathcore contain iron pyrites and oxides that could be the source of iron rich dust. Nearby. and to the east of Rathcore there would have been the large exposure of Namurian shales. These rocks contain an abundance of iron pyrites and iron oxide. Therefore, an alternative origin for the relatively iron rich clays could be wind blown iron rich dust called Loess from the areas around.

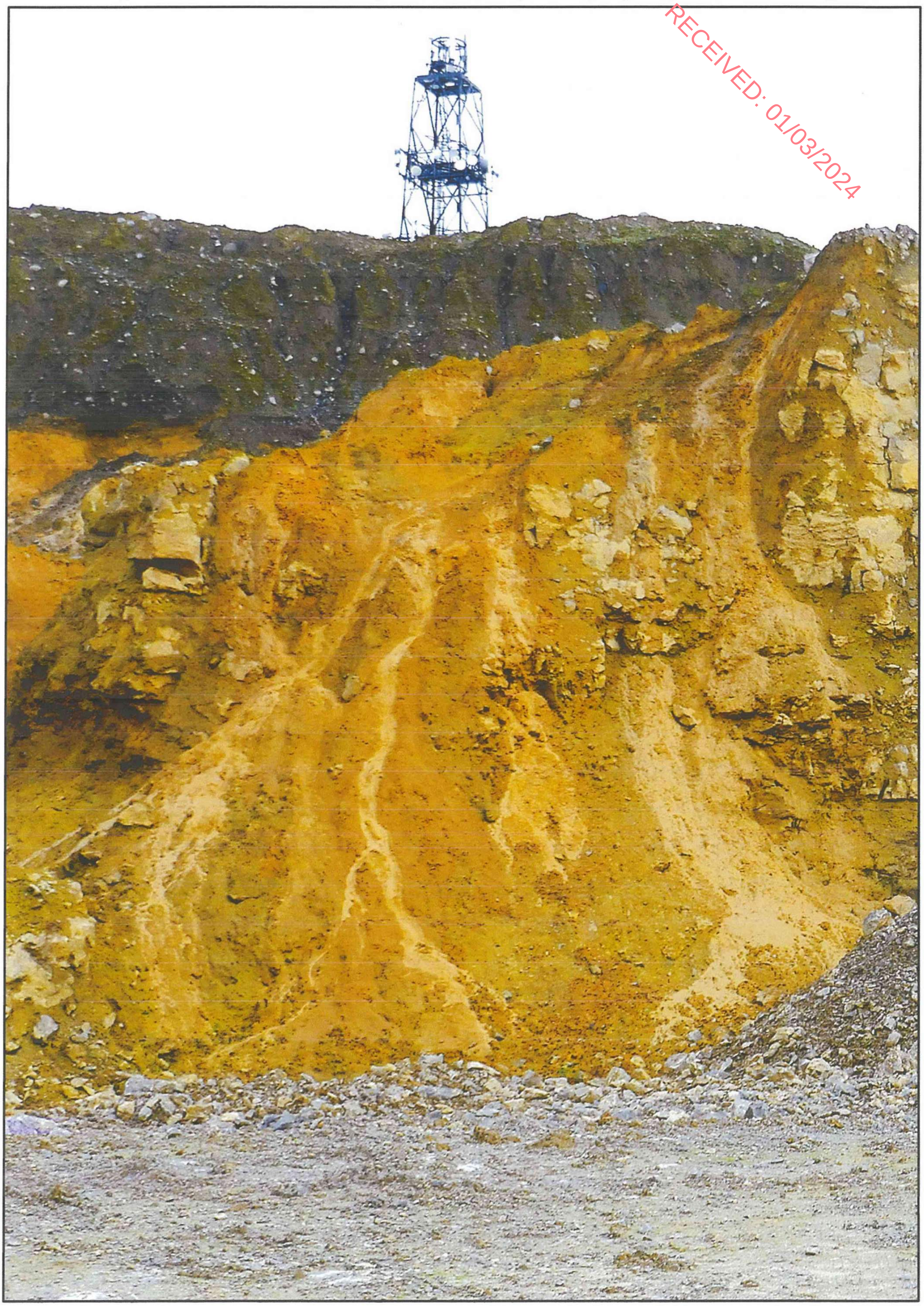
To add to the complexity there is a small depression on the east sidewall of the quarry that contains rich dark brown clays, that appear almost organic. I have tried igniting them and they don't burn or smoulder. Therefore, they are not lignite and the organic content is low.

The orange clay and other debris filling in the karst depressions appears to have either slumped into the depression or have been washed or blown into the depression. Therefore, part of the clay deposit may have been moved by water on the surface.

The yellow clay at Rathcore can also be found underground. This clay is both tough and competent and also soft and easily moved. It is a pale yellow clay found in the karst conduits in the bedrock. It is assumed that it has been washed into the karst conduits from the surface and is not an in-situ deposit

The brown clays and yellow clays must have been created or laid down before the last advance of the ice sheet, because they lie below the dark grey and lighter coloured sandy tills and boulder clays. There were multiple periods of glaciation in the 2.6 million years before the final retreat of the ice sheet, that is generally taken to have ended 11,700 years ago. The brown and yellow clays were perhaps created during a temporary recession of the ice sheet during the preceding 5000 years . The buried topography of the Waulsortian limestone around Rathcore

Figure 2.24 Rathcore Quarry Boulder Clay overlying clay filled karst depression



hill could be an ancient topography, created before 2.6 million years ago and then heavily modified during the numerous glaciations.

The glacial and interglacial deposits have a considerable groundwater significance in the context of the quarry and its connection to the area around.

It appears that the karst weathered limestone core of Rathcore Hill has been smothered by clays/loess and then sandy tills and boulder clay. The covering appears thinner on top of hills, and thickens on the flanks. These glacial or interglacial deposits can have a low permeability. Hence, they can form a seal, or confining layer above the limestone.

What this may mean is that a groundwater flow system in the limestone conduits would be separated from the groundwater in any shallow groundwater aquifer in the sandy tills and gravel deposits above boulder clay and yellow clays

It would also mean that the groundwater flow system in the limestones away from the open window created by the quarry excavation could be hydraulically confined, and in effect a pressurized groundwater system.

2.7.2 Exploration drilling

Exploration drilling in or around an existing quarry is usually limited to a few holes, or considered unnecessary because the geology is well understood. The objective of the structural geology assessment was to identify structural lineaments that might give rise to the formation of karst conduits in the bedrock. The findings of the structural survey existing information strongly indicated that there would be karst conduits in the bedrock under the quarry floor.

Kilsaran agreed to a determined effort to try to find the distribution and nature of karst conduits under the quarry floor for three reasons.

First, to assess any linkage there may be between groundwater under the quarry floor with groundwater outside the quarry.

Second to obtain information on the nature of any conduits and the flow of water that might occur during a deeper excavation.

Third, to assess the quality of the rock in different areas under the present quarry floor.

John Paul Moore and I, drew up a map of potential drilling target areas based on the site visits and the structural geology interpretation.

We had unrestricted use of a modern shot-hole drilling rig operated by MK Drilling Ltd. We drilled 52 boreholes to find and assess karst conduits under the quarry floor. Some parts of the centre of the quarry were covered with large stockpiles of crushed rock and were inaccessible, but most of the quarry floor could be explored.

The location of the boreholes is shown in green on **Figure** 2.17. The holes are often in lines or

Figure 2.25 Rathcore Quarry Exploration Borehole 2, Exploration drilling rig and crusher

clusters, because the objective was to explore structural geology targets.

The site for an initial hole was chosen on the basis of the structural geology interpretation. The location of subsequent holes were chosen in the light of the findings during the drilling of each hole.

Figure 2.25 provides an example. It shows exploration borehole 21 in the foreground. The drilling rig can be seen on another site in the background on the left. The structural geology target was the inferred extension of Cenozoic strike-slip faults shown in **Figure** 2.17 and the photograph in **Figure** 2.19.

Borehole 21 was drilled to the east and close to borehole 4 (out of the photograph to the left), that previously had encountered a cavity and water at 22.5 metres depth. Borehole 21 was 29.5 metres deep, and encountered a series of cavities below 25 metres containing unusual chocolate brown clays similar to the brown clays that looked as if they contained organic matter, found in the doline in the east wall of the quarry, described above. The brown clays can be seen around the black standpipe in the top of the borehole.

When borehole 21 penetrated the cavities, water was blown up and out of borehole 4. The air used to drive the drill hammer working in borehole 21, found it easier to travel sideways into the cavities and up the adjacent borehole 4. This showed that the cavities found in both holes were open and connected.

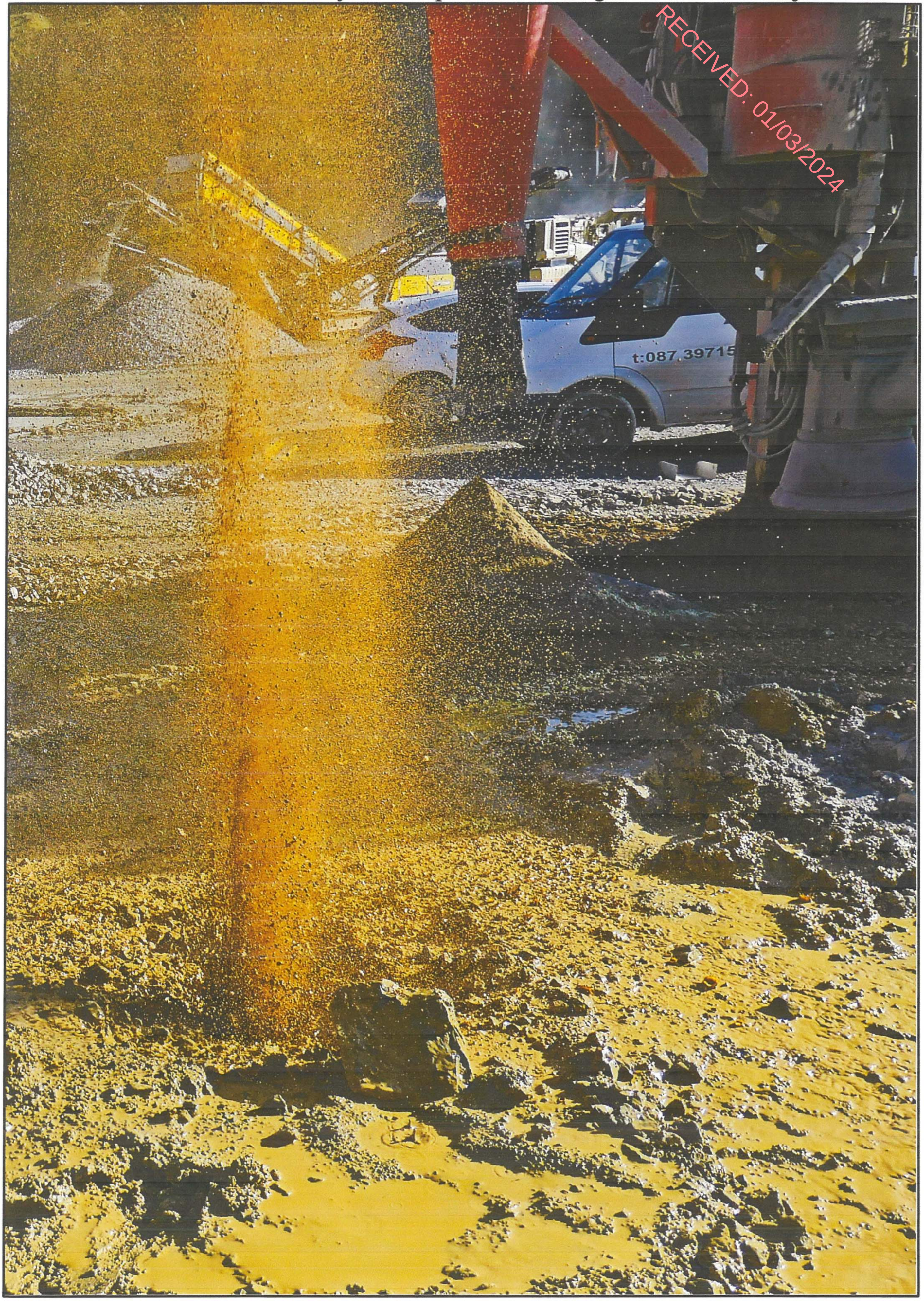
To explore the width of the Cenozoic strike-slip fault zone, and the open cavity system, a further borehole, 22, was drilled to the east of borehole 21. The pile of dry fine limestone dust from the drilling of borehole 22 is seen in the centre right of the photograph. Borehole 22 was also 29.5 metres deep, but there was no evidence of cavities or chocolate brown coloured clays. Borehole 22 appeared to indicate the eastern limit of the strike-slip fault zone, but to test this assumption, borehole 23 was drilled 20 metres further to the east. Borehole 23 found no cavities or chocolate brown clay.

A combination of full-time supervision and direction, and a manoeuvrable very efficient drilling rig and driller (Des McKeown) meant that we were able to quickly explore targets and define the extent of structural features below the quarry.

Figure 2.26 shows air water and clay coming out of borehole 27 whilst the rig is drilling borehole 28.

Borehole 27 had hit open conduits at 13 and 14 metres depth and then clay in cavities at 15 and then from 19 to 23 metres depth. Borehole 28 did not encounter cavities until it reached 25 metres depth. This is the depth when the photograph in **Figure** 2.26 was taken. Borehole 28 showed that there is a hydraulic link between the deeper cavities at 25 metres and the shallower

Figure 2.26 Karst conduits revealed during exploration drilling - water and clay being blown out of a finished hole by the compressed air being used to drill an adjacent hole.



cavities at 13 and 14 metres in borehole 27. It showed that there are open vertical and horizontal conduits. This result was not surprising because boreholes 25 to 29 were drilled at the southwestern edge of the large in-filled karst depression in the north of the quarry. It was expected that there would be conduits containing clay and water in the margins around this large feature.

In contrast, numerous exploration boreholes were drilled at the foot of a similar in-filled karst depression in the southwest wall of the quarry, and no karst conduits containing water or clay were discovered. We even drilled a 45° angled hole for 30 metres towards the centre of the in-filled depression, but only found solid Waulsortian limestone.

12 boreholes were drilled in the north of the quarry excavation between two Cenozoic faults, and between the large and smaller in-filled karst depressions. Several boreholes were shallow because the floor of the quarry was made up of rock shattered by blasting that was very unstable. The combination of water, loss of air circulation and unstable rock, meant there was a risk that the drill rods would become trapped. Shallow holes that managed to get through the 'shatter zone' encountered hard rock with no cavities, but one successful deeper hole to 15 metres did encounter clay and water filled cavities below a depth of 11 metres.

Boreholes 31 and 32 close to the intersection of two Cenozoic faults both encountered deeper cavities down to 33 metres. Some of the cavities appeared to be 5 metres deep and contained abundant soft clay. The flow of air and water out of one hole whilst the other was being drilled showed that the cavities in each hole were linked.

Exploration drilling down the east and south east edges of the quarry excavation found far fewer instances of fractures cavities in the rock. The occasional cavity seemed to be associated with identified Cenozoic faults, but contained clay and little water. No borehole encountered large cavities that provided a relatively prolific quantity of water, as had been found in the northern boreholes. The nature of the rock in the south and southeast of the quarry seemed to be different. The rock was more massive, less broken and there were a few zones containing dark argillaceous limestone or shale; mostly just wisps of dark rock in a matrix of pale grey or brown limestone. However, there appeared to be up to 5 metres of dark grey rock in boreholes 35 and 39 on the southeastern edge of the excavation in October 2019.

The excavation has since extended further to the southeast, where blasting revealed a white calcite filled massive breccia. The orientation of the breccia could not be precisely determined because it was removed by the blast, but the general orientation appeared to be east-west; i.e. along the Carboniferous/Variscan structural orientation. The large blocks of broken breccia showed no evidence of karst solution weathering, or iron-staining. The complete absence of weathering and staining indicates that the breccia did not form a line of weakness or become a preferential flow pathway for the movement of water. The breccia may have represented a completely sealed lower Carboniferous normal fault zone or late Carboniferous Variscan thrust or strike –slip shear zone.

The exploration drilling was a success. It revealed that small and large caves exist below the quarry floor. It revealed that all the caves contain clay. Some appear to be filled with clay and contain little free flowing water. Other caves seem to have the potential for greater flows of groundwater.

The exploration boreholes were just 4inch in diameter. Because this diameter cannot accommodate a high yielding borehole pump, it was necessary to drill wider diameter test boreholes to assess the flow of water in the conduits below part of the quarry.

2.7.3 Wider diameter boreholes for test pumping

One of the prime objectives of the hydrogeology investigation at Rathcore was to find out if there was a system of open, connected, karst conduits below the quarry, and then put stress on the groundwater system within them, in order to observe the effect both inside and outside the quarry. The word stress is important.

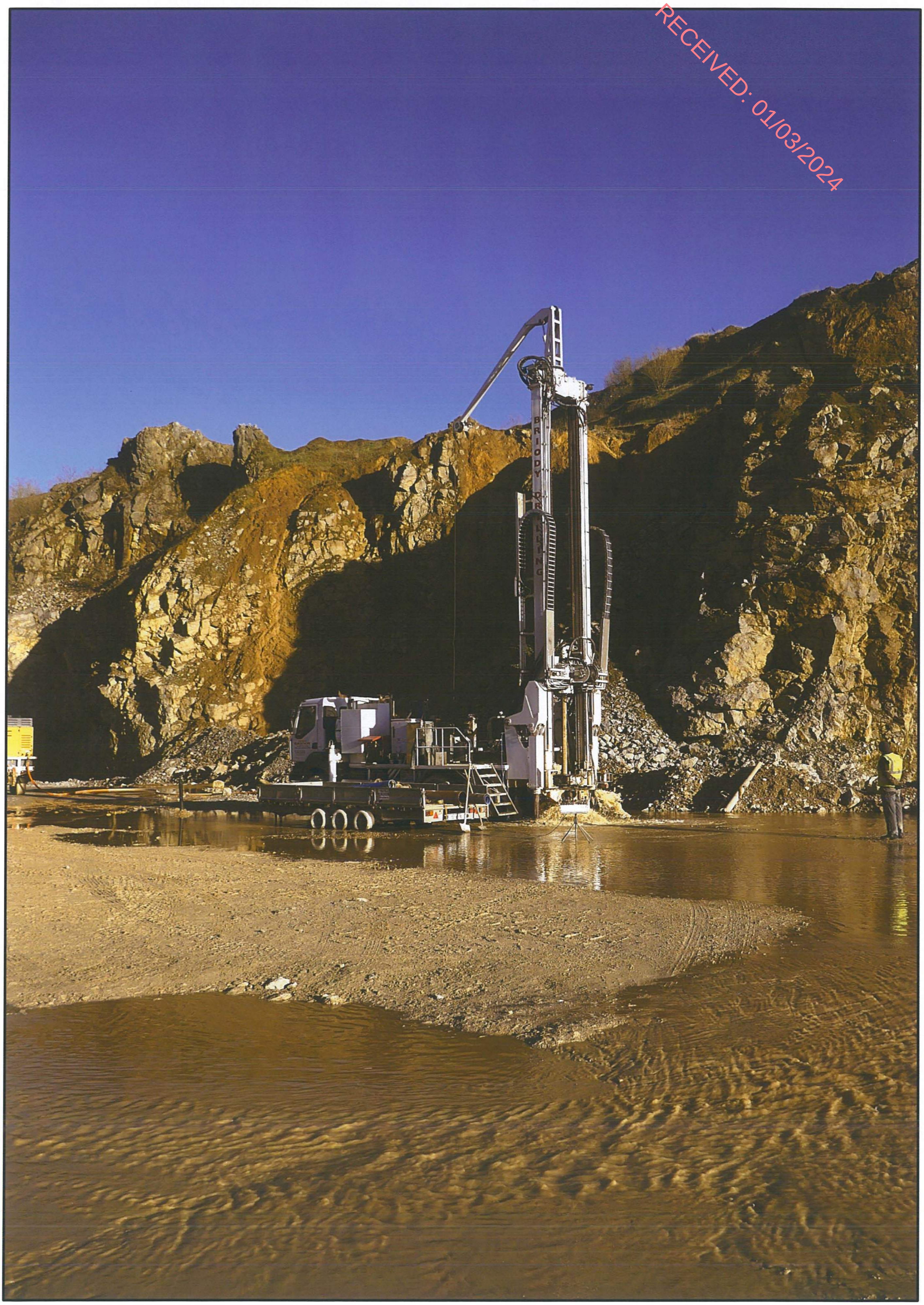
Sometimes, a borehole is drilled for a quarry planning application in order to carry out a pumping test to obtain data with which to calculate 'aquifer' characteristics. The data is often used to calculate or model the predicted water level drawdown in the 'aquifer' inside the quarry and the adjacent area. The test duration is often short, and just a matter of a few days.

The problem with this approach in a karstified limestone groundwater flow system is that groundwater flow and storage is governed by extreme heterogeneity. The aquifer characteristics determined from a borehole will be specific just to that borehole, and its dimensions, and the characteristics the network of conduits making up that part of the groundwater flow system that feeds water to that borehole. A short test may give plausible information on the yield of water that can be obtained from a single specific borehole at a moment in time, but will not reveal the sustainable yield of the whole system during different seasons, or during prolonged pumping.

The objective at Rathcore was to install three high yielding boreholes tapping into structures and cavities revealed by the exploration drilling, and then pump these boreholes at the maximum rate for a long time in order to stress the system and measure the response.

The exploration drilling revealed several potential locations for drilling wider diameter boreholes that could fit large pumps. However, all the potential sites were in the north centre

Figure 2.27 Rathcore Quarry - Drilling Dewatering Test Borehole No.2 November 2019



of the quarry. We did not manage to find any site with both cavities and a potentially high yield of water, in the south or south east of the quarry.

Three sites were chosen on the sites of existing exploration boreholes 21, 32 and 28. These are shown as green dots surrounded by a red ring on **Figure** 2.17.

Borehole 1 is located on the cavity system identified just to the east of the intense pecked red lines depicting the northeast-southwest aligned Cenozoic strike slip faults.

Borehole 2 is on the eastern side of the quarry next to the intersection of two faults.

Borehole 3 is sited to the north and between boreholes 1 and 2 on the major northwest to south east aligned fault on the southern edge of the large in-filled karst depression.

The geological information obtained during the drilling of the test boreholes is summarised in the borehole logs in Appendix 1.

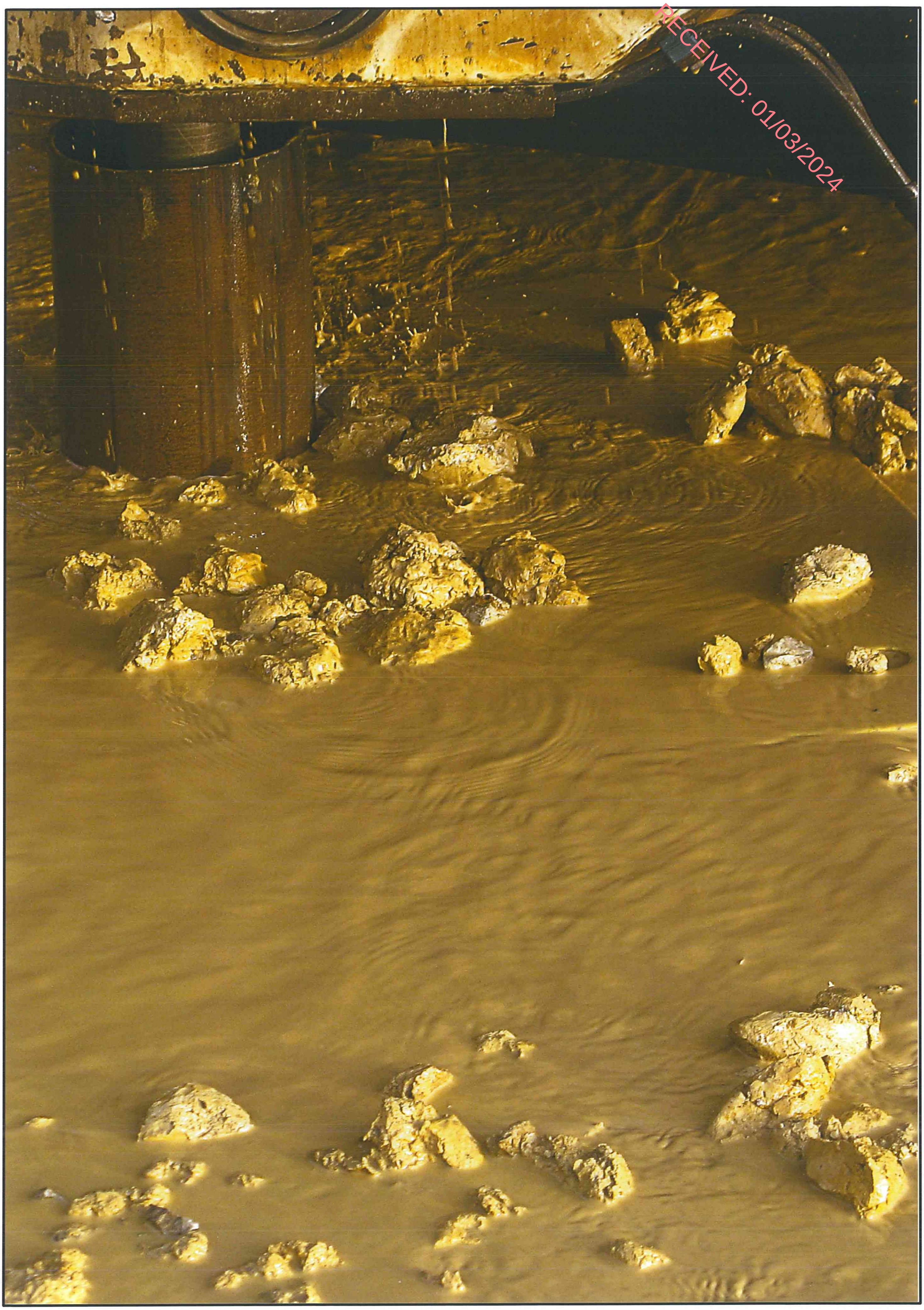
Borehole 1 was drilled down the site of exploration borehole 21. It went to 36 metres. The cavities found in exploration borehole 21 turned out to be an unstable fault zone from 17 metres down to 26 metres. The fault zone contained abundant pale yellow to white clay, but in addition there was a flow of water at a rate equivalent to about half a million litres per day. Drilling stopped at 36 metres because the hole was very unstable. I made a decision to secure the hole by lining it with Boode PVC casing and screen to support the rock but let the water flow into the hole.

Borehole 2 was drilled on the site of exploration borehole 32 that had been drilled to 33 metres. Borehole 2 was drilled down to 56.5 metres. It encountered large cavities in the same zones as exploration borehole 32 at 17-18, and 24-30 metres depth. The cavities appeared to yield large quantities of water, and orange yellow clay. Between 30 and 50 metres depth the rock consists of hard pale grey limestone and softer more easily drilled light brown dolomite. There are three small cavities between 30 and 53 metres depth that appeared to provide additional water. Drilling in this zone produced an unusual result. The compressed air, used to drive the down-the-hole hammer drill, temporarily disappeared into these cavities. This became evident when drilling stopped, and the airflow from the compressor was turned off. Water continued to flow up and out from the hole for several minutes lifted by the pressurised air as it returned from the deep cavities.

Figure 2.27 shows the Knebel 97TBR rig during the drilling of borehole 2 in November 2019. The flow of water from the hole and the clay content can be seen flooding the area around the rig and flowing towards the foreground of the photograph.

Borehole 2 was airlift surged and airlift pumped for several hours to scour clay from the cavities and increase the yield. The clay in the cavities appeared to be soft. There were no hard lumps

Figure 2.28 Rathcore Quarry - Large pieces of hard clay lifted during drilling borehole 3 from cavities found 37 metres below the quarry floor at the northern end of the quarry



of clay in the material scoured from the cavities and brought to the surface by the flow of water and air.

Borehole 2 appeared to be a stable, very high yielding hole, with multiple open cavities containing clay. Subsequently, during the long pumping tests, it appeared that clay from a 3 metre cavity at 24 metres slumped into, and across, the borehole blocking the flow of water from the cavities below, and severely reducing the sustainable yield.

Borehole 3 was drilled on the site of exploration borehole 28. This exploration borehole had stopped after penetrating a large cavity containing water and clay that was hydraulically linked to three previous exploration boreholes to the west; numbers 25, 26 and 27. Exploration borehole 28 did not reach the bottom of this cavity because clay blocked the drill bit.

Borehole 3 was drilled down to 62 metres below the quarry floor. When the hole reached the cavities at around 25 metres water and air started blowing out of the three exploration boreholes to the west, proving again the presence of a major cavity system heading west from this drill site. The direction of the cavity system would suggest a possible direct link with the cave at the bottom of the karst depression (now back-filled) south of the fixed plant. This was the cave explored by a cave diving member of staff. Though the direction of the cavities linking borehole 3 and exploration boreholes 25, 26 and 27 suggest a link, the cavities in these boreholes are approximately 30 metres lower than the cave explored to the west.

Borehole 3 encountered further small cavities and clay down to 32 metres, and then a 4.5 metre cavity mostly filled with hard clay from 36 to 41.5 metres. Airlift surging and pumping was used to successfully erode the clay and develop the yield from this cavity.

Figure 2.28 shows the large lumps of pale yellow hard clay scoured from the cavity in this zone. The flow of water became so copious that drilling was stopped in order to take this photograph of the clay on the ground at the top of the borehole.

The borehole progressed down through 12 metres of solid rock before encountering a 3 metre thick layer of clay that did not appear to provide additional water. Below this large cavity, the borehole encountered a further 2.5 metre deep cavity producing a large flow of water. The cavity appeared to be open and contained pale brown sand rather than clay.

In summary, the exploration and test borehole drilling proved the value of the structural geology investigation. The drilling revealed, as expected, that there are numerous karst cavities below the quarry floor. These cavities contain clay but are not completely filled with clay, and hence blocked as others had supposed.

One of the advantages of drilling using the down-the-hole hammer method is that the drill cuttings and any water flow from openings in the rock are lifted out of the hole by the air used to drive the hammer. With continuous supervision of the drilling by a hydrogeologist, the change of lithology and the inflow of water are logged in real-time. By contrast, mineral exploration boreholes in the area and exploration boreholes at Rathcore were drilled by diamond drill coring. It is less easy to notice inflows of water when drilling with this method, and if the holes were not supervised full-time it is probable that water inflows were not noted. Hence, the previous presumption that karst cavities were wholly clay filled, and therefore hydrogeologically inactive.

The exploration and test borehole drilling at Rathcore showed that the karst cavities contain water as well as clay. This would be expected because a flow of water would be required to deposit the clay in the cavity. Therefore, there must be some space above the clay for water to flow and deposit clay.

The drilling at Rathcore did not find evidence that the extensive zones of dolomitised Waulsortian limestone are porous and permeable. In other places in Ireland the dolomitisation has created a loose sugary textured dolomite that is permeable. The dolomite at Rathcore does not appear to be loose and permeable. With the exception of the sand found in the lowest cavity in borehole 3, the sediment in the cavities appears to be mostly soft and hard pale yellow clay.

2.8 Geophysical Data and Interpretations

2.8.1 Introduction

The drilling at Rathcore was not the final phase of the geological investigation.

This drilling had added considerable information to the existing information from previous drilling at St Gorman's Well, Ballinakill and Longwood, and the information on maps produced by mineral exploration companies and the GSI. However, it still left several large parts of the area with no information on the subsurface lithologies and structures.

The main uncertainty relates to the bedrock lithologies and structures, around the Waulsortian, proven at Rathcore, Ballynakill and Longwood. It was obvious that structural geology is most important in understanding the development of karst and hence groundwater flow.

It was also obvious that the current bedrock map, partly because of mapping scale, is not a base map that can be used with confidence to either understand the structures, or the nature of the bedrock. BHP core holes 1500-98-1 and 3 and the Longwood water supply boreholes had found ABL, or Lucan, dark grey limestones and shales where the current map shows Waulsortian limestone. Sarah Blake's AMT and conductivity information suggests a north-south aligned anomaly to the west of St Gorman's spring. This may be a north-south structure in the Waulsortian, or a completely different lithology.

After carrying out the long pumping tests in 2020 and 2021, I realised that it was necessary to obtain a better understanding of geology and structures in the intervening areas between the places with good borehole data. As exploration drilling in these areas was not feasible for various reasons, I decided to follow Sarah Blake's lead and try to obtain a better understanding of the geology from the GSI's Tellus airborne geophysical information.

The Tellus airborne geophysical survey programme provides data in the form of easily accessible maps on a Public Viewer website. Up until recently, the maps on the Public Viewer were at a large scale, but not very informative in the detail required for small areas.

I compared the conductivity map shown by Sarah Blake, reproduced in **Figure** 2.15. with the resistivity maps on the Tellus public viewer website. Though the rough pattern of high resistivity (low conductivity) areas were similar, there were also significant differences. I emailed the GSI to ask for clarification, and in return I was informed that more detailed conductivity maps were available from the team of geophysicists working on the Tellus project in the GSI.

I was asked to specify the area of interest, and Jim Hodgson (the Tellus Programme Manager) asked Mark Muller in the team if he could handle my search for information.

Mark rapidly produced two conductivity maps for the area at two different nominal depths: 10 metres and 30 metres. These maps were similar to the conductivity map used by Sarah Blake.

I subsequently found that these maps are produced by the airborne survey contractor, Sander Geophysics Limited (SGL) from Ottawa, using their 'extended range apparent resistivity algorithm' that combines two other algorithms; a pseudo layer algorithm for areas with a strong signal (high conductivity layers) and an amplitude-altitude algorithm for low conductivity layers, such as massive Waulsortian bedrock close to the surface. I also found that the Geological Survey uses a different software algorithm to produce the maps for the two frequencies shown on their Tellus public viewer website. This explained the difference.

The airborne conductivity data is obtained by a transmitter on one wing of a survey aircraft transmitting electromagnetic signals into the ground below at four frequencies. A receiver on the other wing of the aircraft picks up the response of the subsurface materials to these electromagnetic signals.

The frequencies are 0.9 kHz, 3 kHz, 12 kHz and 25 kHz. The theory is that each frequency penetrates, and induces a response from, the subsurface at different depths. The low 0.9 kHz frequency penetrates to a greater depth, though the signal returning to the receiver is weaker than others, because of the masking effect of the conductivity of the rocks and overburden at shallower depths.

The higher frequency 25 kHz signal does not penetrate very deep into the ground, but evokes a response from materials at shallow depths. The 3 and 12 kHz signals obtain a response from the middle depths.
Separate conductivity maps can be made from the individual signals.
There are several different ways of processing airborne conductivity data, and the Tellus programme is providing an opportunity to develop new methods
Dr Duygu Kiyan, a Schrodinger fellow in the Dublin Institute for Advanced Studies (DIAS) along with Volker Rath, Mark Muller, Mohammednur Ture, and James Hodgson from DIAS, ICRAG and the GSI, have been developing a new way of processing and modelling airborne conductivity data. When I started making enquiries in November 2021 this research team had just submitted a paper describing the computational tools and model to the Journal of Applied Geophysics. Mark Muller shared a pre-print of the paper that was subsequently published in 2022. The tools and model had been tried out on Tellus conductivity data for four test sites in Ireland, but had never been used to provide information for a scientist outside their institutions working on an applied project for industry. Mark, with Jim Hodgson's agreement, offered to process the conductivity data for the Rathcore area using the new technique.
The work with Mark Muller also revealed a further feature of the way that the conductivity data had been processed and maps created in the past. Early airborne conductivity/resistivity surveys had had a problem with altitude relative to the earths surface. It was found that just a small unrecognised and uncorrected drop in altitude of, say, 10 metres, could create an apparent conductivity anomaly when the data was later processed. Also many of the early airborne surveys had been focussed on the deeper bedrock and the possible identification of mineralisation targets within it, The early surveys also found that variations in the conductivity of the overburden often obscured or distorted the information from the bedrock below. An industry standard algorithm called Airbeo was developed to derive resistivity values from the conductivities measured on the different frequencies. This algorithm had two effects. First it removed the effect of variable flight height above ground level. Second it subdued the effect of the over burden leading to conductivity/resistivity maps more representative of the bedrock. In a sense the conductivity data was 'tuned' to subdue the sensitivity to vertical and lateral variations in the overburden, down to an unspecified depth. The SGL processing algorithms, referred to above, incorporate the Airbeo effect of subduing the information from the overburden.
I and Mark both realised that details of changes in the overburden are important for hydrogeology investigations, and for this reason, he produced sections and maps that used the

DIAS research team's latest software algorithm to ensure that variations in the overburden were not under represented.

The Tellus survey aircraft uses GPS and an altimeter to fly at a constant altitude of 60 metres above the surface of the ground in a straight line. The transmitter sends out a signal on the four frequencies every 6 metres along the flight path, and measures the response from the ground beneath. Therefore, for every 6 metres along the ground there is a measurement point with a set of data. Mark used the measurement point data to create a vertical profile, or one dimensional (1D) section, of the change in conductivity of the materials below each measurement point. He then gridded these 1D vertical profiles together to create a two dimensional (2D) horizontal section along the length of the flight line over the area of interest. There were 48 flight lines across the area. The flight lines were 200 metres apart. This produces a lot of data, and the computational requirement and processing time involved were considerable.

Mark then used the information on the 48 sections to create conductivity maps for different depths below the ground. We decided on nominal depths of 10m, 20m, 30m, 50m and 75m, which, more precisely became 10.7m, 19.8m, 29.3m, 52.1m, and 74.8m depth slice maps.

It had become obvious when comparing the SGL and the GSI viewer maps that colour coding for the same conductivity or resistivity, differed between maps. Mark made it possible to directly compare and correlate sections and maps by using the same linear colour colours for all. The initial focus was to try to obtain detail in the low conductivity (i.e. high resistivity) unweathered bedrock to find out if there were faults or conduits in the rock. Mark later created a second version of the maps and sections using an extended colour scale to try to obtained more detail in the areas with a high conductivity.

I would like to repeat the acknowledgement at the start of this report, that I, and Kilsaran, are very grateful to the GSI for all the innovative work, and the careful effort made to produce information in a form that could be used by a non-geophysicist for an applied geology and hydrogeology project.

An iterative process of map and section production and correlation with available borehole data, then feed back, discussion and a final revision of the sections and maps took place between November 2021 and February 2022.

The quality control software removed data in the sections where it appeared unstable. Some final sections were created with this re-instated. This was done in order to see if the instability was created by artificial factors, variations in the altitude of the aircraft, or natural reasons.

As noted above, the conductivity data is very sensitive to aircraft altitude. It is difficult to process data from parts of flight lines where the aircraft has had to climb and descend. The Tellus survey aircraft, by its license, had to fly at higher altitudes over towns and villages and other sensitive sites such as stud farms.

Figure 2.29 shows the number and orientation of the airborne geophysics flight lines superimposed on an extract from the Discovery Series 1:50,000 scale base map. The positions of the quarry and St Gorman's spring are shown. In addition the position of the ESB's high voltage, overhead power lines and steel support towers, is highlighted. These conductive features are prominent in the south of the area. Another feature picked up by some EM frequencies is the old N4, Dublin to Galway road, west of Enfield. It is presumed that there is some form of cabling along this road alignment that gives high conductivity readings.

Figure 2.29 also shows the Northings of the Ordnance Survey grid across the area. The conductivity sections are plotted with this grid marked on each section. Therefore the grid on the sections and the map, are essential for correlating features observed on the sections and transferring their position onto a map. It is tricky to observe features on the sections and relate them to the national grid, because the flight lines and sections are oriented north northwest to south southeast, and not north-south or east-west.

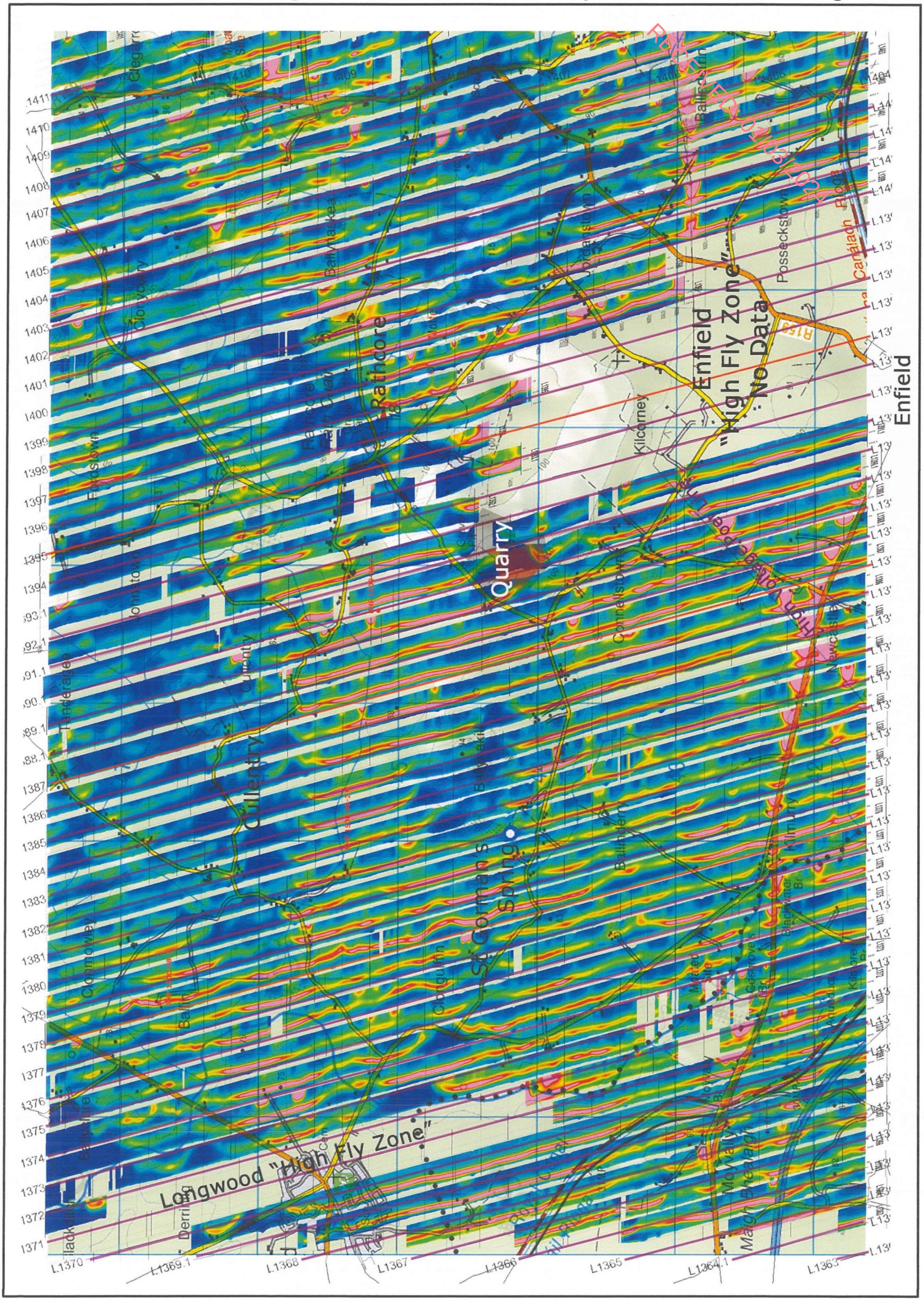
This orientation arose because the Tellus airborne survey started in Northern Ireland, and then extended into Donegal and the counties south of the border. The geological strike, or grain of the geology and landscape in the northern part of the island, is dominated by the alignment of Caledonian tectonic structures. These have a west southwest to east northeast alignment. It was decided at the outset of the Tellus Survey to fly at an angle to this Caledonian alignment, to better pick out the boundaries between the different rock types and the numerous faults. This flight line alignment has been maintained throughout survey of the rest of the island.

Under normal circumstances the Survey aircraft maintain a height of 60 metres over the land surface, but there are long gaps with no data on each flight line where the aircraft is climbing or descending. These 'High Fly Zones' can be seen on the maps and sections along the flight lines northwest of Enfield and south east of Longwood.

The flight lines are 200 metres apart. The plane flies up one flight line, then turns and flies down the next flight line. Hence the 'High Fly Zone' gaps in the data, maps and sections are not the same length.

It is very informative to view all 48 flight line sections on one sheet in order to be able to follow trends across adjacent sections. However, to create a print of the sections at a working scale, requires a roll of paper 80 cms wide by 4 metres long. It is the size of print that can only be

Figure 2.30 Tellus Conductivity Sections oriented to flight lines



studied in full if it is laid out on a long boardroom table. Therefore, most work on the sections has been carried out on individual sections or sometimes two or three on the screen or a single page.

2.8.2 General interpretation of conductivity sections

For the purposes of this report, the 48 sections have been displayed in **Figure** 2.30. The way of presenting the sections is somewhat unusual. The objective is to try to illustrate the overall patterns in the data, and the apparent changes in the geology.

All the sections have been copied and placed into a single image file composed of 48 layers. The image has then been shrunk and slanted, in order to fit the sections onto the flight lines on a Discovery Series map base layer. This map is not perfectly to scale, but the image provides an overview of the conductivity information on the sections. The sections are shown with the bottom of each section facing the northeast corner of the map. In essence, it is a 3D map, or Fence Diagram. It is informative to look at the figure from different orientations, because the mind's eye will detect different lineaments.

The **Figure** clearly shows the 'High Fly zone' areas with no data extending northwest from Enfield and south from Longwood.

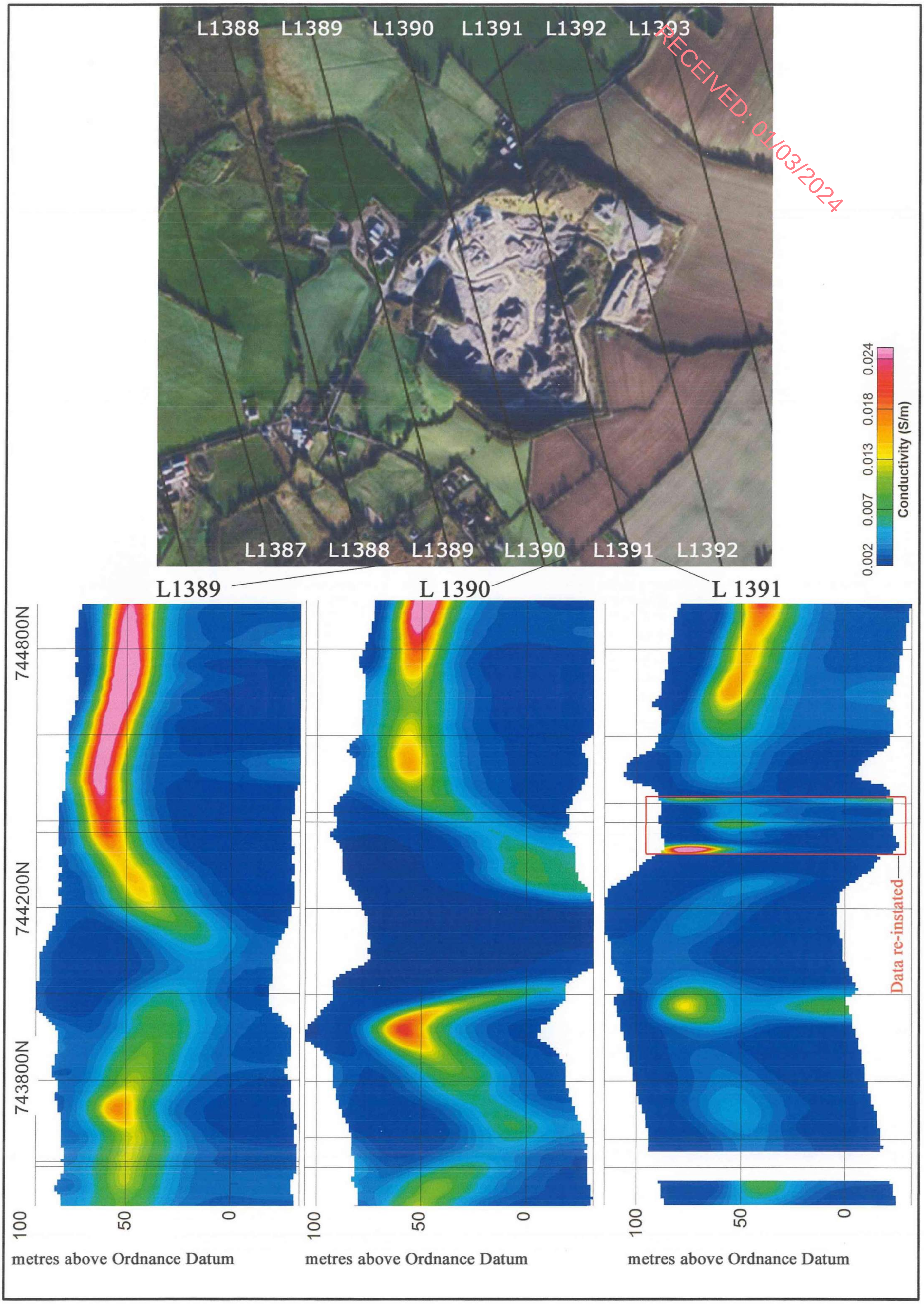
The pink and red anomalies along the ESB's high voltage power lines and the old main road the N4, can be seen on the **Figure**. The quarry and St Gorman's spring are marked for ease of reference.

Taking an overview of the **Figure**, the first striking feature are the areas of dark blue. The dark blue and cyan colours depict low conductivities (or high resistivity). The very low conductivities are those expected from solid, largely unweathered pure limestone bedrock, above or below the water table. Unweathered rocks with abundant shale or pyrite would be expected to have low to mid range conductivities, i.e. cyan to green colours. Weathered to very weathered, water saturated rock containing a lot of metal oxides in clay minerals, or weathered pyrite, would be expected to have relatively high conductivities, and would be shown in the orange, red and pink colours.

The distribution of dark blue colours correlated with borehole records and outcrops indicate that these colours represent the Waulsortian limestone, both close to the surface and extending to depth. Rathcore hill and quarry, as expected, is in one of these areas. Similarly, there is an area of dark blue under the Ballinakill hill east of St Gorman's Well.

Another large area of dark blue is on the northern side of the low valley extending west northwest from Rathcore Hill. This side of the valley is marked as Cullentry on the **Figure**.

Figure 2.31 Rathcore Quarry - three examples of extracts from Tellus Conductivity Sections



A fourth area of dark blue is to the east of Rathcore hill. This may correspond to an area shown on the GSI bedrock map as Visean limestones, or the Allenwood formation, again a clean limestone containing little shale.

Another important feature that can be seen in the overview is that the dark blue areas seem to have well defined linear edges. It is easy for the eye to read along the edges and imagine that they show the alignment of major faults. For example, there is an east southeast alignment along the southern edge of the Cullentry block, and a similar alignment along the south side of the Ballinakill block.

Though there are some gaps in the data, the eastern margin of the Rathcore block has a roughly southwest to northeast alignment. This alignment appears less defined but present on the eastern side of the Cullentry block.

A notable feature in the **Figure** are the large areas underlain by pinks and reds. These bands of colour do not represent materials at the surface such as alluvial or lacustrine clays . The pink and red colours occur 20-30 metres below ground level, and usually lie above intermittent zones of cyan and dark blue low conductivity, as if this low conductivity bedrock below is broken up and not a solid mass of limestone.

It can be seen that the Ballinakill block appears to be disconnected from the Rathcore hill block. There appears to be a long layer of high conductivity material running between them.

In discussions with Mark Muller about the sections, he commented that the presence of an extensive high conductivity layer at 20-30 metres depth is unusual. He does not recall observing such persistent, extensive high conductivity layers at this level in sections across other parts of the country.

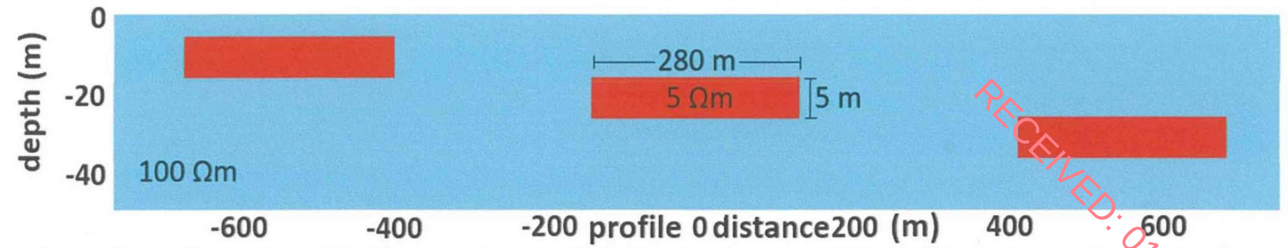
Though the representation of conductivity sections in this way in Figure 2.30 is somewhat unorthodox, the **figure** clearly shows patterns that imply significant heterogeneity and numerous discontinuities in the geology of the area.

Figure 2.31 may appear a simple diagram, but it might also look confusing on closer inspection. It is best viewed from the right hand side.

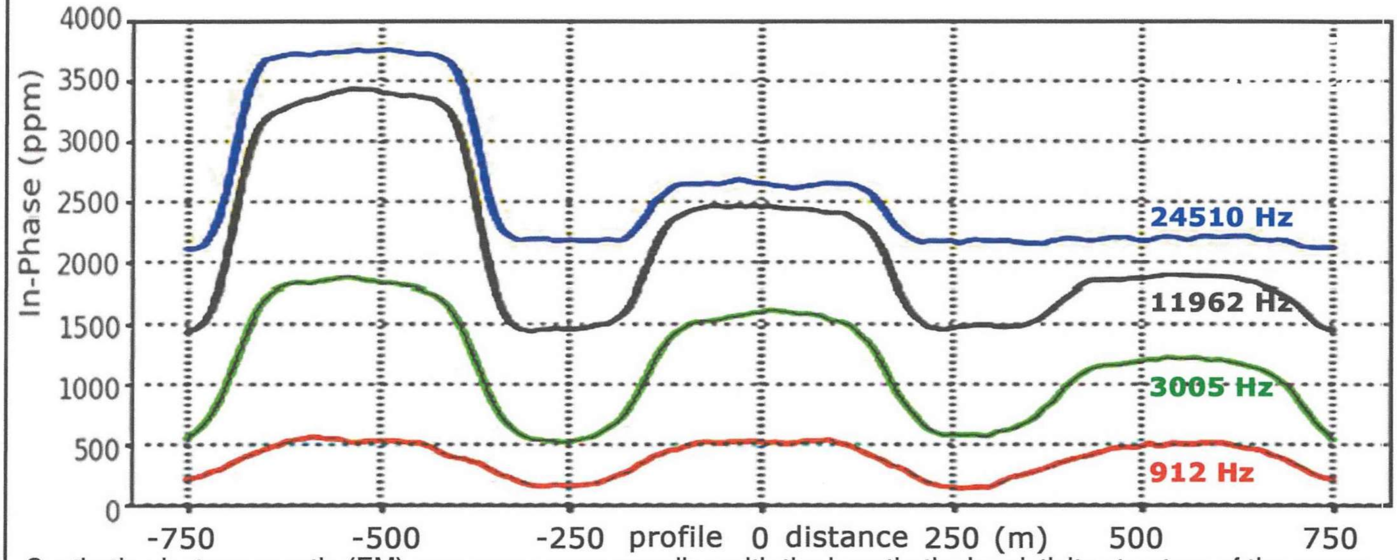
The **Figure** shows a base image of the quarry taken from a 2018 aerial view in Google Earth. The aircraft flight lines and numbers have been carefully overlain on this base. Therefore, it is possible to see the line along which the aircraft's instruments were recording information every six metres across the quarry. Below, or to the left of, the image of the quarry, there are three extracts from the conductivity sections crossing the main part of the quarry. These sections are from the second version of the sections where the conductivity scale has been extended in order to try to provide more detail in the high conductivity zones. The sections have been

Figure 2.32 Hypothetical Structure, Synthetic Responses and 1D Resistivity Section

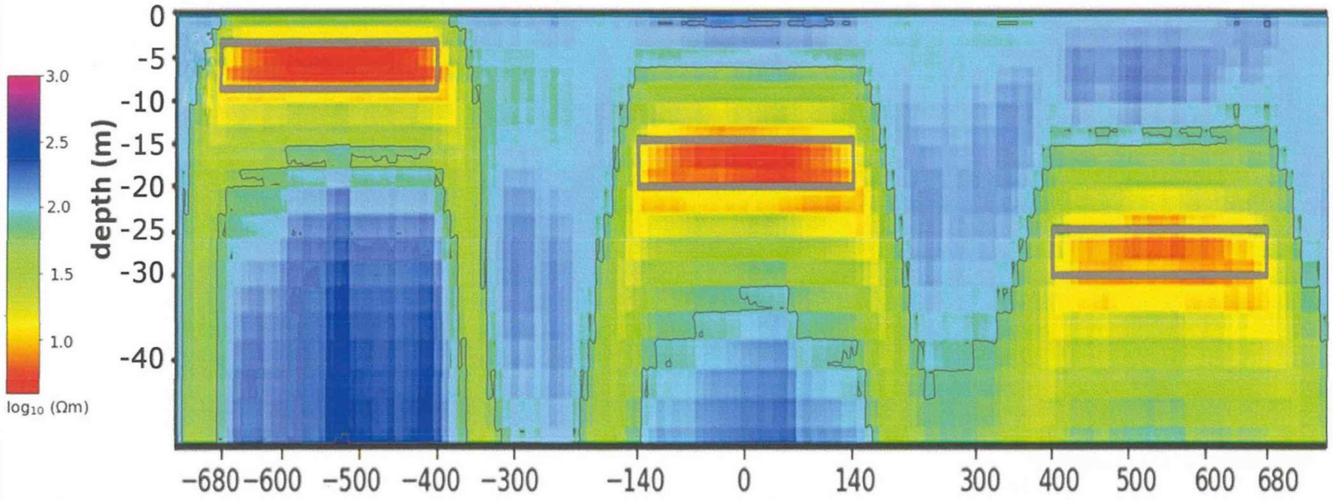
Adapted from Figures 12 and 13 in Duygu Kiyan et al, Journal of Applied Geophysics 198 (2022)



Hypothetical two-dimensional (2-D) subsurface resistivity structure consisting of three low-resistivity bodies embedded at different depths in more resistive host rock. The resistivity structure in the cross-section extends infinitely in and out of the plane of the section.



Synthetic electromagnetic (EM) responses corresponding with the hypothetical resistivity structure of the upper panel. In-phase EM responses are shown for each of the four Tellus frequencies: 912, 3005, 11962 and 24510 Hz. 2-D EM forward modelling software was used to compute the EM responses at locations 10 m apart along the profile, at 60 m elevation above ground level, and with 30 ppm random noise added to simulate "real" airborne EM data recorded over the hypothetical section.



Resistivity cross-section derived through one-dimensional (1-D) inversion modelling of the synthetic EM responses. 1-D inversion models are computed independently at each measurement location (10 m apart) using all four in-phase EM responses (shown in middle panel) and all four quadrature EM responses (not shown). The cross-section is produced by gridding together all the independent 1-D models as one continuous section. Comparison of the upper and lower panels provides an indication of how accurately 1-D inversion modelling (lower panel) is able to recover "real" subsurface resistivity structure (upper panel).

placed on the diagram so that looking at the quarry from the northeast, the sections represent a sequence of profiles across the quarry, towards the southwest.

The topography of the quarry excavation can be easily seen. The aircraft uses a very accurate scanning altimeter that picks up fine detail including the height of trees. The topography on the section does not exactly match the modern topography of the quarry, because the survey was flown on the 28th August 2015 and the shape of the quarry had changed by 2018, the date of the imagery.

The centre section along flight line L1390 shows the south side of Rathcore hill with a small berm of overburden, before a quarry bench, then a steep face down into the western edge of the quarry. The section ramps up to a flat area, the position of the fixed crushing plant, and then over a berm, down to the road and a farmyard with trees on the other side of the road.

The conductivity below the quarry indicates a large solid block of Waulsortian limestone extending to at least 30 metres below Ordnance Datum.

To the southeast and the northwest of the Waulsortian, there are two high to medium conductivity zones. The one on the southeast has a conical shape with both 'arms' bending downwards. The high to medium conductivity zone on the northwest side appears to dip down below the, dark blue, Waulsortian.

Looking at the upper section L 1389, again, a high to medium conductivity zone, or layer dips under the Waulsortian from both sides. This section is to the west of the quarry.

The bottom section L 1391, again, has high to medium conductivity to the southeast and northwest of the excavation, but lighter blue colours seem to come in under the quarry floor. There is a slight uncertainty about the data directly below the quarry floor. Originally, it was automatically removed by the quality control software, because the data appeared to contain 'noise', probably caused by the sudden increase in the height difference between the ground and the aircraft. However, we have manually re-instated the data because the low-medium, light blue colours may correspond with the drilling evidence of large cavities and a clay filled depression in that area of the quarry. In other words, the 'noise' seems to make sense.

All three sections show a high to medium conductivity layer at a general depth of about 20-30 metres below ground on both sides of the Waulsortian core. In the western section the Waulsortian core also appears to narrow and be underlain by an almost continuous layer of medium conductivity rock or material.

It would be useful to explain the origin of the apparent dip of medium to high conductivity layers below the low conductivity Waulsortian limestone.

Essentially, the downward curve at the end of a high conductivity layer or structure is is an artefact created by the computation of a 1-D inversion model used to create the sections.

Figure 2.32 provides the explanation. It is composed of three panels. The graphics have been copied and slightly amended from Figures 12 and 13 in the paper by Dr Duygu Kiyan, co-authored by Mark Muller and others, published in 2022. The text on **Figure** 2.32 was drafted by Mark Muller specifically for **Figure** 2.32.

The researchers wanted to understand why high conductivity structures in the 1-D sections had a downward bending tail. They ran a simulation using three high conductivity structures buried at different levels in a low conductivity material. The middle panel shows the data that would be expected from each frequency. The lower panel shows the section that would be created by the software using these data. The key to understanding the data and section is that it is a 1-D model, even though the section is 2-D.

A 1-D model takes all the data in the single dimension of depth from each individual measurement station (every 6 metres) along the flight path. These are then gridded together to create the 2-D section. The signal, or response from a highly conductive body picked up by the receiver on the aircraft, is much stronger than the signal from a low conductivity, or more resistive, body. When the gridding is carried out by the software, there is a 'tail', or hang over, of the stronger signal, that distorts the boundary between the high and the low conductive material.

Therefore, when interpreting the conductivity sections it is important to ignore the downward bending 'tails' at the end of strongly conductive layers. They do not represent a geological structure such as the dip of a fault or bedding. The boundary between the high conductivity body and the low conductivity body is likely to be close to vertical.

Figure 2.32 is also important because it shows that low conductive bodies (e.g. solid, unweathered Waulsortian, or the dark grey limestones with shales), can still be seen below a highly conductive body. The highly conductive body with its strong signal has not managed to mask out the low conductive material below it. However, it does depend upon the burial depth of the highly conductive body, as seen in the lower panel in **Figure** 2.32.

With this understanding of the 'tails' on the shape of a highly conductive body, it is possible to interpret the conductivity sections with increased confidence.

For example: the curious cone shape at about 743900N on Section L 1390 in Figure 2.31, is probably a round karst cave containing a large amount of clay below the water table, perhaps on a fault. A similar feature can be seen further north on Section L 1391. On the north west side of the quarry on Section L 1391, there is no 'tail' on the higher conductivity layer because the relatively high conductivity layer appears to pass under the quarry perimeter to join with

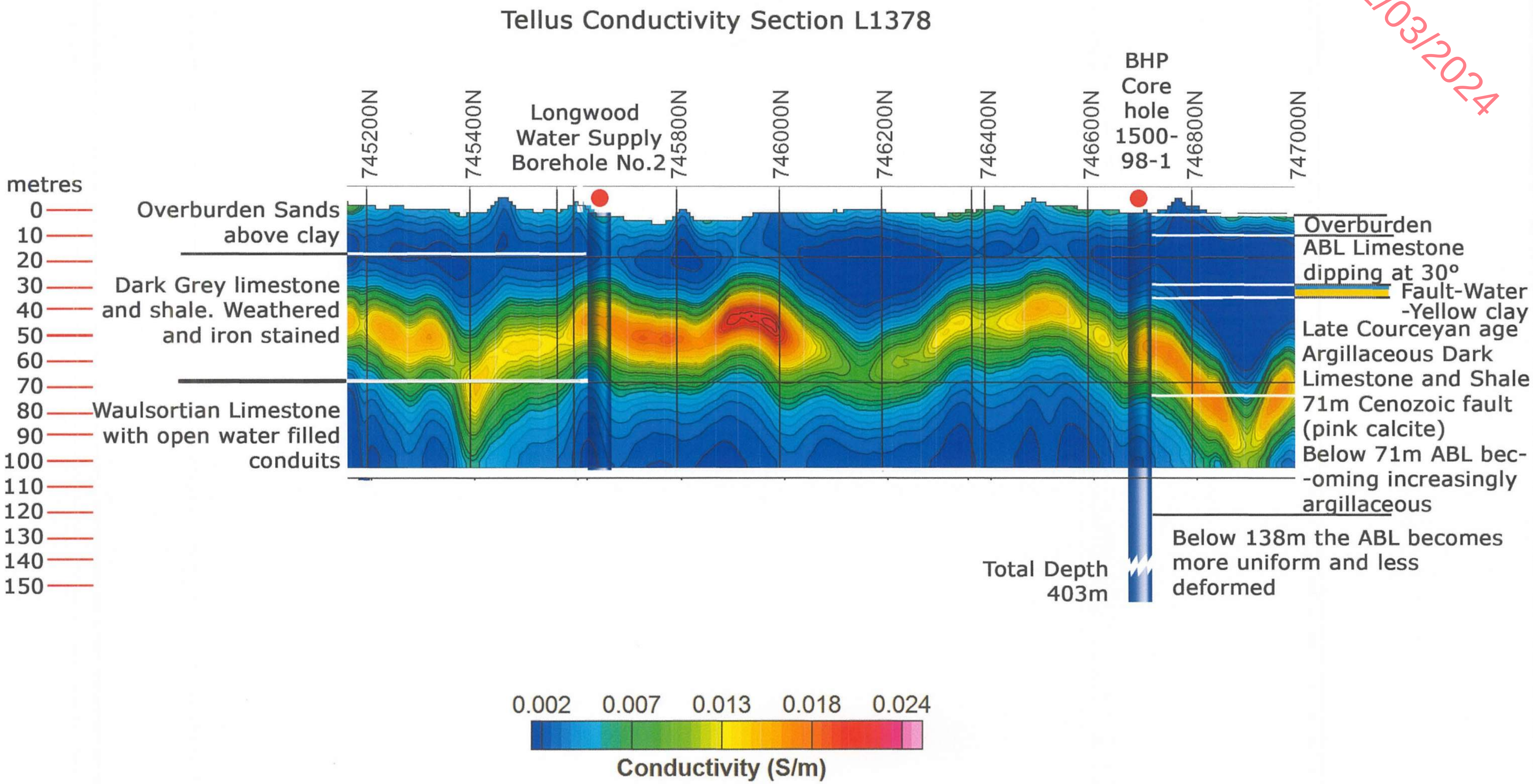


Figure 2.33 Tellus Conductivity Section L 1378 and Longwood Bh. and BHP 1500-98-1

similar conductivities in the area of boreholes 2 and 3 inside the quarry, and the large karst clay infilled depression seen in the quarry wall in Figures 2.17 and 2.24.

It can be seen from Figures 2.30 and 2.31 that the Tellus conductivity data processed this way to create sections potentially provides a significant amount of new information on the geology of the area. The potential is considerable because of the level of detail; the flight lines are close, 200 metres apart, the measurements are taken every 6 metres and the data is collected on four different frequencies that penetrate to different depths. The Tellus conductivity data when processed this way appears to be an important new source of very useful geological information.

However, it is important to 'test' or 'ground-truth' the conductivity information against real information from outcrops, excavations and boreholes. It is also important to bear in mind that the airborne conductivity data is an indirect method of measuring the properties of the subsurface, and no data has a unique solution.

In other words, for example, a low conductivity structure could be Waulsortian limestone containing a few karst cavities, or it could be a solid block of unweathered dark grey limestones and shales. Similarly, a low conductivity at or near the surface could be either solid rock or could be a clean coarse gravel and sand of glacio-fluvial origin.

In order to obtain the information with confidence, it was necessary to try to tie the indirect information on the sections with data obtained by direct measurement during drilling into the same subsurface.

The next series of figures provide examples of how the airborne conductivity data can be correlated with the information from boreholes drilled on, or very close to, the alignment of the conductivity sections.

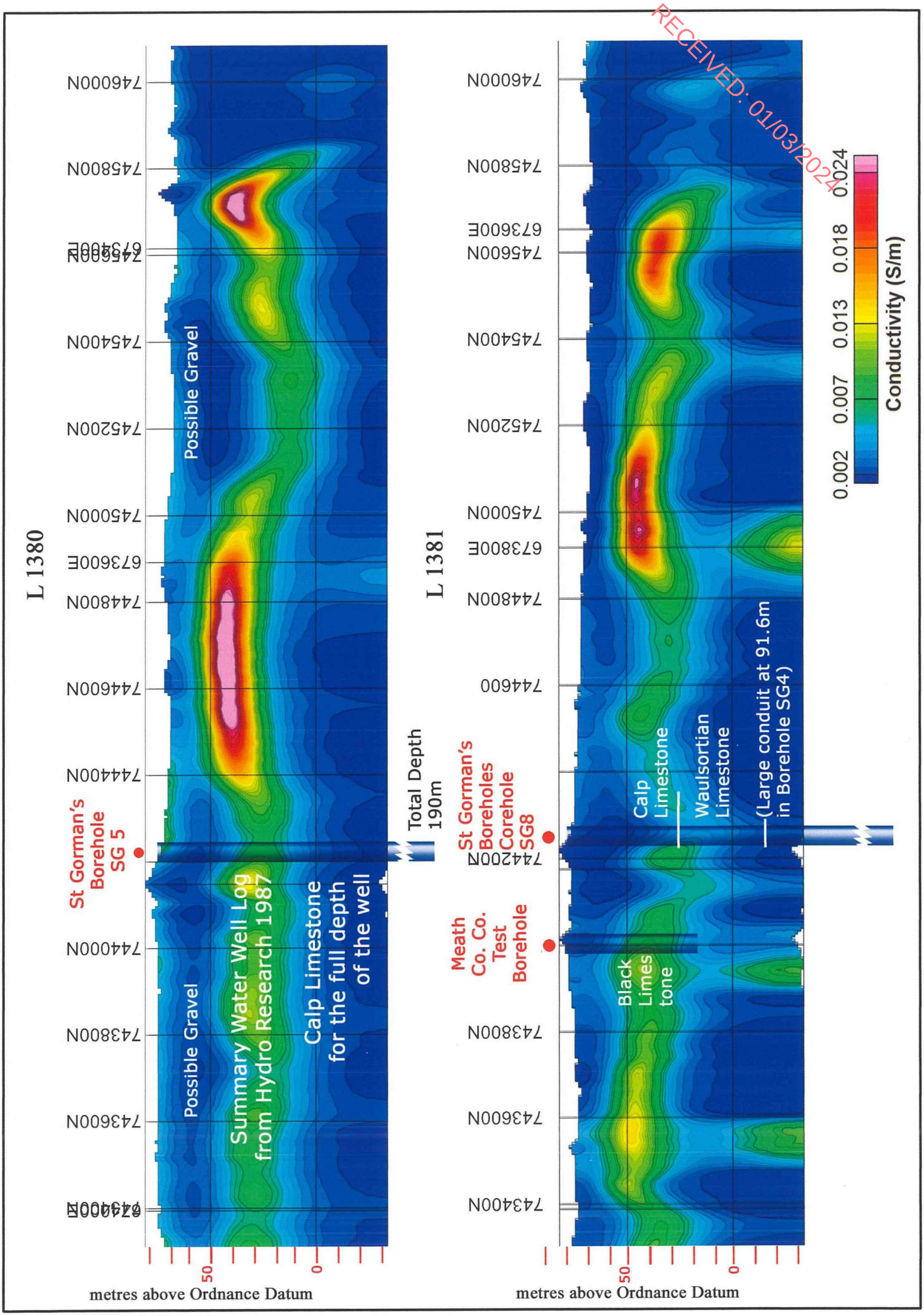
2.8.3 Interpretation of conductivity sections and borehole records

Starting in the west of the area, Figure 2.33 shows part of the section under flight line L 1378, that crosses the sites of the Longwood Water Supply boreholes and the BHP core hole BHP 1500-98-1. The position and depth of each borehole is shown.

The section shows a pattern of conductivities that is found in all other sections in the area:

1. an upper (pale and dark blue) low conductivity layer of varying thickness
2. a middle (green-yellow-red) high conductivity layer of irregular shape but fairly uniform thickness
3. a lower (blue) low conductivity layer

Figure 2.34 Tellus Conductivity Sections L 1380 & 81 and St Gorman's area borehole logs



The pale blue layer immediately below the surface represents the overburden which could be saturated sands and gravels.

The dark blue lower part of the upper low conductivity layer was found in both boreholes to be a dark grey limestone with shales. When I logged the second Longwood water supply borehole, I perhaps erroneously described these rocks as the Lucan Formation (i.e. younger than the Waulsortian), whereas the geologist describing the core from the BHP core hole, took samples for micropalaeontology analysis, that determined the age as Courceyan, which is generally older than the Waulsortian.

The Longwood borehole and the BHP core hole both went through a similar zone of high conductivity. In the Longwood borehole this corresponds with the lower part of the Lucan formation. It was noticeable during the drilling of this borehole, that the joint faces on the fragments of rock brought up by the air flush, were stained with iron oxide. In the BHP core hole the top of the high conductivity zone is just below a fault containing yellow ochre clay, and the bottom of the high conductivity zone appears to be nearly coincident with a second fault at 71 metres depth. This fault contains the pink coloured calcite that John Paul Moore has found to be characteristic of calcite veins along Cenozoic age faults. The shape and sloping dip of the top and bottom of the high conductivity zone also has the appearance of a dipping fault zone.

The position of the base of the high conductivity zone at the site of the Longwood borehole matches the change from the Lucan formation to the Waulsortian limestone.

The presence of a high conductivity zone sandwiched between and upper and lower low conductivity zones is seen in all the geophysical sections, but is an enigma. It will be discussed further, below.

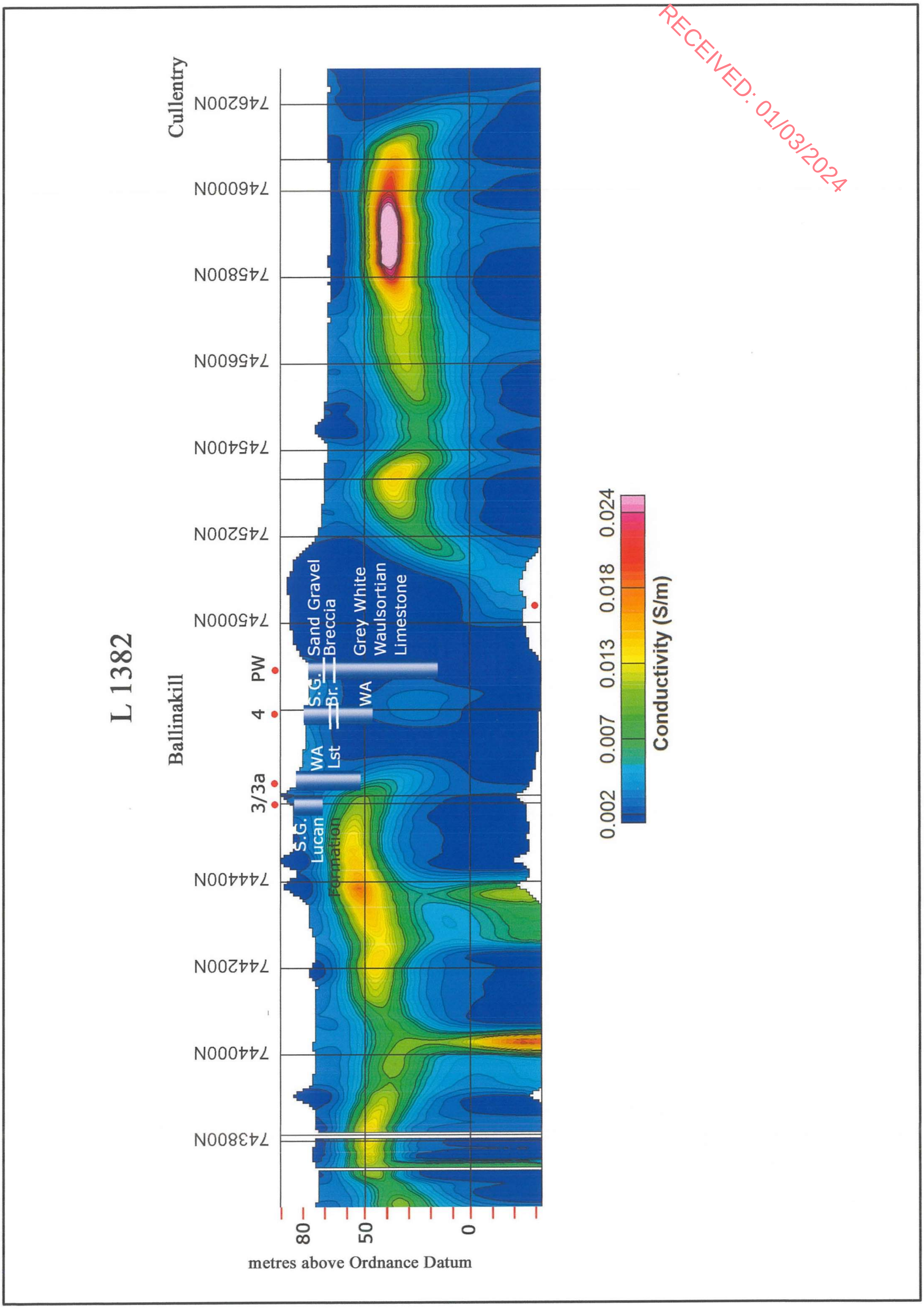
Figure 2.34 shows two sections. L1381 which runs through St Gorman's Well and the main cluster of boreholes around the spring. L1380 is 200m to the west.

The geology in this area has been much studied but is confused. There is a transition from the Ballinakill hill to the east underlain by solid Waulsortian into the lower ground that appears to be underlain by a high conductivity layer sandwiched between two low conductivity layers. The high conductivity layer is closer to the surface than in Section L1378 in Figure 2.33.

In L1380, the layer above the core of the high conductivity layer may be overburden containing gravels. Borehole SG5 drilled by Hydro Research in 1987, does not have a detailed log, but from Frank Murphy's sketch section, in Figure 2.7, it is shown as being entirely in the Calp limestone down to 190m.

The fault contact between the Calp and the Waulsortian in Frank Murphy's very deep core

Figure 2.35 Tellus Conductivity Section L 1382 and Ballinakill borehole logs



hole, SG8, roughly corresponds with the change in conductivity to the low conductivities of the lower layer.

The borehole labelled Meath County Council Test Borehole refers to a borehole next to the farm entrance gate into the grounds of Hotwell House. I understand that it did not have potential as a water well, and that it penetrated dark grey limestone rock.

A notable feature of the section through St Gorman's Well are the large number of vertical changes in conductivity in the lower layer. The higher conductivity in these vertical zones was not obscured by the strong signal from the much higher conductivity layer above. Therefore, the vertical zones are probably real rather than artefacts. The number and clear definition of the vertical zones may indicate that there are a large number of faults to the northwest and southeast of St Gorman's spring.

The orientation of these 'faults' cannot be determined from a single section. Section L1380 is included in Figure 2.34 because it indicates that the 'faults' on the section through St Gorman's do not appear to occur in the L 1380 which is just 200m to the west. This may indicate that the 'faults' seen in L1381 are oriented north-south or northwest to southeast, close to the alignment of the flight lines.

It can be seen at that the high conductivity layer stops abruptly at the northern end of both sections, and the low conductivity dark blue extends from the surface to at least 100 metres depth. This is the southern edge of the Cullentry block, that is assumed to be Waulsortian limestone. It appears to be defined by distinct fault.

Figure 2.35 shows section L 1382 which is 200 metres east of L1381, and crosses the big field and the northern end of the belt of forestry on the western flank of Ballinakill hill. The dark blue 'hump' in the surface topography is the height of the trees in the forestry belt picked up by the plane's altimeter.

The section shows a block of Waulsortian in the middle with two areas on either side underlain by the sandwich of a high conductivity layer between an upper and lower zone of low conductivity. Again there is a block of low conductivity at the northern end of the section under the Cullentry townland.

It is notable that the two layers of high conductivity are at different levels on either side of the Ballinakill block. It is also notable that there appear to be many vertical breaks in the low conductivity layer at the base of the section.

EDA core holes 3 and 3a are fifteen metres apart. One penetrated just a shallow depth into the Lucan Formation, and the other encountered the Waulsortian. The conductivity section indicates a termination of the high conductivity layer roughly below the site of the boreholes,

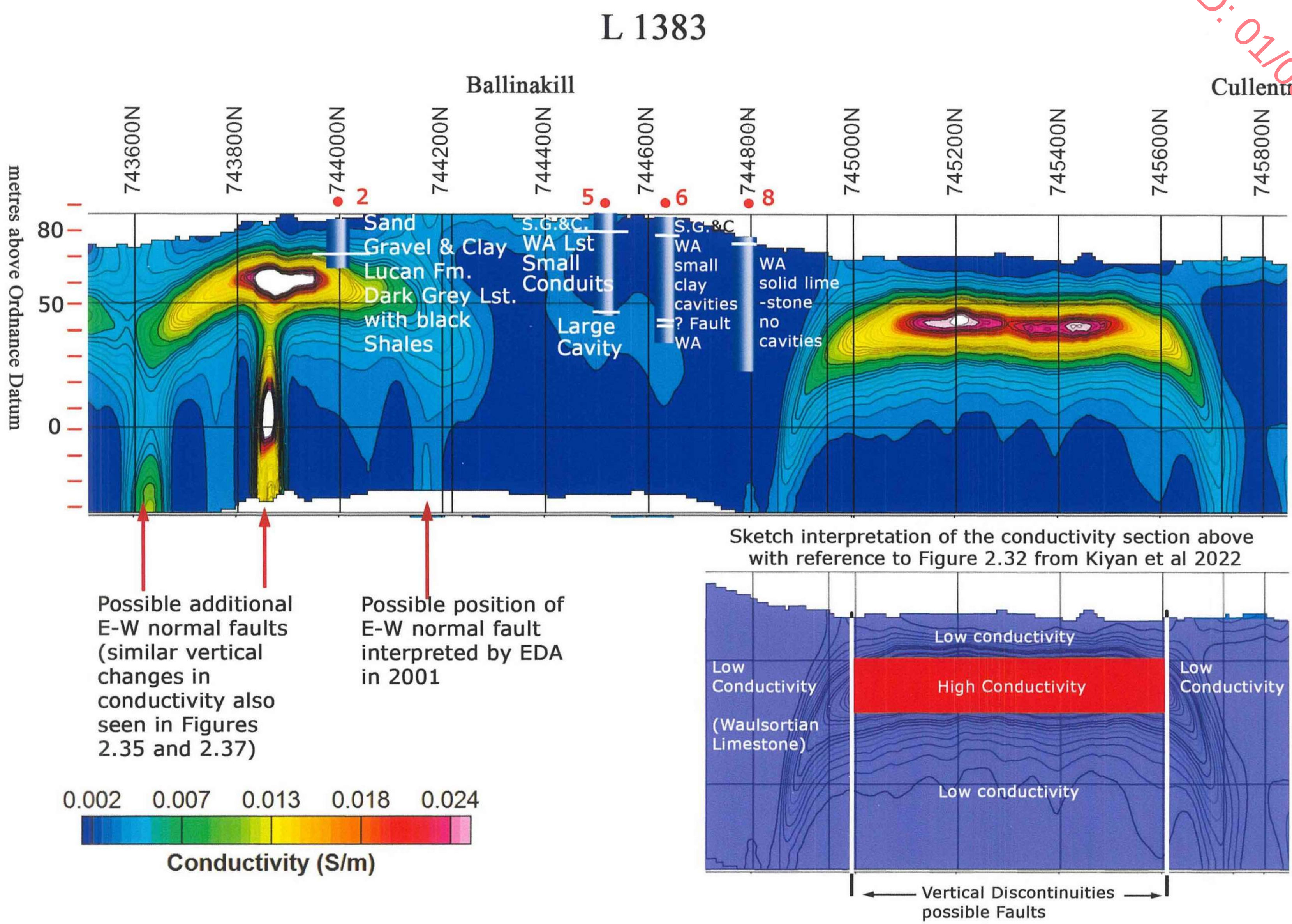


Figure 2.36 Tellus Conductivity Section L 1383 and Ballinakill borehole logs

and a change of conductivity in the lower low conductivity zone. . These boreholes are just east northeast of St Gorman's Well.

There are two wide vertical breaks in the lower conductivity zone to the south of the boreholes, that indicate a continuation of similar vertical breaks, seen in section L1381 in Figure 2.34. The two large breaks and the change in lithology found in boreholes 3 and 3a suggest that there are several significant roughly east west aligned 'faults' defining the southern side of the Ballinakill block.

Finally, the conductivity within the Ballinakill block is not uniform. There appears to be an egg-shaped, slightly lower, conductivity zone in the middle of the block.

EDA carried out a ground level resistivity survey, and found evidence that there were faults in the block, and a wide zone of breccia crossing the block from southwest to north east. Core hole 4 encountered a breccia, as did the borehole drilled for the EDA pumping test, borehole PW. If the egg-shaped zone of lower conductivity represents a karst solution cavity in the breccia, it appears that PW went to the correct depth but just to the north side of this potentially productive conduit. The lower conductivity feature in the Waulsortian is also seen to continue in Section L 1382.

Figure 2.36 crosses Ballinakill hill 200 metres to the east of L1382 in Figure 2.35.

I have added a sketch in the lower part of Figure 2.36 to relate the high conductivity layer at the northern end of the section, to the upper and lower panels in Figure 2.32.

The simulated example of a high conductivity body buried at shallow depth in a low conductivity matrix, and the data modelled in a 1D section by the DIAS/Tellus team's software programme in Figure 2.32, exactly matches the shape shown in the real conductivity data on the 1D section in Figure 2.36.

As a result, the high conductivity layer in Figure 2.36 can be interpreted as a block with well defined, vertical lateral edges, and hence possibly defined by vertical faults. The low conductivity on the southern side is well defined as Waulsortian limestone by the data from EDA core hole 8. The solid block of low conductivity on the northern end of the section appears similar, and is taken to be Waulsortian limestone below Cullentry. The block of low conductivity above the high conductivity block may be rock, but as it is in the same shallow valley as the Longwood boreholes that have a sand and gravel layer above the bedrock, this shallow low conductivity layer is likely to be gravel overburden, rather than rock. Gravels are shown also on the GSI Quaternary sediment Public Viewer website, and the area was further extended by the field observations of Robbie Meehan during a survey by Tobins in 2009 (see Figures 5.12 and 5.52).

The low conductivity layer below the high conductivity block, containing a serrated patterns of conductivities, could be bedrock broken by several faults. The nature of this bedrock is not known under this section.

EDA core hole 2 is an important borehole on the southern side of the Ballinakill hill. It is a core hole that went through thick sand, gravel and clay till, and then penetrated 5 metres into thin beds of dark limestone and mudstone (shale) dipping at 28 to 30 degrees. This rock was dated using micro-palaeontology by Gareth Ll. Jones as being upper Lucan Formation. The Lucan is younger than the Waulsortian. From this identification, EDA deduced that there was a normal fault (a fault where younger rocks move down relative to older rocks) between core hole 2 and core hole 5 in this section. The calculated movement is of the order of 500 metres. The alignment of this fault was interpreted as roughly east-west. This alignment of the normal fault suggests that the fault is very old (i.e. Carboniferous) and likely to be closed.

This fault is clearly picked out by the conductivities in the section in Figure 2.36. The data shows an abrupt edge to the Waulsortian Ballinakill block at approximately grid northing 744200N, and vertical inflexion in the conductivity contours in the deeper layer. Therefore, the conductivity section appears to be confirming the interpretation by EDA gained from their core hole data.

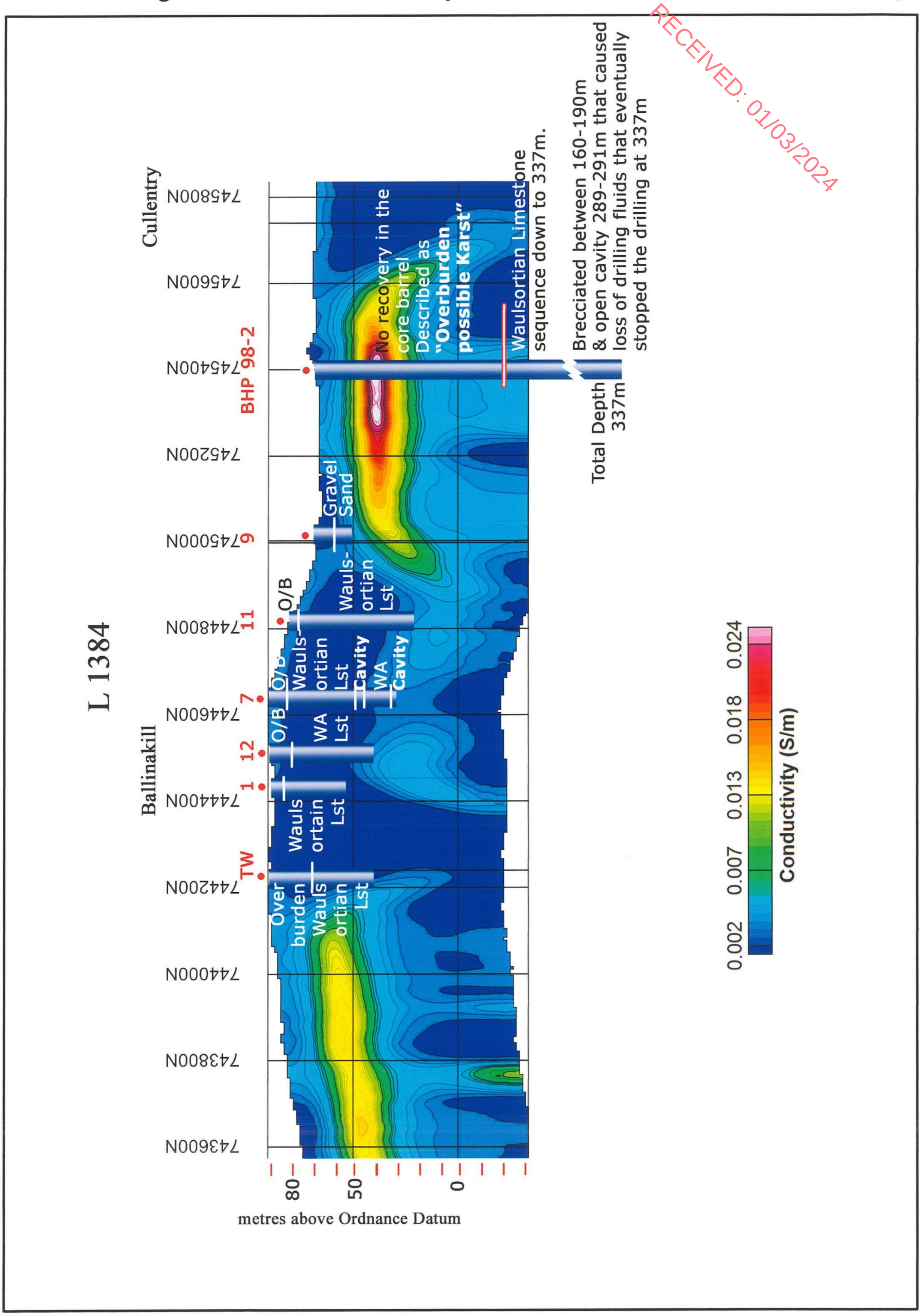
It is reassuring to find that the airborne conductivity data closely corresponds with the findings from borehole drilling.

It is of interest that the conductivity in the deeper bedrock changes, but is still low conductivity <002 Siemens per metre (S/m). There is no sign of high conductivity material in this vertical alignment in the deep bedrock, that perhaps, would indicate that there is broken or karstified rock or clays in this possible fault zone. However, just to the south along the section, there are two clear vertical discontinuities in the 'dark blue bedrock'. These are marked on the section with the comment that there are two similar discontinuities in the adjacent section. There is one caveat to this interpretation. The very high conductivities (yellows reds and pink) in the middle discontinuity, seem unnaturally well defined, or constrained, laterally. It is possible that these unusual conductivities are interference artefacts in the 1D model arising from the combination of a very high conductivity in the middle layer above, and possibly a good conductor on the road on the surface, but not shown. In other words there could have been a large metal combine harvester or truck on the road above the fault as the plane flew over .

The core holes shown on section L1383 provide important information that can be correlated with the conductivity.

Core hole 5 terminated in a large cavity.

Figure 2.37 Tellus Conductivity Section L 1384 and Ballinakill borehole logs



Core hole 6 encountered a probable fault at the same depth. Both of these core holes appear to be in a large zone of slightly higher conductivity in the middle of the very low conductivity Ballinakill Waulsortian block. This is also roughly the position of the zone of breccia identified by the EDA surface resistivity survey.

Bringing together the direct evidence from the core hole log with the airborne and ground geophysical surveys, indicates that there is a feature running diagonally northeast to southwest through the Ballinakill block, and that it could be a cave and conduit for groundwater. This may be significant in the context of collecting rainfall recharge on the Ballinakill block, and creating a preferential path for groundwater flow towards St Gorman's spring. Having said that, I am conscious that geophysical survey data can be over-interpreted and misleading, but in this is a case with direct evidence from a core hole of a cavity over 1 metre in size partly filled with clay.

Figure 2.37 is an important section because it provides a correlation between six core holes/boreholes in the Ballinakill block and one deep mineral exploration core hole down through a high conductivity layer in the valley between Ballinakill and Cullentry.

Starting at the south of the section; there is a near continuous gently sloping high conductivity layer around 50 metres above Ordnance Datum. There is a large discontinuity in the deep low conductivity zone, and the middle-high conductivity zone is stepped; again suggesting a fault crossing this section alignment.

The high conductivity zone or layer stops abruptly with a down-turned tail against the southern edge of the Ballinakill block. An EDA potential pumping well that gave a low yield and became designated a Test Well (TW) is just to the north of the abrupt termination of the high conductivity middle layer. TW encountered only Waulsortian bedrock. The evidence from core hole 2 on Section L 1383 indicates that the high conductivity zone in the south of section L 1384 is the top of the Lucan formation. Therefore, the conductivity section and core hole data indicates that there is a fault to the south of borehole TW.

Core holes 1, 12, 7 and 11 all encountered Waulsortian limestone, but core hole 7 also encountered a 3.5 metre size cavity below 42 metres, and a final smaller cavity at 59 metres at the end of the hole. The position of these cavities is approximately at the same depth as the top of a higher conductivity feature in the middle of the Ballinakill block, that is shown in pale blue on the section.

The size and shape of the conductivity contours in the centre of the block of Waulsortian produced by the 1D inversion model probably indicates a small but significant conductivity contrast; most likely a cavity system containing conductive clays and water. There appears to be something similar below the bottom of core hole 11.

Core hole 9 is an important hole even though it was only 20 metres deep. It is sited at the change of slop between Ballinakill hill to the south and the flat valley to the north. The conductivity section shows low conductivity. The core hole log shows that this represents gravel and sand layers that are over 20 metres deep. The data from the core hole confirms that the dark blue low conductivity layers at or close to the surface could represent sands and gravels in the overburden.

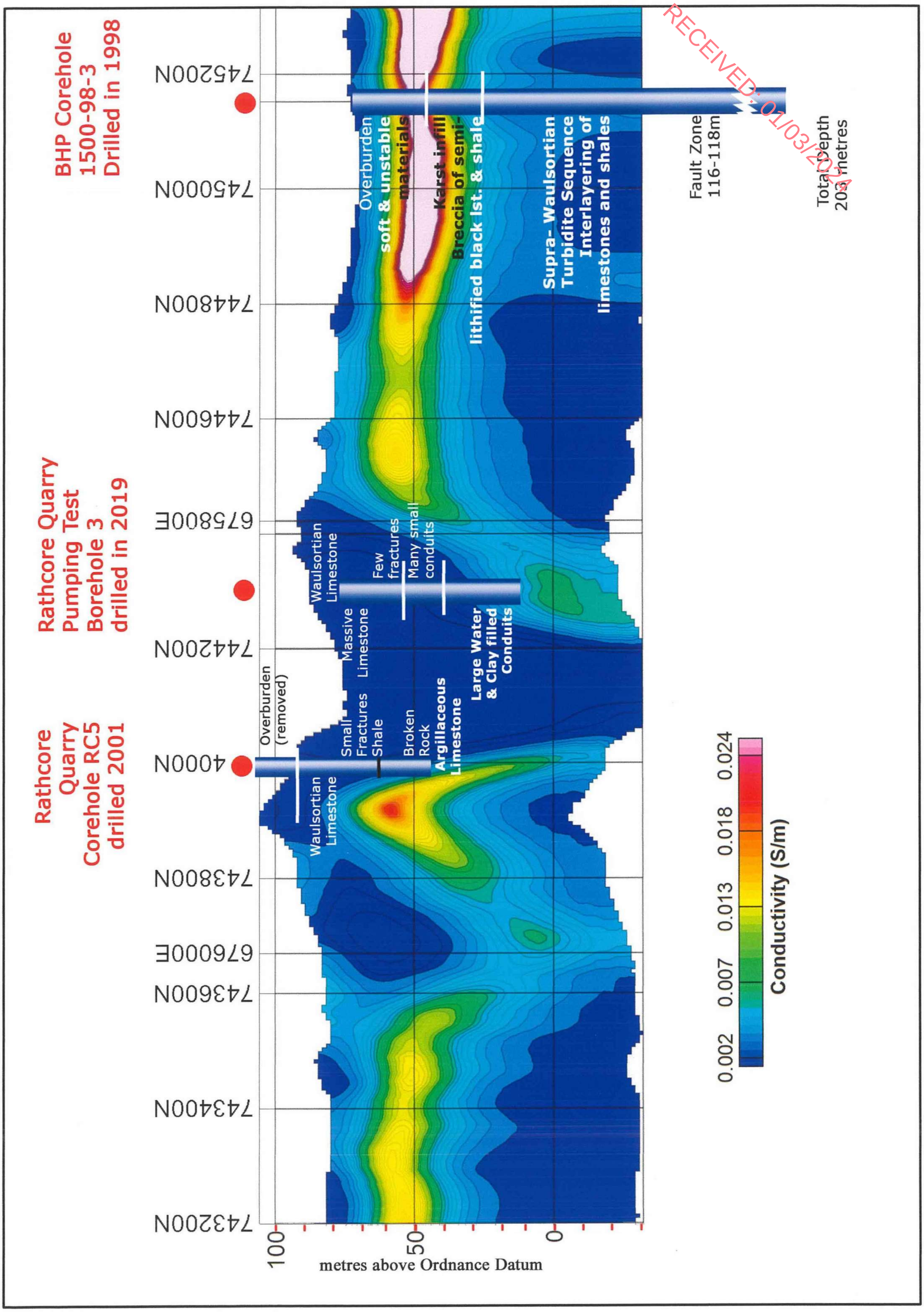
Core hole BHP 1300-98-2 is another important core hole on this section. It is a remarkable hole, because it went through 90.5 metres of "overburden presumed to be karst infill". The first 90 metre section was probably drilled with a tri-cone bit with following steel casing to support the unstable walls of the hole. From my drilling experience, it is probable that the full 90.5m did not consist of unconsolidated sediments deposited in a karst depression, because from 90.5 metres depth the drillers immediately achieved 100% recovery of core. In other words they started coring when it was hard competent stable rock and they were confident that they could get core. It is not likely that the bottom of a karst depression would see a sudden change from soft sediments into hard rock. It is more likely that the bottom of the depression was higher up and that there was an unstable transition zone made up of soft limestone, cavities sands, and weathered boulders that could be drilled easily by a tri-cone bit. It is unfortunate that the geologist, or more likely the un-supervised drillers, did not make a more detailed description of the material between 0 and 90.5 metres, but this absence of a record is understandable, because this was a mineral exploration core hole looking for lead zinc ores in the bedrock. It wasn't a geological exploration borehole for general mapping purposes.

Correlating this core hole log with the conductivity section is informative. The conductivity section shows a layer of very high conductivity materials below the sand gravel overburden projected across the valley from core hole 9. This high conductivity layer is about 50 metres thick. We therefore know that this high conductivity layer at this location represents a soft unstable material that cannot be cored successfully.

There are three possible obvious explanations for the material that could make up this high conductivity layer:-

1. It is a thick zone of deep karst weathering of the underlying Waulsortian limestone that creates a residual zone of yellow clays, dolomite sands and irregular boulders of partly rotted pale grey limestone. The material making up this layer was created in situ.
2. It is a thick deposit of material that did not arise in situ, but was transported from elsewhere and deposited by ice, water or wind. It could be a deposit of brown clayey,

Figure 2.38 Rathcore Quarry Tellus Conductivity Section L 1390 and Borehole Logs



stony, material washed into a major karst depression; perhaps, similar to the materials that are in the in-filled karst depression shown in Figure 2.24.

3. It is a block of dark grey limestone and shales that were deposited on top of the Waulsortian limestone. These limestones and shales then have been deeply weathered. This possibility would require a fault on the northern and southern margins to down throw a block of Waulsortian with a cap layer of, say, Lucan formation above.

Option 3 is possible, but intensely weathered dark grey limestone and shale in the Dublin Basin does not break down completely. These rocks are argillaceous AND contain clay minerals that are less susceptible to karst solution weathering than the pure calcite and dolomite comprising the Waulsortian limestone. The weathered argillaceous limestones and shale do not decompose completely, and usually presents some resistance to drilling and can be cored, albeit, probably with less than 100% recovery of core in the core barrel. Therefore, option 3 is less likely at this site.

Options 1 and 2 are equally likely because the underlying limestone is clearly described as standard Waulsortian limestone.

The conductivity section also indicates that there appears to a wide and deep vertical discontinuity in the bedrock directly below the very high conductivity layer. It gives the impression that the karst feature is deep, and not filled with high conductivity material. This zone could be a large fault zone containing many cavities and broken rock or a simple large sink hole filled with less conductive material than the material in the very high conductivity zone above.

Figure 2.38 provides further help in the identifying the material giving rise to the high conductivity layer sandwiched between an upper and lower low conductivity layer.

Section L 1390 in Figure 2.38 crosses Rathcore quarry as already shown in Figure 2.31. In Figure 2.38 I have added summary logs and depths for three boreholes.

Core hole RC5 was drilled in 2001 and the site had been excavated during the quarry development by the date of the airborne survey in 2015. This is why the log appears to start in mid-air. Conversely, test borehole 3 was drilled in 2019, by which time the quarry had had been excavated to a lower level; hence, on the 2015 topography, this borehole appears start underground.

RC5 may have picked up some evidence relating to the large high conductivity anomaly shown on this section, but it did not encounter large cavities containing clay. The borehole 3 log appears to correlate with the change from very low to higher conductivity shown in the section.

The borehole encountered a number of large cavities containing water and clay near the bottom of the borehole where the colour on the section changes from dark blue to cyan.

BHP core hole 1500-98-3, like BHP 1500-98-2 also went through 'karst in-fill', and then into "Supra Waulsortian". This is a stratigraphical label used in 1998 to refer to dark grey limestones and shales that were deposited above the Waulsortian, but without giving the rock a specific name such as Tobercolleen or Lucan formation.

The description of the upper part of the borehole sequence written by Jorge Cirett for BHP is more detailed and informative than the description in BHP 1500-98-2. It is useful to correlate his description with the conductivity section.

Jorge Cirett states that the upper borehole was cased to 57.5 metres depth, implying that this section of the hole was regarded as unstable and needing support.

Below 57.5 metres the rock encountered in the core hole was sufficiently competent to not require support. He describes the first 27.5 metres as overburden that was drilled with a tri-cone rotary bit.

From 27.5 to 49 metres he describes it as "karst in-fill". They managed to get some core from this section but with recovery rates as low as 10% or 13%.

He describes the core overall as a Breccia consisting of semi-lithified fragments of dark grey to black shale, in filaments with disseminated pyrite, in a thick black mud matrix. He also identifies that there are small quartz crystals in this mud, and that the material is generally non-calcareous. From 44 to 49 metres he describes the core as a breccia with a diverse composition of chert, siltstone and limestone.

Below 49 metres, Jorge Cirett describes the much more competent rock with 100% core recovery as a Turbidite sequence of 0.15 to 1.5 metre thick beds of fine grained black limestone and carbonaceous black mudstone with centimetre thick chert bands. He also describes thin white calcite veins cross-cutting the limestone beds, but not invading the mudstones.

Standing back from the detail, the description of the core suggests a deeply weathered almost decomposed rock from 27.5 to 44 metres where the calcareous component has been mostly lost by dissolution. Below 44 metres it is less decomposed and below 49 metres the rock is barely weathered.

The 29.5 metres upper overburden 'karst in-fill's', is marked in the log on Figure 2.38 and it corresponds well with the bottom of the very high conductivity layer in reds and pinks on the conductivity section. The 'karst in-fill' breccia of shales with pyrite in a mud matrix is also marked on the log and this corresponds with the transition from pink through orange, yellow, green and pale blue on the conductivity section. The start of competent black limestone and

Figure 2.39 Drill cutting slurry from deep weathered dark grey limestone & black shale

mudstone corresponds with the depth of the start of low conductivity dark blue colours on the section.

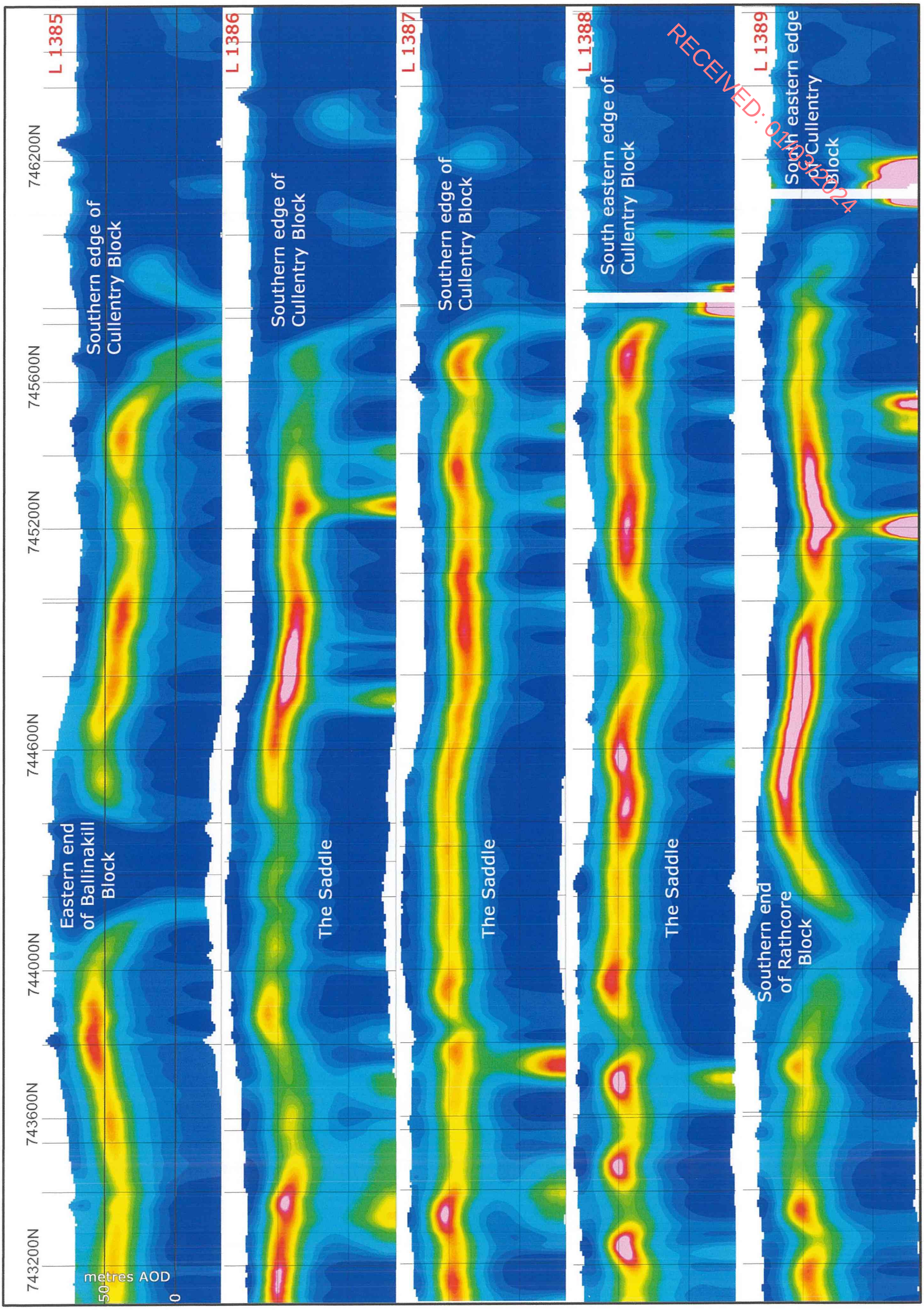
The good correlation of depths between the core hole log and the conductivity section does not necessarily mean that the conductivity section is highly accurate. Saturated rock that has been so weathered, or rotted, by solution weathering that it can be barely described as a rock, containing carbon and pyrite, is likely to be very conductive. It seems therefore that the Airborne conductivity data has correctly detected this high conductivity material but that the processing to create the 1-D section has placed it slightly too high in the sequence. In other words the pink and red in the section might more accurately extend down to 44 or 49 metres below ground.

I have gone into extra detail correlating the BHP core hole log with the conductivity section for several reasons:

- First, Jorge Cirett's log shows that the rocks below this area, which is just to the northwest of Rathcore quarry, are not Waulsortian limestone as shown on the GSI bedrock map Sheet 13.
- Second, there must be a fault zone between the Waulsortian limestone making up the Rathcore block, and these younger rocks under the valley to the northwest. The obvious position for this fault is around Northing 744500N on the section in Figure 2.38. The older Waulsortian rocks have either been pushed up or the younger rocks dropped down along this fault
- Third, there is clear evidence that karst weathering of dark grey limestones and shales has taken place. In other words karst solution decomposition of rock in this area is not confined just to the pure calcium carbonate and dolomitised Waulsortian limestones.
- Fourth, the deep weathering, or near decomposition of argillaceous limestones and shales is found below nearby areas and it can have a hydrogeological significance.

For example, Figure 2.39 shows the black muddy slurry created whilst drilling the upper 60 metres of a water supply borehole west of Ashbourne in 2016. The rock was soft but became more competent with depth. The upper part of the weathered rock came up as small fragments or flakes in a black, almost oily slurry as shown in the photograph, with occasional wisps of dark grey-brown clay that suggests there is clay originally from fractures and joints in the less weathered rock. Water had to be injected through the drill hammer to sufficiently liquefy the slurry, to bring it to the top of the borehole, because insufficient water was entering the hole from the weathered rock.

Figure 2.40 Five Sections across the ‘Saddle’ between the Rathcore & Ballinakill blocks



The significance of this example is that the upper weathered rock zone in this borehole acted as a very low permeability layer that confined the abundant groundwater flow system in fractures and conduits in the less weathered bedrock below it.

In other words, the groundwater deep in the less weathered rock was held under pressure by the decomposed form of the same rock above. The confined nature of the groundwater flow system was proven when pumping started in one borehole and the water level went down in a borehole over 100 metres away within a few seconds. Pumping lowered the groundwater pressure in one hole and the pressure dropped immediately in the second hole.

The evidence from the two conductivity sections correlated with deep mineral exploration core hole logs shows that there is an extensive conductive layer, that appears to consist of in-fill in a deep karst depression overlying weathered rock. The karst depression has been formed above both pure Waulsortian limestone and dark grey limestone and shale.

It is likely that groundwater in conduits formed in fractures in either type of bedrock below these layers of 'karst infill' is likely to be confined or under pressure. This interpretation would mean that if pumping caused a drop in pressure at one side of the bedrock under the 'karst infill' then the pressure drop would be rapidly observed at the other side.

It appears that there are blocks of Waulsortian limestone forming the core of low hills and between and around them there are limestones covered by a zone or layer of highly weathered limestone.

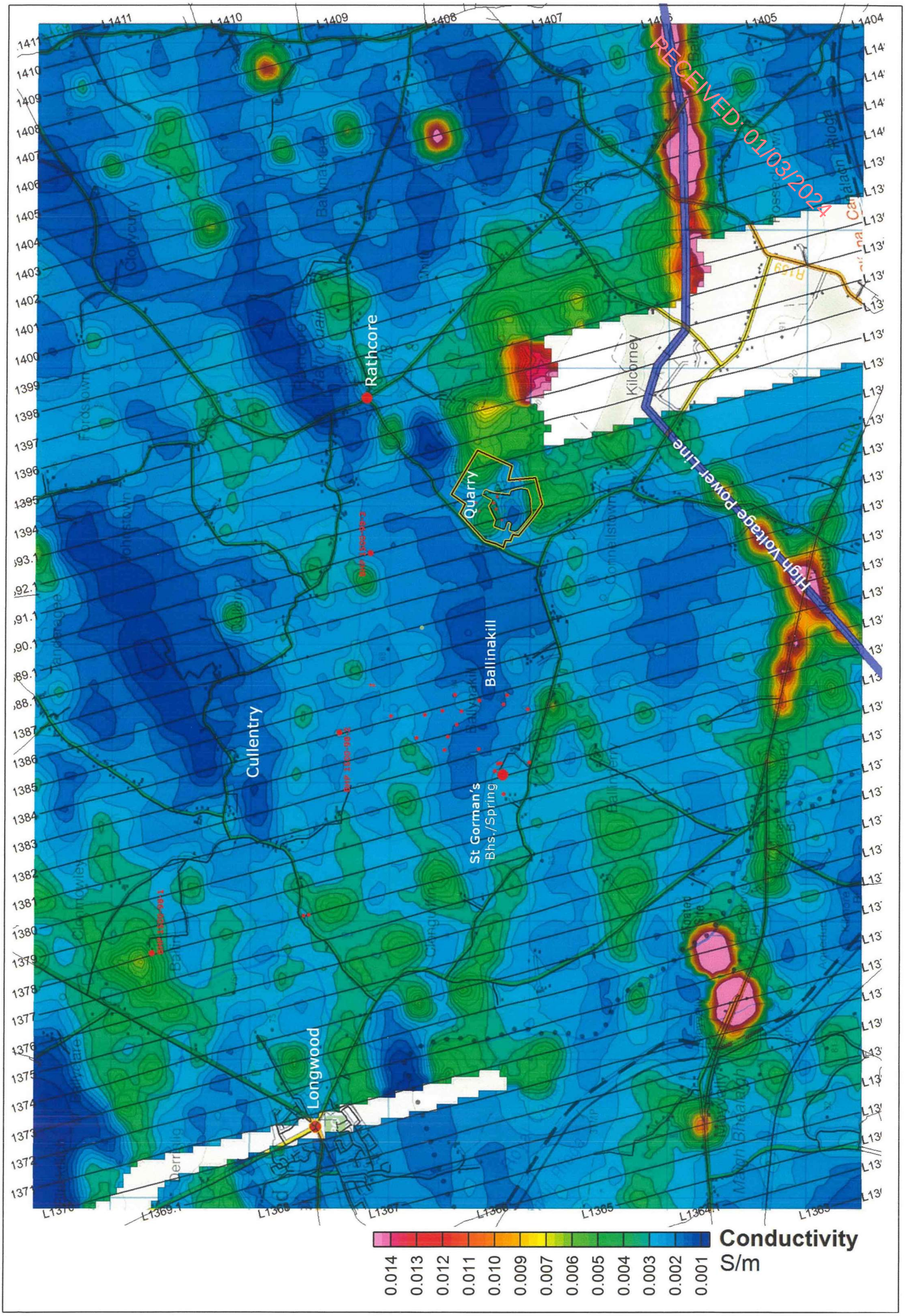
Figure 2.40 shows five conductivity sections illustrating the nature of the geology below the land between the Ballinakill and Rathcore blocks of Waulsortian limestone.

The upper section L1385 just clips the tapering end of the Ballinakill block. A high conductivity layer is on both sides of the block. The bottom section L 1389 crosses the southern tip of the Rathcore block, that forms a divide between two layers of high conductivity material. The high conductivity layers have 'tails' that appear to bend down under the Waulsortian but as explained before, this is a product of programme to create the 1-D section.

A block of low conductivity bedrock, assumed to be Waulsortian limestone can be seen on the right in all five sections. I have called this the Cullentry block as a quick reference name for ease of reference.

The three middle sections show how a high conductivity layer extends across the whole section south of the Cullentry block. It looks as if the high conductivity layer rises slightly over a lower bedrock block, that I have informally named 'the saddle', again for ease of reference. The saddle maybe Waulsortian limestone. There are no boreholes with lithological logs in this area.

Figure 2.41 Tellus Airborne EM Survey Conductivity at 74.9 metres .below ground level



A superficial observation of the sections suggests that the rock forming the saddle (in dark blue) is a down faulted or eroded block of Waulsortian limestone. The evidence from the sections, described in the earlier text, indicates that the high conductivity layer (yellow, pink red) is a clayey karst in-fill, or simply the upper weathered zone of the bedrock below. In both cases the high conductivity layer is probably composed of conductive clays. The implications of the high conductivity zone extending across the top of the bedrock forming the saddle is that a groundwater flow system in the saddle is likely to be confined by the clayey layer, as described above.

If this is correct, the five conductivity sections may indicate that the Ballinakill block and the Rathcore blocks are linked by bedrock below a thick layer, or zone, containing conductive clays that may form a confining layer.

2.8.4 Interpretation of depth slice maps

The 1-D conductivity sections were used to create Conductivity Depth slice maps. Mark Muller produced two versions of the sections and the depth slice maps. The first version used a linear conductivity scale from 0.001Siemens per metre to 0.014 Siemens per metre. The second version used a conductivity scale of 0.002 to 0.024 Siemens per metre. The object of the first version was to try to observe detail in the lower conductivity ranges; i.e. in the unweathered bedrock. The object of the second version expanded scale was to see if more detail could be obtained in the high conductivity areas.

I chose to reproduce sections using the second version.

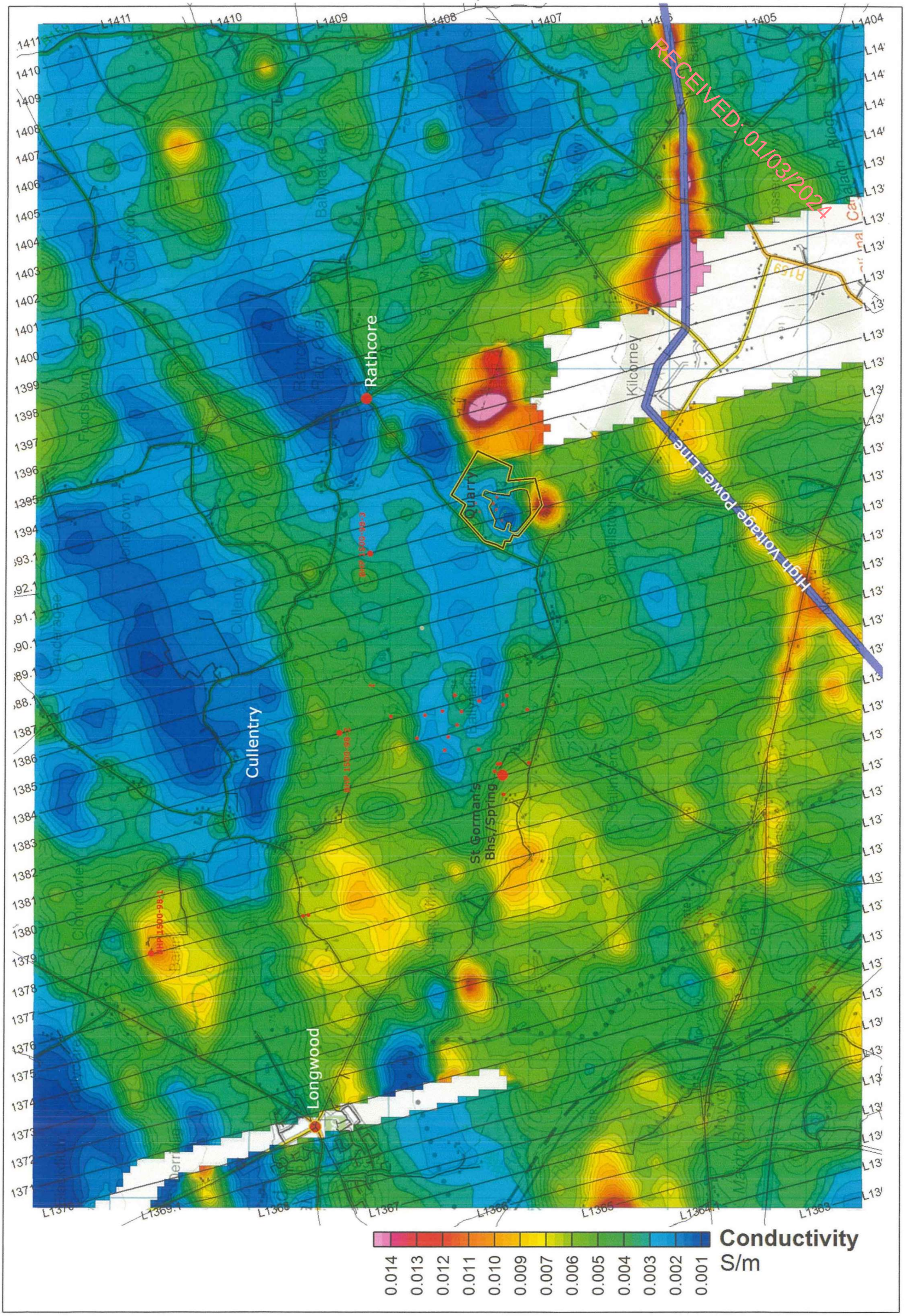
I have chosen to use the first version for the depth slice maps because subtle details in the low conductivity areas are more evident.

The first map is shown in Figure 2.41. It is a depth slice at 74.9 metres below ground level, and not at a constant level of, say, 10 metres above Ordnance Datum. It is also compiled from the 1_D sections. Therefore, the 'tails' at the edge of high conductivity layers tend to bend down under low conductivity areas and narrow the width of low conductivity blocks. The 74.9 metre depth slice map shows the Tellus flight lines, the quarry, St Gorman's spring and the main boreholes in the area.

The map shows that there are no high conductivity layers at this depth. The pink-red 'bull's eyes' are artefacts or interference from the ESB high voltage power lines.

The map shows a northeast to southwest trend in the Rathcore block with a circular break, west south west of Rathcore cross roads and also in the northern part of the quarry under the area where overburden has been stripped and stored. The area due west of the quarry and north west

Figure 2.42 Tellus Airborne EM Survey Conductivity at 52.1 metres .below ground level



of the quarry appears to be the same, but the area to the northwest was found to be Supra Waulsortian in BHP 1500-98-3 (shown on the map). Therefore, a blue or pale blue colour on the map does not equate to just Waulsortian limestone.

There are interesting lineaments of moderate conductivity circular areas to the south of the Cullentry block and the Ballinakill block. There is a moderate conductivity pale green lineament to the northwest of St Gorman's spring. All these lineaments may represent fault lines or linear zones at depth containing karst conduits full of water..

Figure 2.42 shows a depth slice at 52.1 metres. The shape and orientation of the low conductivity blue and pale blue areas is similar to the pattern at 76.9 metres. There appears to be a west northwest to east southeast trend on the southern margin of the Ballinakill block and the Cullentry block. The Cullentry lineament appears to carry on and project through the Rathcore village cross roads, but between Cullentry and Rathcore it seems to be intersected by a northeast to southwest Cenozoic strike-slip fault trend or lineament.

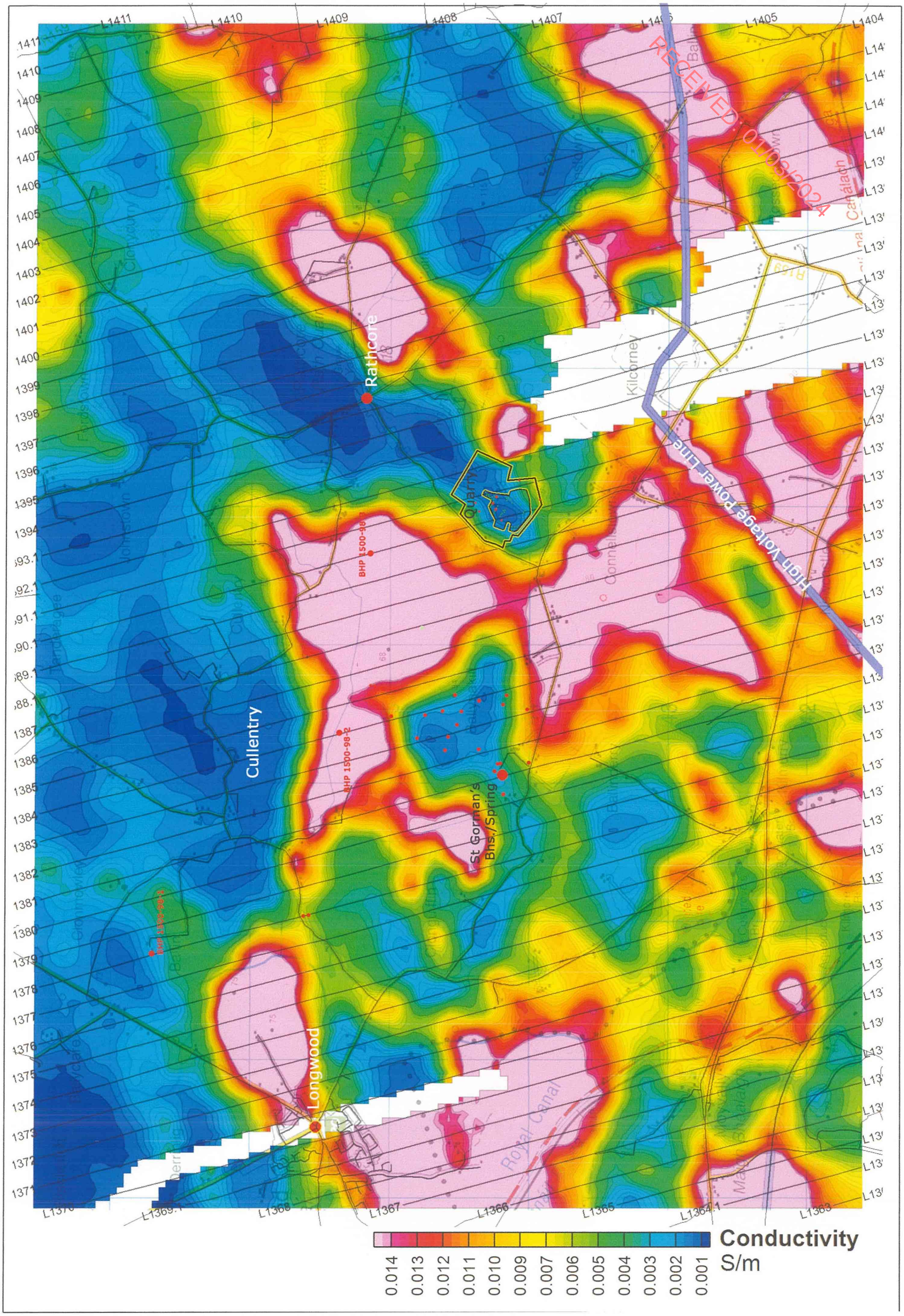
A lineament with the same orientation appears to form the eastern edge of the southern part, and the northern part of the Rathcore block. The Rathcore block at this depth appears to be divided into three. The northern part north of the cross roads is the most extensive. There are two smaller blocks to the south. The area within the quarry for a proposed deeper excavation is shown as low conductivity. The high conductivity to the south is the possible cave containing clay.

Figure 2.43 shows the depth slice at 29.3 metres. It is a dramatic image showing isolated low conductivity dark blue areas separated by large areas of very high conductivity in pink, red, orange and yellow.

The Ballinakill block north east of St Gorman's Well has an area of high conductivity to the west, north and east. It appears disconnected from the Rathcore block and the Waulsortian under the quarry. The large pink and red high conductivity areas appear joined across 'the saddle', discussed above and shown in Figure 2.40. If these areas depict a layer of low permeability 'karst in-fill' or intense karst weathering, then it could mean that rainfall recharging the groundwater system in the karst in the Waulsortian in the Cullentry block to the north and the Rathcore block to the east could influence the water resources in the Ballinakill block only if the karst conduits extend below the low conductivity area.

The 29.3 depth slice map shows a sharp contrast between the Rathcore block and the high conductivity areas to the east and west. The northeast to southwest orientation of the Rathcore

Figure 2.43 Tellus Airborne EM Survey Conductivity at 29.3 metres .below ground level



block on this map continues the trend, or lineaments, seen on the deeper depth slices.
The west northwest to east southeast trend along the southern edge of the Ballinakill block is seen clearly at this depth, but another northwest to south east lineament is clearly seen to define the northeast side of the block.
The deep karst encountered in BHP 1500-98-2 above Waulsortian, due north of Ballinakill, seems to be in a smaller area of high conductivity, separated by a narrow neck from the much larger high conductivity area to the east, where BHP 1500-98-3 encountered heavily weathered Supra Waulsortian rocks. Without further evidence, it seems possible that these two areas represent a large enclosed palaeo-karst depression, or 'Uvala', above the two different rock types. It is also notable that the large high conductivity area appears to flow over 'the saddle' to link up with another large, very high conductivity area to the south.
An overview of the pattern of high and low conductivity areas shown in the map suggests a karst landscape of physically robust Waulsortian limestone 'towers', rising above closed depressions. The tops of the towers have been stunted by glacial erosion, and the karst landscape hidden below layers of boulder clay and glacio-fluvial sands gravels and clays. Deep karst solution weathering creating small and large depressions is to be expected in an area where open caves have been encountered in boreholes at considerable depth. These caves contain clays. The dissolution of the original caves and the subsequent sediment deposits within them, all demonstrate that an active karst drainage system existed at depth. In effect there is a well developed 'plumbing system' of caves or conduits, fed by sink holes at the surface.

Figure 2.44 is a conductivity depth slice map at 19.8 metres. It shows a pattern with the same features shown in Figure 2.43. It adds detail because it shows that the very high conductivity layer between the Rathcore and Ballinakill block starts at a shallower depth than the smaller area with high conductivities due the north of Ballinakill. The karst in the smaller area is deeper. The karst in the larger area is shallower but more extensive.
The map shows that the high conductivity north northeast aligned feature to the west of Ballinakill also persists at a shallow depth. It also shows that the large high conductivity area to the southwest of Rathcore quarry and south of Ballinakill appears divided into two.
Both figures 2.43 and 2.44 show a ridge of relatively low conductivity material extending first to the south west from St Gorman's, then continuing along a west northwest alignment along the direction of the road to Longwood, and then abruptly turning to the northeast back towards Cullentry. There is an outcrop of the Lucan Formation noted by the GSI on the road to Longwood. It is important to note that the blue and pale blue low conductivity areas do not just

Figure 2.44 Tellus Airborne EM Survey Conductivity at 19.8 metres .below ground level

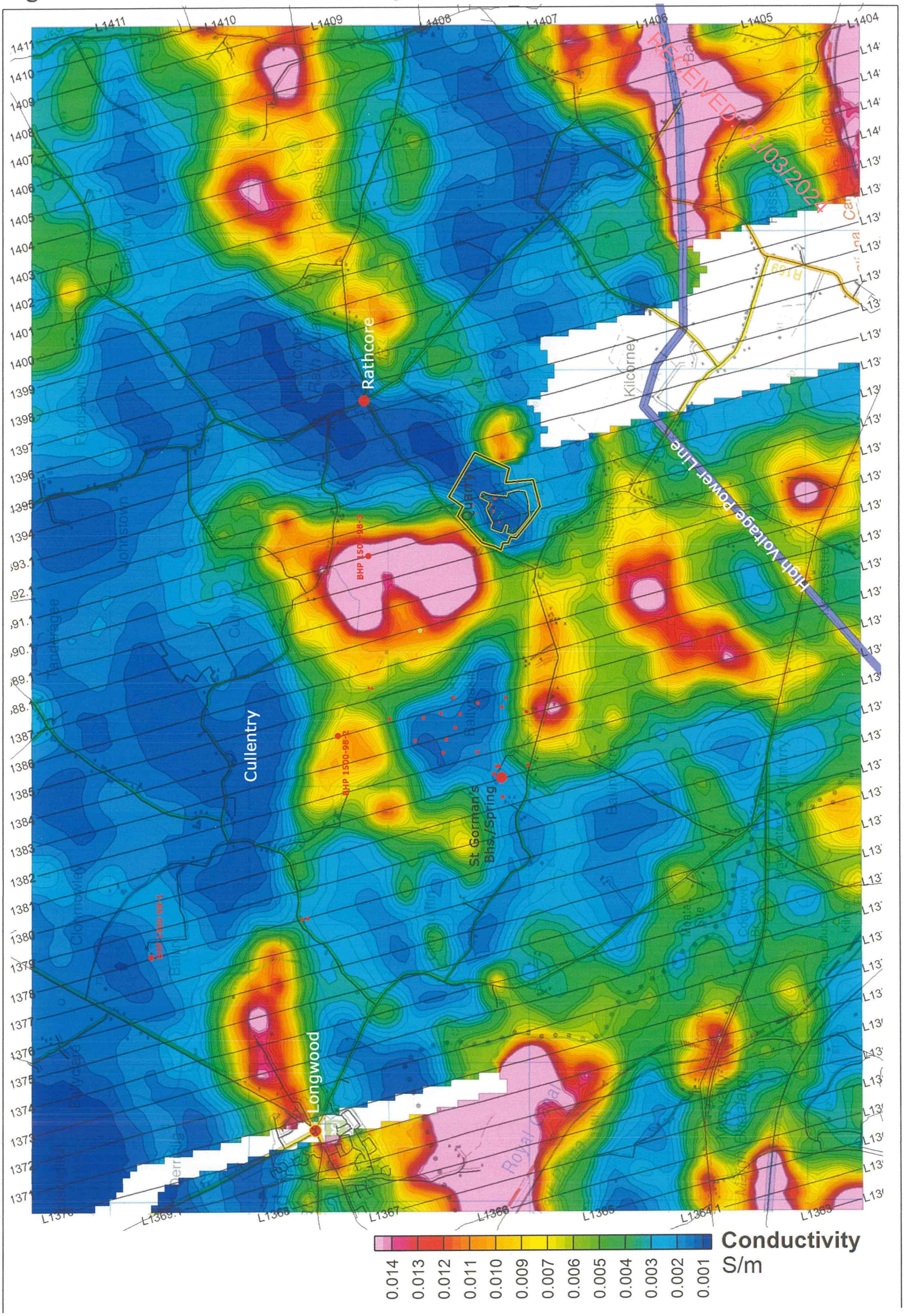
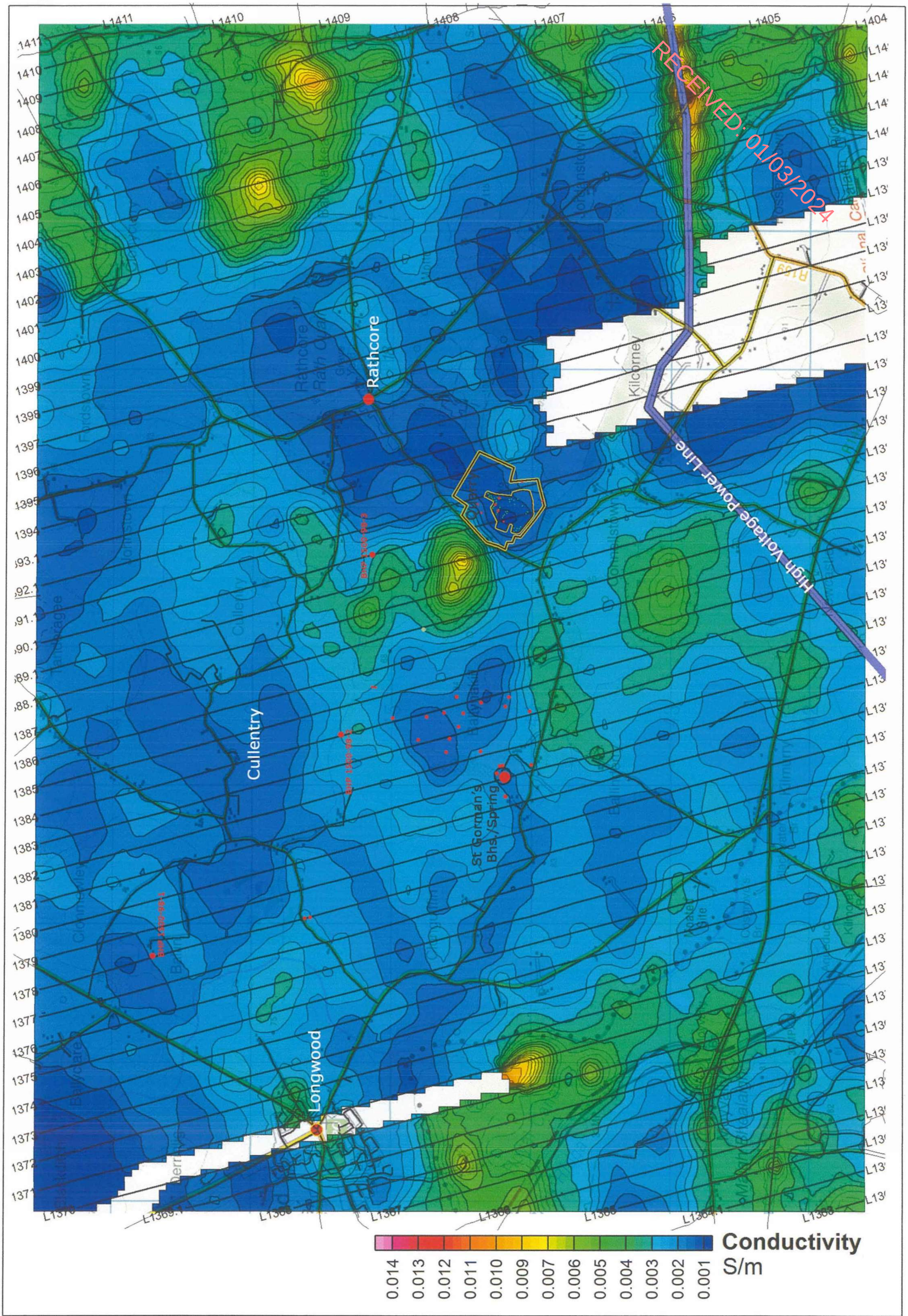


Figure 2.45 Tellus Airborne EM Survey Conductivity at 10.7metres .below ground level



represent Waulsortian limestone. The low conductivity ridge probably represents Lucan south west of St Gorman's and along the road to Longwood, but the ridge running to the north east towards Cullentry may be a gravel deposit in the overburden, that is also shown in the GSI Quaternary sediment web site map. This map also shows extensive gravel deposits above the Cullentry block particularly at the eastern end at the northern end of the large pink and red low conductivity layer.

Figure 2.45 is a depth slice conductivity map for 10.7 metres depth below ground. Therefore, it depicts bedrock close to the surface in areas such as the quarry where there is no overburden on the quarry floor. It also shows areas of unsaturated overburden as low conductivity areas, and the ridge described above is a notable feature. The higher conductivity green and yellow bull's eyes to the northwest of the quarry are the upper part of the karst infill but also saturated clays and cut over peat bog as noted by Du Noyer in 1859. The less defined shape of the low conductivity in the Cullentry block at this depth further suggests that the bedrock is covered with overburden (gravels) and the Waulsortian bedrock is not as close to the surface as it is in the south and central part of the Rathcore block.

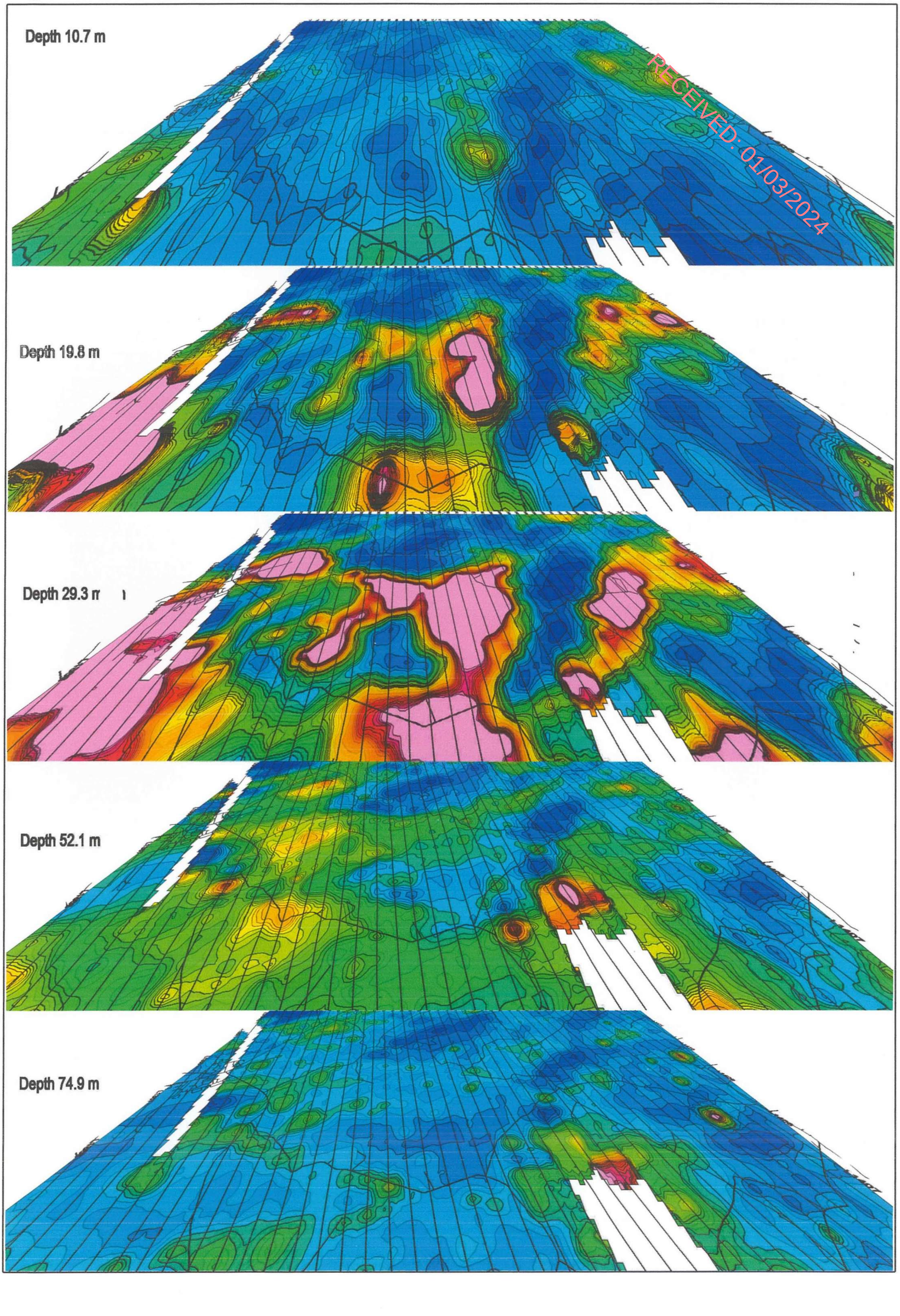
It is difficult to compare and correlate conductivity depth slice maps when viewed individually. Figure 2.46 is an attempt to create a perspective of stacked conductivity depth slices. The perspective allows the eye to observe how a the conductivity of a feature, or area changes with depth. For example the large pink high conductivity are in the centre seen at 29.3 metres, starts as a very small yellow area at 10.7m, then expands to a 'kidney shaped; pink area at 19.8m depth, but becomes a low conductivity area at 52.1m and 74.8m depth. The patterns of high and low conductivity shown in the depth slice maps, particularly the 19, 29 and 52 metre maps, invite a structural geology interpretation.

2.8.5 Interpretation of fault lineaments from the conductivity sections and maps

The sections are better for interpreting structures or faults. Though the downward bending 'tails' on the edges of high conductivity layers abutting low conductivity blocks in the sections (discussed above), make it difficult to determine the dip of a fault structure, it is still possible to approximately define the position of apparent faults on the sections.

I have gone through every conductivity section in turn. I have picked out what appear to be vertical boundaries or discontinuities. I have then plotted the position of these apparent structural changes from each section onto a map. I have not referred to adjacent sections, or

Figure 2.46 Tellus Airborne EM Survey Conductivity Depth Maps-Stacked Perspective



the maps, whilst doing this. The aim was to find out if a pattern of points on a map, would revealed a structural pattern. If there appeared to be an alignment of points on the map from adjacent or nearby sections, then I have joined them with a line.

Figure 2.47 is the map showing the lines joining up what appear to be faults from each section. The map also shows the conductivity depth slice for a depth of 29.3 metres and, for comparison, the line work from the GSI's Bedrock map. The GSI's bedrock map faults are in thick red lines. The GSI's boundaries between formations are in thin red lines.

Figure 2.47 shows that there appear to be many more faults in the bedrock, than previously known. Many of them in different parts of the map follow a similar alignment. There is a strong northeast to southwest Cenozoic alignment. There is some evidence of a corresponding northwest to southeast alignment, but this is less obvious because the northwest to southeast alignment is similar to the north northwest to south southeast alignment of the flight line sections.

There is a strong west northwest to east southeast alignment, similar to the alignment Carboniferous and Variscan fault alignments shown on maps from other surveys.

To help understand the significance of the orientation of the different potential fault lineaments in Figure 2.47, I have reproduced a diagram that John Paul Moore compiled to summarise the findings from his PhD research.

John Paul's block diagram, in Figure 2.48, shows the alignments and relationship of faults and joints in the bedrock of Ireland since the Devonian period. The diagram marks due north, and it can be seen that the major Carboniferous faults are aligned roughly east west. The east west or east southeast to west north west white lines on Figure 2.47 probably represent these Carboniferous age faults. The compression of Ireland currently is from north and south. Therefore, these faults if they were open are now squeezed closed. The same broadly applies to other east-west aligned faults such as the Variscan or late Carboniferous age reverse faults or strike slip faults.

John Paul's research found that the much more recent Cenozoic strike slip faults caused by the north-south compression, are much more open than the Carboniferous and Variscan faults. The Cenozoic faults are the main alignments for the flow of groundwater in the bedrock, and the widening of fault zones by karst solution weathering. John Paul also found that karst solution weathering is enhanced at the intersection of the Cenozoic faults and the Carboniferous age faults. He and Sarah Blake suggest that this is the reason for the occurrence of St Gorman's Well.