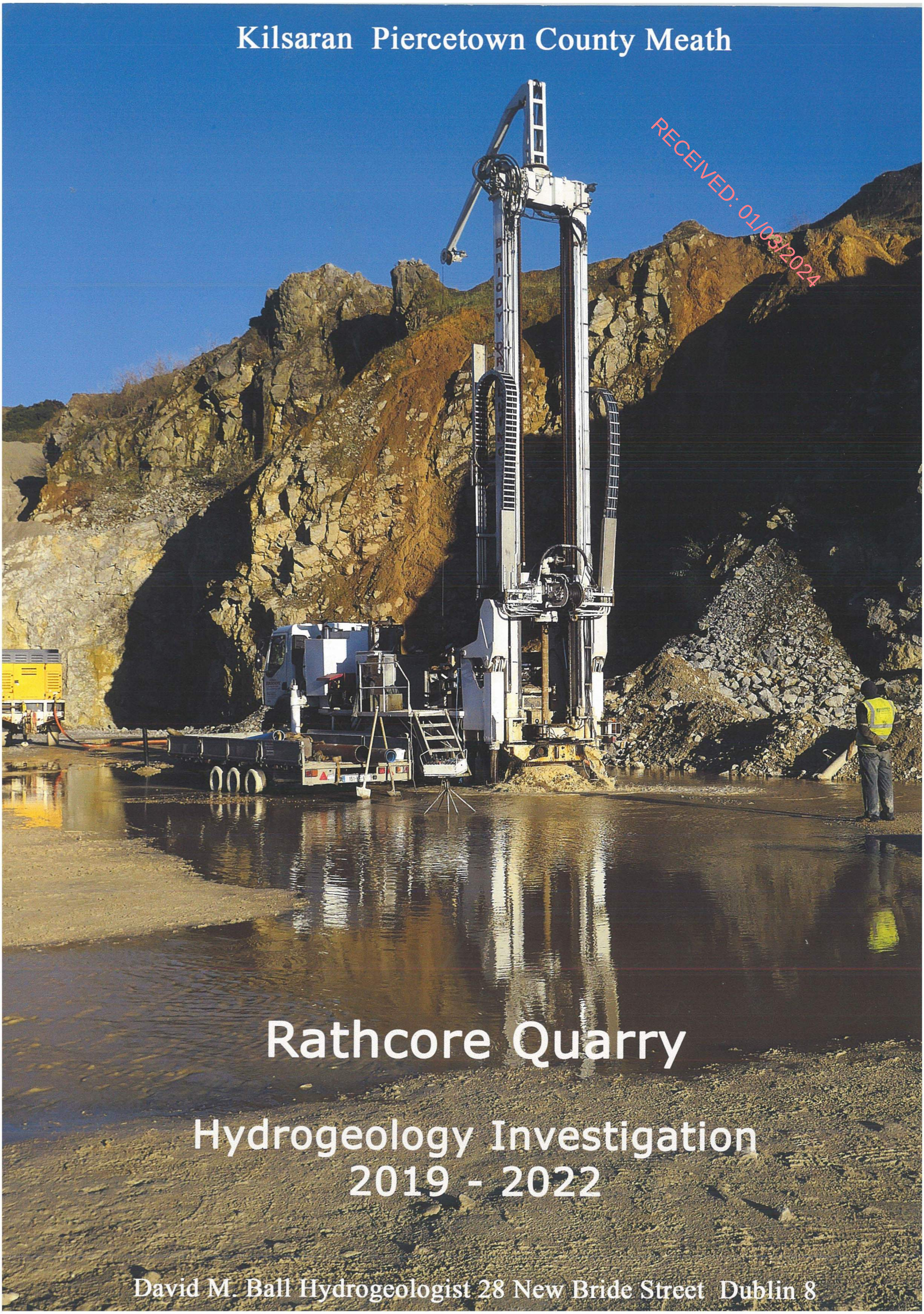
Kilsaran Piercetown County Meath



Rathcore Quarry

Hydrogeology Investigation 2019 - 2022

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Chapter 1 Introduction

The report, and the fieldwork upon which it is based, arose because Kilsaran Concrete submitted a planning application to deepen their existing quarry at Rathcore in 2016, and permission was refused by An Bord Pleanála.

It was refused primarily because the inspector and the Board did not think that Kilsaran had paid sufficient attention to assessing the hydrogeology of the quarry with regard to St Gorman's Well, a warm spring on private land, about two kilometres to the west. The owners of the spring had been appellants in the planning process.

I read the documents and said that I understood the third party appeals, and broadly agreed with the inspector's recommendation to the Board. I was aware that several investigations had been carried out over many years at St Gorman's Well, and that the conditions contributing to the spring's intermittent flow and variable temperature were complex. I was also aware that a direct investigation of the quarry, by exploration drilling and testing, had not been carried out in detail, or for some time.

I was asked by Kilsaran to carry out an investigation of the hydrogeology of the quarry and objectively gather the necessary information to establish whether there was, or could be a link between the quarry and the spring. I agreed to do this, with the qualification that to test whether there is a link, it would be advisable to seek permission to monitor the spring. I also advised that the findings of the investigation, as they arose, could be shared with the owner of the spring and local residents. Kilsaran were in complete agreement about transparency and objectivity, and the owners of the spring gave me unrestricted access. I was also fortunate that Sarah Blake (now, Senior Hydrogeologist in the Geological Survey) gave me the large amount of raw data that she had gathered whilst monitoring a key borehole adjacent to the spring for her doctoral research on the spring.

It was known at the outset that the investigation would take time because it would be necessary to site and construct high yielding boreholes, and then measure the effect of pumping these boreholes on water levels under the quarry, and the area around, throughout several seasons. There were many phases in the work, where the findings in one adjusted the scope of the next. The first was an assessment of the exposures of rock within the existing quarry, followed by a detailed assessment of the structural geology of the quarry to identify the nature of faults and fracture patterns. This assessment was then used as a guide for an exploration drilling programme designed specifically to find out whether karst weathering had created open conduits within the, otherwise, massive Waulsortian pure limestone. Exploration boreholes were drilled at 52 sites in the quarry. Some were shallow because of unstable ground, whilst others reached depths of 36 metres. Conduits were found containing clay and water at different depths in the rock, in some areas, and not in others. Three high yielding boreholes were drilled on targets identified in the previous phases. There then followed a six month process of well development and proving tests to clean clay out of the karst conduits, so that the pumped water could be put into a settlement pond followed by a hydrocarbon interceptor and then a reed bed, before being released from the site.

A routine manual water level monitoring programme had been carried out by Kilsaran since 2006, to measure water levels in the dug wells and boreholes used by neighbouring homes and farms. This programme continued throughout the drilling and well development phase, and it was augmented by the installation of several water level pressure transducers in boreholes in the quarry, close to the quarry and a key borehole adjacent to St Gorman's Well. The manual monitoring and the instrument data were used to establish baseline conditions before a pumping test phase began, and during the tests. The manual and digital water level monitoring is on-going.

The objective of the pumping tests was to pump as much water as possible in order to stress the groundwater system in the karst conduits, and observe whether there was any response two kilometres away at St Gorman's well. At the same time, it was important to monitor water supplies adjacent to the quarry to ensure that there were no adverse impacts from this pumping. A second objective was to obtain information on the heterogeneity of the groundwater system below the quarry and the quantity of water that would need to be pumped to lower water levels sufficient to enable a deeper quarry excavation.

The duration of the pumping test was not known at the outset; it would depend upon the findings and their interpretation as they arose. It also would be affected by rainfall and the response of the multi-component groundwater system. The pumping test was sustained with some difficulty for over 140 days, from the summer through the autumn until December. A second long pumping test was carried for over 40 days in the following February and March, when groundwater levels were at their highest, and the spring was flowing. In short; the tests and monitoring of water levels found that initially, in summer, pumping from quarry boreholes can lower the water levels in the borehole adjacent to the spring 2km away. It did not affect the spring because it was dry. However, as the pumping continued, the rains in autumn and winter, recharged the groundwater systems, and the water levels rose in the borehole next to the spring, the spring overflowed, and the borehole also flowed under artesian pressure.

The monitoring of the long pumping tests generated a large amount of digital and manual data. The next phase was to process these data, and find, process and integrate the data from investigations over the previous forty years. The measurement of water levels and water temperatures in the monitoring holes and the spring borehole, continued whilst the processing of the existing and new data took place. It became increasingly apparent that the hydrogeology of the area was complex, and that there were several hydrogeological components affecting the water levels, the infrequency of flow from the spring and water temperatures, and also the apparent seasonal nature of the hydraulic link between pumping from the quarry boreholes and the spring. It became evident that the geology, in particular the structural geology, of the area controlled the development of karst, and hence the movement of groundwater, but the geology was obscured and not well understood.

In the search for the necessary information, geophysicists in the Geological Survey agreed to use recently developed techniques for processing the Tellus airborne electromagnetic data, for a detailed groundwater investigation of buried karst limestones. There was an iterative process over several months where I used our new and existing data to ground truth the sections and depth slice maps generated by their new process. The results were revelatory, and provided a new context for the hydrogeology of the quarry, the spring, and the area between. It is understood that the Tellus data has not been processed and used in this way for this purpose.

An overarching question during the investigation has been the search for a reason for an apparent decline in the frequency with which St Gorman's Well fills with water, and the quantity and temperature of the water that flows from it. There is evidence from the 1980s, site visits in this century, and the recollections and specific observations of the owner of the spring that the spring used to be a small pool that overflowed for many months of the year starting in the autumn and lasting through to the following spring or early summer. There is a delicate balance of the several components comprising the driving forces behind the flow from the spring, and the activity of the spring varies from year to year, but the general impression was that the water levels and pressures had declined over recent years. In support of this, the long term manual monitoring of groundwater levels in wells and boreholes adjacent to the quarry appeared to show a decline in water levels over the past 15 years. The first obvious potential reason could be the operation of the quarry and pumping water from the quarry. However, the answer is not obvious or straightforward, because the quarry only started pumping in October 2013. A significant part of the investigation has been to assemble and interpret all the previous and new time-series information on the spring site, in particular the borehole close to the spring, and assess the fluctuation of water levels in response to rainfall and other factors. This borehole, though not the spring, has the curious characteristic that the water levels respond to the gravitational distortion of the earth by the moon. The water levels appear to be tidal, but instead of a high tide when the moon is overhead, there is a low tide in the borehole. This complicates the analysis of water levels and water temperature in the borehole in relation to rainfall recharge. Chapter 5 of this report interprets all the previous and new data in detail and then carries out an assessment of the changes in rainfall in recent years, and the observations and predictions of climate science on the changes in rainfall amounts, and distribution throughout the year. 2022 was the warmest year on record in Ireland, and the 12th year in succession of above average temperatures on the island. Increasing air temperatures, and extreme weather events around the world, are well recognised as evidence of climate change, but behind the headlines, and during the course of this investigation, there is evidence that the current climate change model's predicted reduction in rainfall in the east of Ireland, has already started. The analysis of this, and a discussion of increased abstractions in the area, including the quarry, are in Chapter 5. The final chapter of the report steps away from the detailed analysis in previous chapters, to pose and answer the questions of probable concern to Kilsaran and local residents. It should be said that the following report has not been prepared as an environmental impact statement or assessment, but the findings within it could form part of such planning documents. Finally, this report is an investigation for Kilsaran, but it is anticipated that it will be shared with local residents and the Geological Survey of Ireland

It is anticipated also, that the findings from the investigation will be useful to the Geological Survey and other organisations, because it provides an up-to-date basis for these organisations to review their characterization and classification of the geology and hydrogeology of this area, and their understanding of the characteristics St Gorman's Well.

This report is a heavy document. I have tried to make it lighter to read, though not easier to carry, by placing the individual illustrations close to their description in the text.

Chapter 2 Geology

2.1 Background

The following chapter is a story about what lies below a small area of a gently undulating landscape, north west of Enfield in County Meath. The story describes the findings revealed during an investigative process over the past 160 years. In this time, more than 30 geoscientists have mapped and explored the subsurface of this area, in different ways and for different reasons. Yet to the casual eye, there is little in the landscape to indicate any reason for such prolonged effort.

The main reason for the effort is that the land is underlain by a complex assemblage of limestones, that are hidden from view, and an unusual spring. The spring is an enigma, because it does not always flow. It has not flowed in the past eighteen months.

A spring that does not flow would not seem to be interesting. This one is, because when it flows, it can produce water that is warmer than normal 'spring water'. The spring is called St Gorman's Well.

The limestones in the area are interesting for their intrinsic resource value. The pale grey Waulsortian limestones are consistent in their composition and easily excavated and crushed. The limestone generally does not contain impurities, such as pyrite, that could limit its use. The limestone can be used for a range of building and agricultural products. The Waulsortian limestone is also interesting because it can be the host rock for lead/zinc mineralisation. The area around Rathcore, Longwood and Summerhill has been explored for minerals.

Rathcore quarry is an existing quarry to excavate the Waulsortian limestone. The quarry has nearly reached the vertical and lateral limit of its planning permission. The current investigation has carried out a site exploration drilling programme that has proved that the valuable limestone extends to at least 36 metres below the present quarry floor. The lateral extent of the limestone, on three sides, appears to be limited. Therefore, Kilsaran wish to deepen the quarry. This will entail the quarry being excavated further below the 'water table' level in the bedrock.

Normally, a report on the feasibility of extending a quarry below the water table, and the potential impacts of such an extension, would focus on the quarry, and the area immediately adjacent to the quarry. Such a report would focus on the potential impact on the adjacent water resources used by others, and the ecosystems dependent on these water resources. A limited area of study often would be appropriate where the rocks, soils and water resources are well understood.

The starting point for most studies and reports on the geology and hydrogeology of a quarry are the various maps published by the Geological Survey of Ireland (GSI). The maps are available on-line. The maps would include a map of the bedrock at 1:100,000 scale. This base map is the foundation under-pinning other derivative maps. For example, the map of the bedrock has been used as a basis for classifying the bedrock into different aquifer types. This bedrock aquifer map then becomes one component of other maps. For example, showing the calculated average amount of rainfall recharge that a bedrock aquifer will receive. The data on such a map, in turn, can be used to estimate the renewable groundwater resources in an area underlain by the particular bedrock and aquifer type. The bedrock/aquifer type in conjunction with the overburden type and thickness, is used to create maps showing the vulnerability of groundwater in the bedrock to contamination.

This multi-layered hierarchy of base maps and derivative maps would normally form a foundation for a report on the hydrogeology of a quarry. These maps are often accepted, as the basis and framework for investigations and reports produced to accompany planning application. As a result, if the maps appear to fit with other site specific data, then the description for planning purposes, of the geology of the site and area around, is often just a few pages accompanied by a few maps copied from the GSI's web pages.

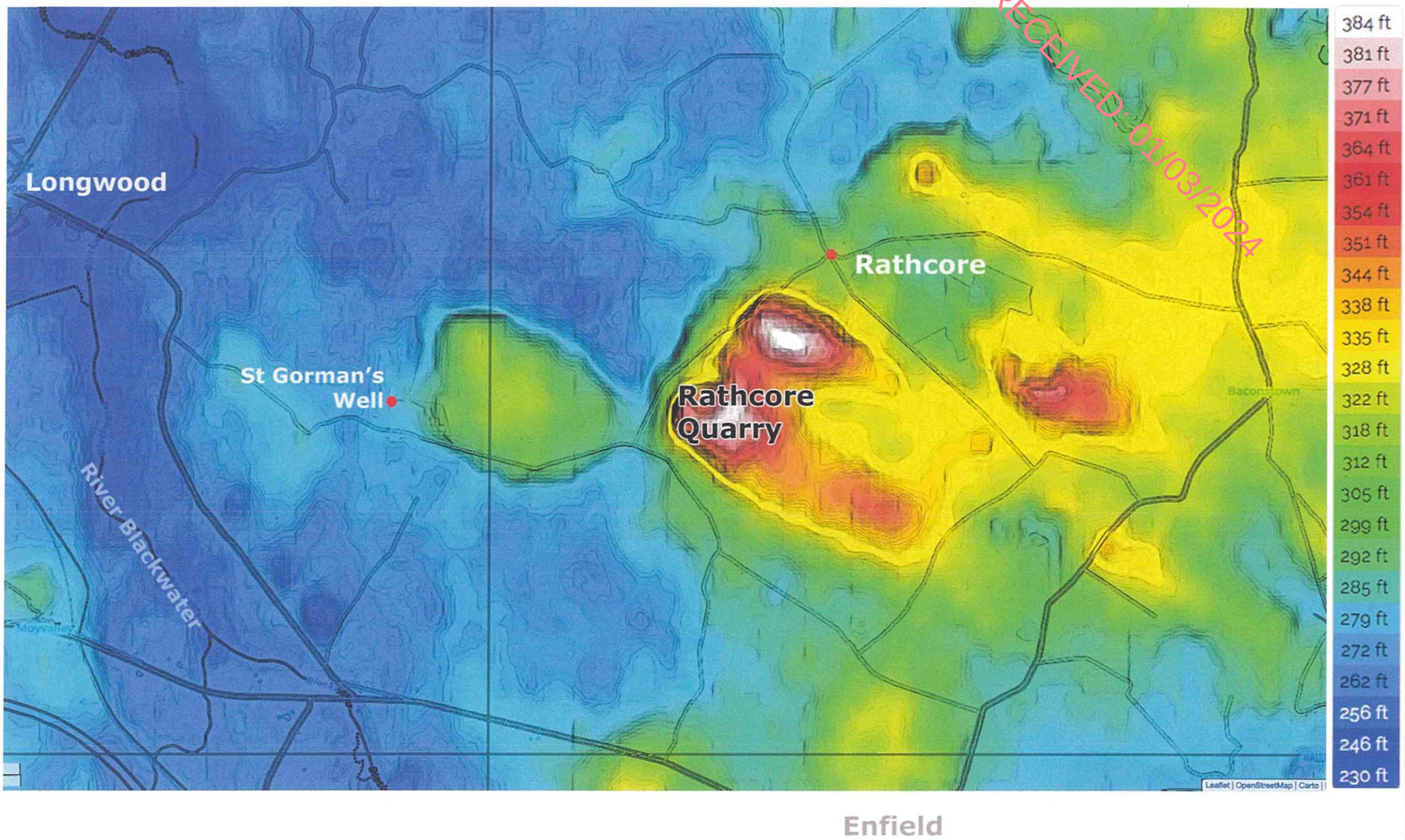
But, if the published bedrock map and derivative maps, do not appear to fit with new site specific information, or information on nearby areas made available since the GSI's bedrock map was published, then it is essential to step back, and look at all the old and new geological information afresh.

This could mean that the published bedrock map needs to be re-evaluated, and if necessary, amended. An amendment of the bedrock map would have a knock-on effect on the other maps derived, in part, from the original bedrock map.

A soft, homogeneous bedrock containing open, connected pore spaces allows the movement of underground water in a predictable manner. Such a bedrock is the type of rock that is often used in text books when describing the principles of groundwater flow. Because the solid fabric of such a rock can both store and allow the flow of water it would be called an aquifer. If it was not sealed-in by an impermeable layer of clay above it, then the water level within this aquifer would be called a 'water table'. If, on the other hand, the rock is sealed-in, and is fully

Figure 2.1. Rathcore Quarry Location Digital Terraine Model and Landscape

Digital Terraine



Google Earth View

saturated with water, then it would be described as a confined aquifer, and the water within it, would be described as pressurised. There would be no water table. Instead there would be a pressure level, or piezometric level, which is the level to which water would rise in a borehole if the borehole penetrated through the overlying confining or sealing layer.

The study area is not underlain by a text book bedrock aquifer, where the rock itself is porous and permeable. The unaltered solid limestone rock in the area, has no open pores, because they have been squashed by compression during the last 330 million years. Water cannot flow through the solid fabric of the rock. Instead, water can only flow through the breaks in the rock. In other words, the gaps between the solid pieces of rock.

Therefore, a hydrogeology investigation of the area needs to focus on the breaks or gaps in the rock; the fractures, faults, joints and bedding planes in the rock.

The area is underlain by different types of limestone. The limestones have been weathered by a dissolving process called solution weathering. Water that is slightly acid can slowly dissolve calcium carbonate in the limestone. The solution weathering is commonly called karst weathering. The term 'karst' is often used as a short-hand for solution weathering. Solution weathering can widen small cracks in the limestone. When these are interlinked, they can become an underground drainage system of small and large flow routes, or conduits, for groundwater.

The normal focus of a report on the hydrogeology of a quarry is covered in this report, but this report, and the investigation behind it, also wished to focus on understanding the groundwater system that periodically causes the warm spring to flow. This meant trying to understand the hidden geology, and also the nature and extent of breaks or conduits in the rock created by the karst weathering process relating to the spring. Though the spring and the quarry are nearly 2 kilometres apart, they appear to be underlain by the same rock, the Waulsortian Limestone, which contains conduits created by karst weathering.

The applied science of hydrogeology is based on the understanding of the movement of water through a framework of rock and soil. The general principles governing the movement of water underground are straightforward. But where the water flows and where it is impeded, is controlled by the size, abundance, orientation and openness of the framework of linked breaks within the rock. Therefore, the starting point for an investigation and subsequent assessment of the hydrogeology of an area is the geology of the bedrock and the materials (overburden) above the rock.

The published 1:100,000 scale bedrock geology map, the overburden map, and other derivative maps, do not appear to fit with both new information obtained during this investigation, and the available information from other investigations completed since the maps were published. Therefore, the subject of this chapter is to pull together and re-evaluate all the old and new information on the geology of the area of the quarry and St Gorman's Well. It is an interesting story that starts 160 years ago and ends with new findings that illustrate the complex nature of the rocks, materials and structures hidden below the surface.

2.2 Geology Introduction

The subject site is the limestone quarry in Rathcore Hill owned by Kilsaran. The proposed development is to deepen the existing quarry. The proposed excavation will be below the water table in the limestone bedrock. Groundwater will need to be removed from the excavation to keep it sufficiently dry for work to take place on the quarry floor.

In general terms, the removal of groundwater from an excavation will always create the potential to draw water into the excavation from the surrounding groundwater resource in the bedrock, and the overburden above this bedrock. Therefore, the starting point for an understanding of the potential to influence the groundwater resource outside the site of a quarry is the understanding of the bedrock and overburden geology of the site and the area around.

The landscape and topography in the area of Rathcore is an important factor limiting the understanding of the bedrock and overburden geology.

Rathcore Hill is the most pronounced topographic feature in an otherwise gently undulating rural landscape. **Figure** 2.1 shows a digital terrain model and a recent airphoto image of the quarry and the lands around.

The terrain model has a colour coded elevation scale. The legend for the scale is shown next to the map. The scale is in feet. Rathcore quarry is an excavation in the centre of Rathcore Hill. The terrain model shows a high area extending to the north east and east of the quarry. Due west of the quarry there is a low hill in the townland of Ballinakill, and on its western edge is the site of St Gorman's Well. To the northwest and southwest of Rathcore Hill there are two broad valleys gently sloping to the west and the Blackwater River valley. The terrain model shows that the slopes on the north western side of the Rathcore and Ballinakill hills are steep,

Figure 2.2. G.V. Du Noyer 6inch to the mile Field Geology Sheet Meath 48a 1 1859

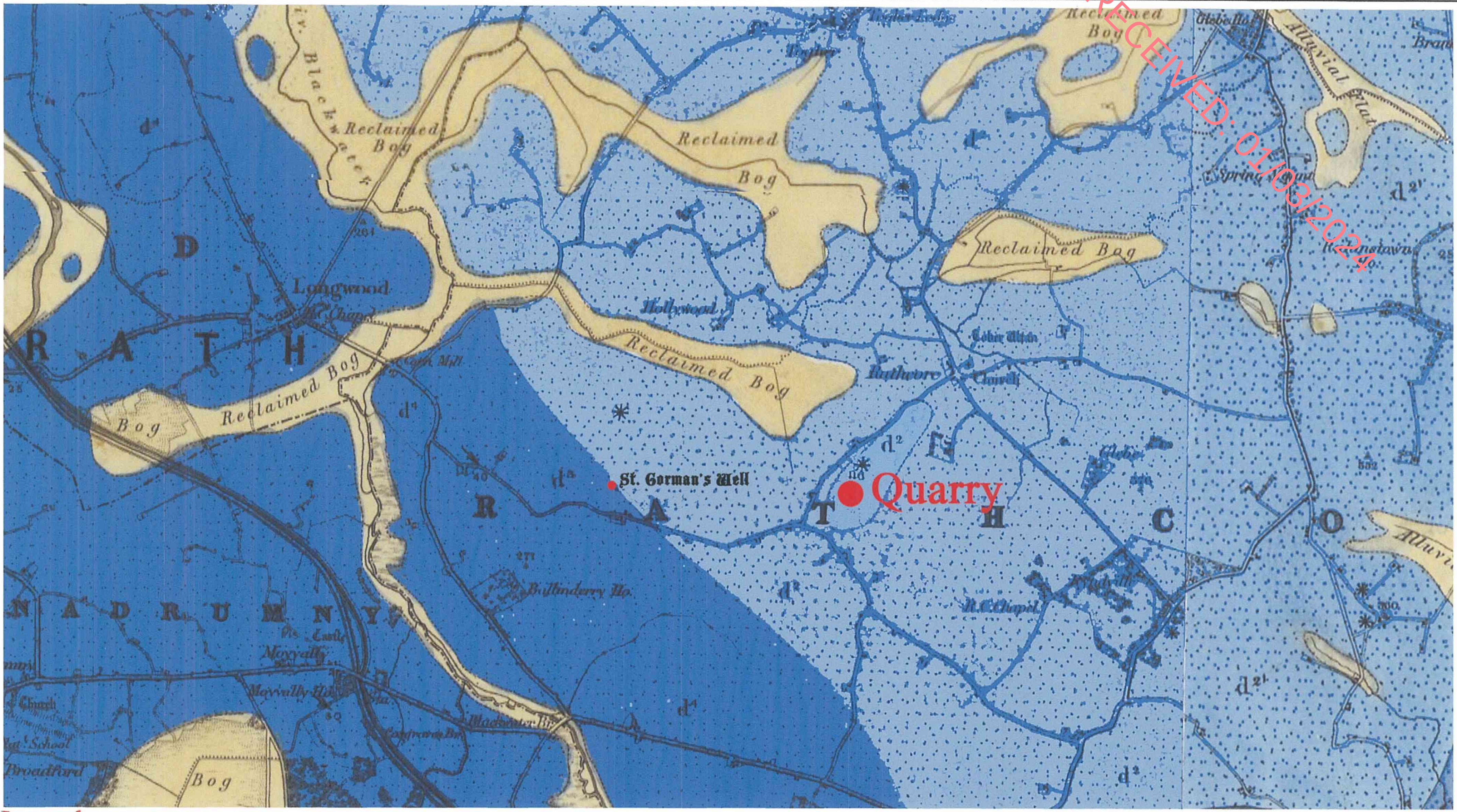
whereas the land slowly becomes lower to the south east. The quaternary section of the GSI has identified that this shape of topography is an example of 'crag and tail' landforms, that indicate the direction of movement of the last ice sheet. The bedrock on the north western end is the 'crag' and consists of a residual boss of competent Waulsortian limestone that was resistant to erosion by the ice moving from the north west towards the south east. The tail to the south east of each highland usually consists of softer less resistant limestones or overburden that was protected from the erosive forces in the ice sheet by the resistant Waulsortian limestone. Therefore the topography shown in the digital terrain model provides a clue to the places where the bedrock is composed of Waulsortian limestone that is sufficiently solid and massive that it can resist the strong erosive force of the ice sheet. The areas shown in dark blue to the north west in the map are supposed to also be the same Waulsortian limestone. It is notable that there is a pronounced, nearly 90 degree angle formed by the axis of the Ballinakill hill and the Rathcore hill, suggesting a structural or lithological boundary.

The airphoto in the lower part of Figure 2.1, shows that the landuse is mostly pasture and tillage. There are small areas of commercial forestry. The low-lying areas of pasture are often on reclaimed bog. The pasture and tillage on the more elevated areas are on better drained soils.

The bedrock geology is mostly obscured by this overburden. There are very few outcrops exposures of solid bedrock. Therefore, it has always been difficult to obtain a clear confident understanding of the nature and structure of the bedrock by direct observation.

An understanding of the bedrock is important for the investigation described in the report. Equally, the structures within the bedrock and the nature of the weathering of the bedrock, are very important for the investigation. The composition and thickness of the various layers of overburden above the bedrock are also important.

Most geology investigations, relating to groundwater and planning, start and end with the GSI 1:100,000 scale bedrock maps. These maps were produced in the late 1980's through to the late 1990's. The present GSI 1:100,000 bedrock map is Sheet 13 which was produced in 1999, with the memoir describing the geology shown on Sheet 13 being produced in 2001. All the GSI's bedrock maps were compiled on the basis of the information available at the time the map was being drawn. The maps are based on the previous investigations. No map is ever completely accurate, particularly in an area where the bedrock is almost completely obscured from view.



Legend

d^2 Lower Limestone	d^3 Middle Limestone not distinguishable from Upper Limestone	Drift chiefly limestone gravel	Alluvium or peat bog and other superficial covering

Age: Carboniferous

Figure 2.3.Bedrock and Drift Map Geological Survey of Ireland June 1860

Geological maps are open to revision in the light of new findings. There have been several investigations in the Rathcore area since 1999. The following sections of this report describe how the understanding of the nature of the bedrock has evolved over time.

2.3 19th Century Geology Investigations and Maps

The first geologist to map the area was George Victor Du Noyer, who was famous as an artist, as well as being a pioneering geologist. He was the first District Surveyor of the Geological Survey of Ireland and died at a young age of scarlet fever in 1869.

Figure 2.2. is a reproduction of Meath Sheet 48a-1. It is the 6inch to the mile scale field sheet upon which Du Noyer wrote and coloured his field observations. He used solid colour and handwritten notes to describe the rock where he found solid rock at the surface. Du Noyer found just three outcrops. One was in a small quarry on the Ballinakill hill northeast of St Gorman's Well and west of Rathcore Hill. The other two exposures were on Rathcore Hill and the ridge running to the north northeast. He described the rock in all three places as 'Light grey, fairly crystalline Lower Limestone'. This description equates to the modern lithology called the Waulsortian Limestone.

Du Noyer defined the area of 'reclaimed bog' in the valley to the northwest of Rathcore Hill. He also wrote a detailed note describing his visit to St Gorman's Well in July 1859. (The interesting content of this note will be discussed in Chapter 5).

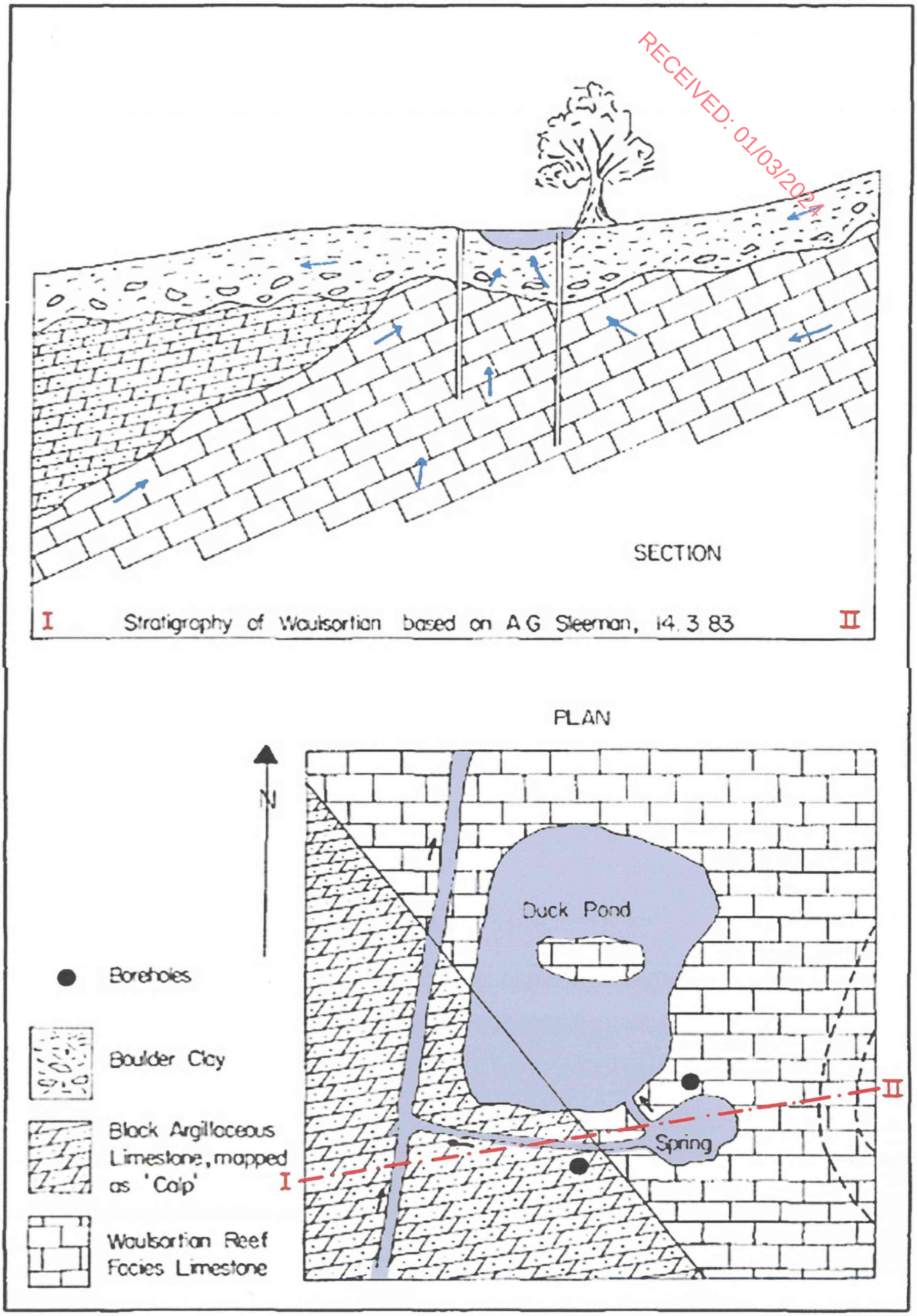
Shortly after Du Noyer's visit to St Gorman's well the Geological Survey published a 1inch to the mile Geology and Drift map of the area in June 1860. ('Drift is a common term used in Britain, and it is equivalent to the term 'Overburden' commonly used in Ireland today.)

The 1inch to the mile map is shown in **Figure** 2.3. It covers a larger area than **Figure** 2.2. I have marked the Rathcore Quarry and St Gorman's Well on both maps for ease of reference.

The 1860 map shows two limestone units; the Lower Limestone (pale grey and crystalline) and the Middle Limestone (dark grey and bedded). There are no bedrock faults shown on the map. The boundary between the two limestones runs northwest to southeast through St Gorman's Well.

It is probable that the boundary was drawn through the Well by Du Noyer, because the Well is a spring, and springs were known to rise at major changes in rock type. The supposition is, and

Figure 2.4 Geology Section and Plan of St Gorman's Well Spring
(from Aldwell C.R. & Burdon D. J. QJEG 1986 "Energy Potential of Irish Groundwaters"



was, that groundwater freely moving through one rock type would rise to the surface when its flow path encountered a another rock type that might impede its flow.

Du Noyer did not find an outcrop in the area shown in **Figure** 2.3 where the pale grey limestones and the dark grey limestones are in contact. Therefore, the boundary between the two limestones is a gentle curved line, that suggests a change of rock type occurs somewhere in the area.

Most of the area in the map is also stippled, indicating that the 'drift', or overburden, is chiefly a limestone gravel. The limestone on the top of Rathcore Hill ridge is shown as not being covered in limestone gravel.

2.4 20th Century Geology Investigations and Maps

2.4.1 The 1980s

The 1860 map in **Figure** 2.3 remained the published base map for geologists for the next 120 years. The map showed that the sites of both Rathcore Hill (the site of the future quarry) and the St Gorman's Well spring appeared to be in the same limestone formation, and hence, there would appear to be a geological link between them.

There was a considerable increase in geology exploration in Ireland during the 1960's 70's and 80's. Part of this was driven by the mineral exploration boom in the 1970s that discovered several new important lead-zinc mines. In addition, the Geological Survey expanded in the 1970s with a new Groundwater Section.

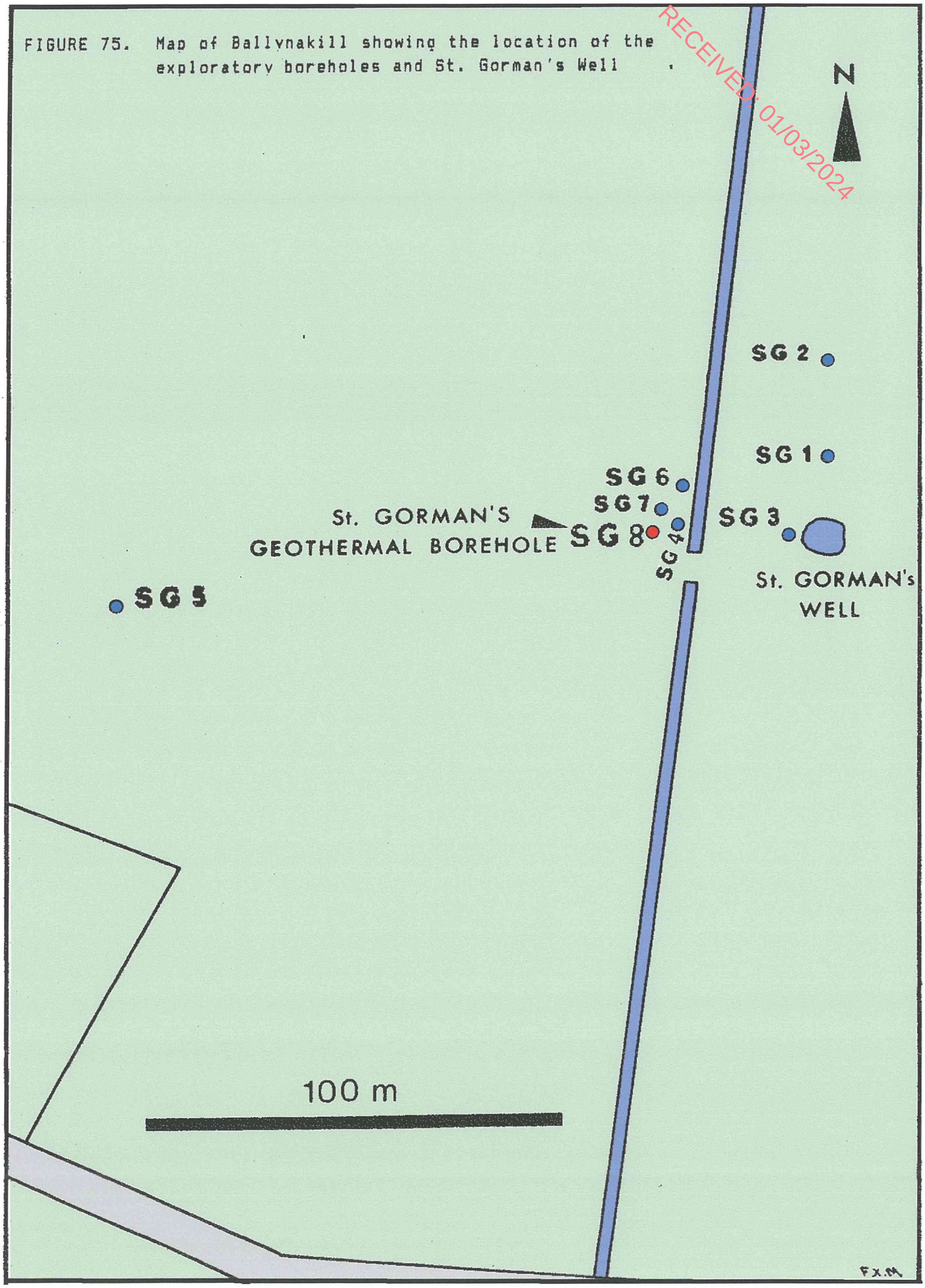
This new Section in the Survey took an interest in geothermal energy and an exploration of sites of warm springs.

An EEC funded research project into "Irish Groundwater Resources in Relation to Geothermal Energy Investigations" was carried out by David Burdon in Minerex in the early 1980s and the report submitted to the GSI in 1983. This study first monitored the St Gorman's Well and drilled two shallow adjacent boreholes .

The understood geology of the area from the 1860 map was still prevalent in 1980s as shown in **Figure** 2.4.

This **Figure** shows a section and a plan of St Gorman's Well published in 1986. The **Figure** refers to the two shallow boreholes drilled by the Minerex/GSI in 1983. One borehole was 12 metres deep next to the spring and the other was 13 metres deep. The section shows Calp limestone unconformably lying against Waulsortian Limestone. It is noted that the sketch map

Figure 2.5 St Gorman's Well: Hydro Research and F.X.Murphy's Borehole in 1980s



and section do not agree in one important detail. The map shows the western borehole drilled in Calp limestone. The section shows this borehole in Waulsortian limestone. These boreholes appear to have been lost.

The arrows on the section indicate that the spring arises because shallow groundwater flowing laterally through the Waulsortian meets the less permeable Calp and rises into the overburden to be joined by deeper warm groundwater flowing up through the Waulsortian below the contact with the overlying Calp limestone.

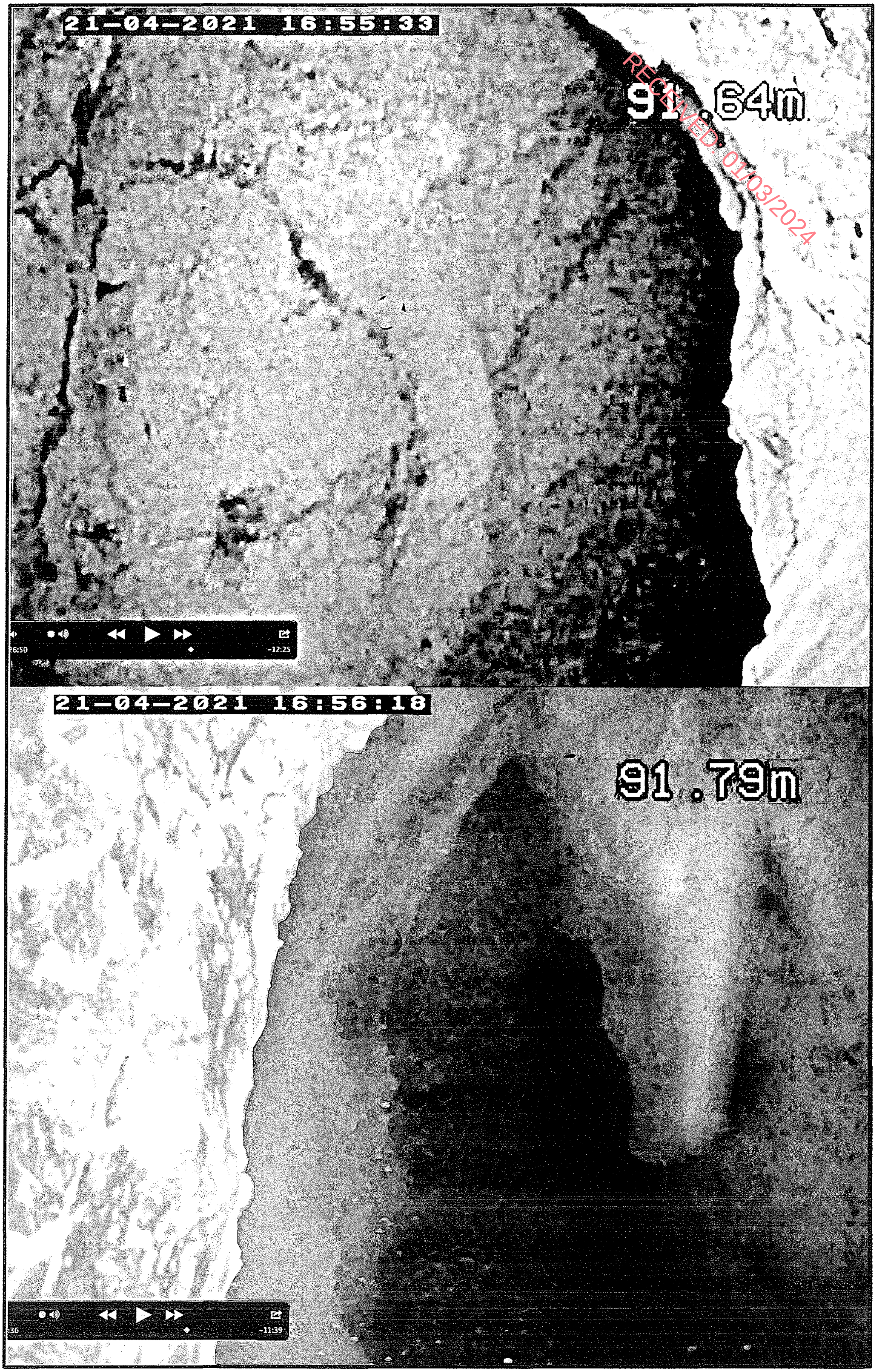
There is no suggestion in this **Figure** that a fault was considered to separated the Calp and the Waulsortian Limestone, or that the warm spring flow might be related to a fault.

Geothermal investigations and drilling continued in the mid to late 1980s. F.X. Murphy undertook research including deep drilling at St Gorman's Well and published his PhD findings with P.M. Bruck in a report in September 1989. The report was entitled, "An Investigation of Irish Low Enthalpy Geothermal Resources with the aid of Exploratory Boreholes".

In Frank Murphy's report he refers to `a company called Hydro Research' who drilled seven boreholes close to St Gorman's Well to explore geophysical anomalies identified in 1987-8. Hydro Research were investigating whether water wells drilled close to St Gorman's spring could be used for geothermal energy. The seven Hydro Research boreholes were named SG1 -7. The 12 metre deep borehole just west of the spring shown in Figure 2.4 appears to have been replaced by a borehole 180 metres deep drilled by Hydro Research and labelled SG3.

Frank Murphy describes the results of the Hydro Research work that he used as the basis for his own investigation. The Hydro Research geophysics indicated an E-W aligned anomaly next to the spring, but the anomaly curved round to a NW-SE alignment west of the spring, and curved to a NE-SW alignment east of the spring. He reports that two Hydro Research wide diameter boreholes SG4 and SG7 (25 metres west of the spring) encountered well developed fracturing on the steeply dipping contact between the 'Calp' and the underlying Waulsortian limestone at between 38 and 55 metres depth. Both Hydro Research boreholes then encountered very large caves at 90-95 metres. The caves were 11-13 metres in depth. Both boreholes did not proceed below the bottom of the caves because it would not have been safe for the driller to do so. (The drill cuttings would have gone into the caves, rather than returning to the surface. When the air was turned off to add another drill rod, the cuttings could have fallen back into the hole and trapped the drill rods and drill hammer.)

Figure 2.6 Solution widened clefts in the roof of the large cave in Borehole SG7



The caves yielded artesian flow. A pumping test was carried out at a rate of $76m^3/h$ (a high flow rate, nearly equivalent to 2 million litres a day), and with minimal water level drawdown in the adjacent borehole. This showed that there was an extensive interconnect system of large caves connected to the cave in SG7.

The Geological Survey of Ireland carried out a video camera survey of the Hydro Research borehole SG7 in April 2021. I am grateful that they shared this video.

The GSI borehole video confirms the Hydro Research observation of the fractured contact between the Calp and the Waulsortian at 54.1metres, and the large cave starting at 91 metres. The video camera was not lowered deep into the cave, but the view with the camera pointing down was of a large dark abyss with irregular sides akin to a jumble of boulders.

Figure 2.6 shows two screen grab images taken from the GSI video whilst the camera was looking sideways at the roof of the cave. The images show a vertical, solution widened, cleft in the roof of the cave on both sides of the borehole.

Frank Murphy decided to use his research budget to drill a deep geothermal exploration core hole. He chose a site next to SG4 and SG7 because these holes produced the highest volume of water with the highest temperatures of 22.3 (SG7) and 21°C (SG4) during pumping.

The core hole reached 510.3m depth. The drilling stopped at this depth because the drill rods broke next to a large cavity at 260m depth. It appeared that there was a large cavity at 510m depth.

Frank Murphy's description of the Calp and the Waulsortian encountered in this hole is one of the most detailed for the Ballinakill/ St Gorman's spring area.

The core hole encountered an upper 3m layer of sticky, grey boulder clay above the Calp bedrock.

The Calp consists of thin beds, or layers, of dark grey to black shales interbedded with laminated non-argillaceous and argillaceous dark grey limestones. There were rare small patches of dolomitisation in the limestone beds.

The Waulsortian limestone is quite variable in composition. The dominant facies is bryozoan 'Reef' where vugs or holes and vein like cracks in the original reef have been infilled with large zones of pure calcite. There are zones with abundant crinoid detritus and rare thin wisps of black shale.

Figure 2.7 F.X.Murphy Geological Section East-West through St Gorman's Well

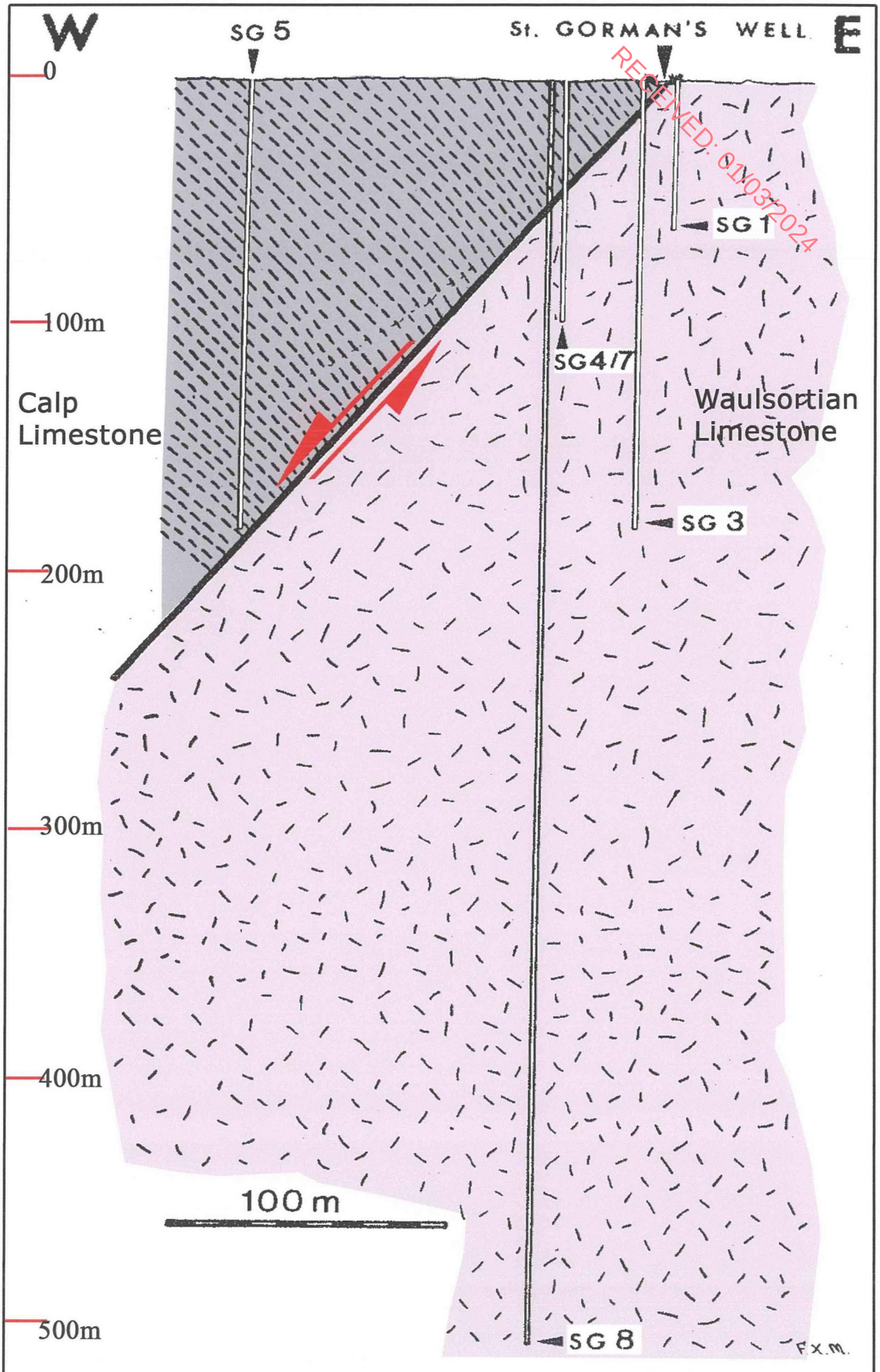


FIGURE 77. E-W geological cross-section through Ballvnakill showing borehole positions.

Frank Murphy deduced that the contact between the Calp and the Waulsortian is a fault where much younger Calp rock has been faulted against the Waulsortian. In other words, the block of Calp has moved downwards some distance against the side of the Waulsortian block. The fault is at a steep angle as shown in Frank Murphy's sketch section Fig. 77, reproduced in an amended form in **Figure** 2.7.

Frank Murphy studied the cores in detail and found that the Waulsortian had a sub horizontal bedding of about 10 degrees whereas the bedding in the Calp was dipping at 65-80 degrees. Importantly, he found that the fracturing along the fault was minimal in the Waulsortian but formed a thick zone of breaks and calcite veining in the Calp above the fault. There was very little recovery of core in the Calp directly above the fault. Frank Murphy also found evidence that the Waulsortian had been faulted between 256 and 264 metres depth coincident with two large cavities in this zone. A zone of numerous small cavities and vugs continues down to 273m.

Other cavities were found in the Waulsortian between 68-74 metres depth. Frank Murphy supervised the drilling of SG8, and he observed that when the drill bit went into this zone of cavities, water level fluctuations and discolouration were noticeable in the artesian flow from boreholes SG4 and SG7. This clearly showed that the cavities at 68-74 metres in SG8 were linked by high angle conduits to the big cavities below 92 metres in SG4 and SG7.

Frank Murphy concluded that the evidence from all the boreholes strongly indicated a major N-S oriented fault, but this did not fit with his geophysical anomaly or the position of a roughly E-W aligned fault shown on the GSI's bedrock map. He suggested that the N-S fault might be a minor fault splaying off the E-W fault.

However, as will be seen later in this chapter there is recent surface and airborne geophysical information that indicates that there are numerous faults in the vicinity. The faulting is complex. There appears to be a large block of low resistivity (probably highly weathered) limestone and shale to the west and north west of St. Gorman's spring. There is also Calp limestone south of St Gorman's spring and a major E-W fault.

A temperature log of SG8 was carried out. The results were surprising. The maximum temperature was found in the upper zone of conduits that are linked to the large caves found in SG4 and SG7. The temperature was 21.7°C. Below the upper conduits in SG8 the temperature dropped rapidly to 20.5°C and then gradually dropped further to 18.5°C at a depth of 250 metres. The surprise is that though there are several zones of conduits, it appears that there is

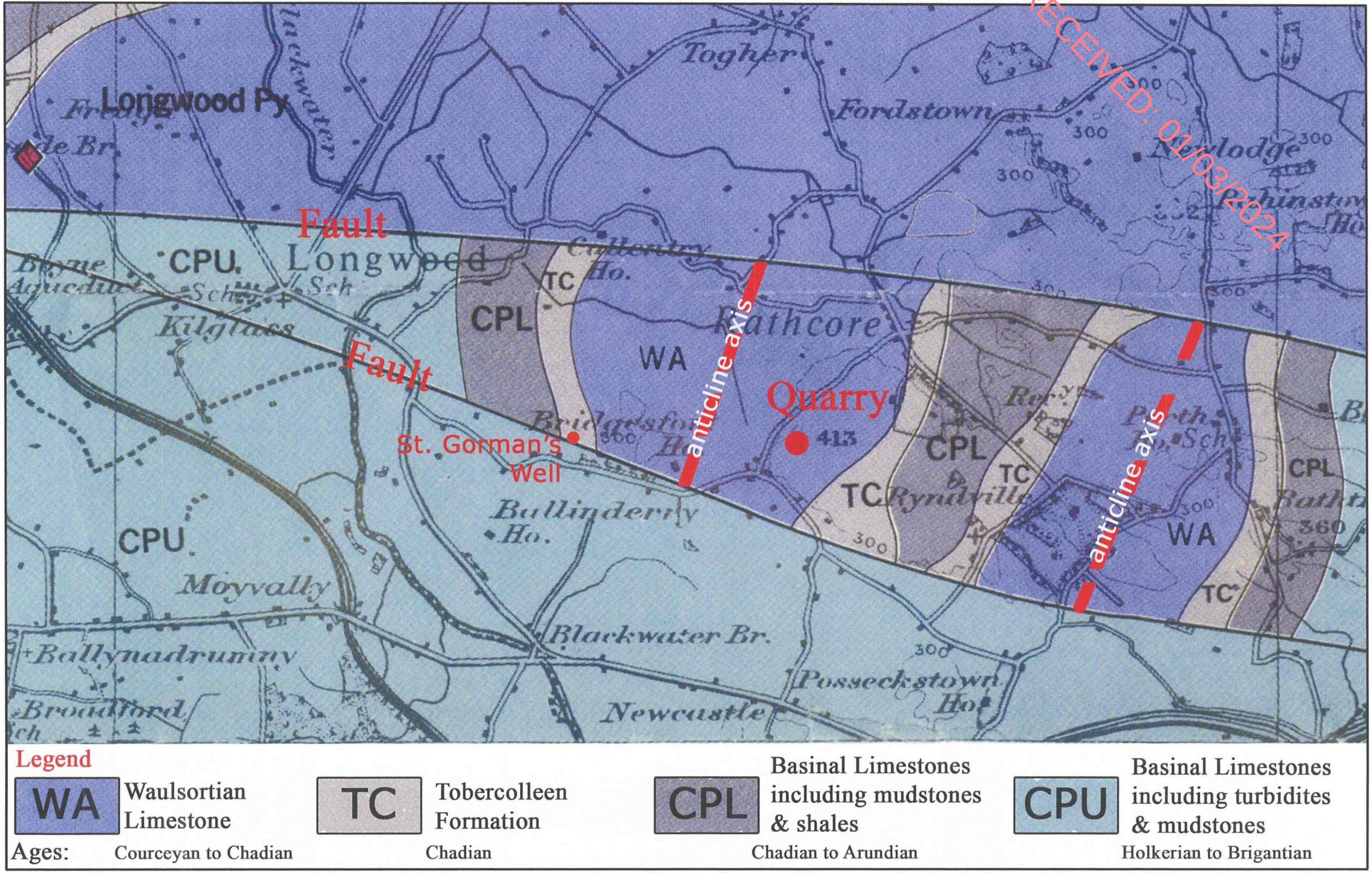


Figure 2.8 Bedrock Map Chevron & GSI 1992

just a single conduit system containing a flow of warm water up from depth. It also seems that the main conduit system is not along the fault contact between the Calp and the Waulsortian but is within the Waulsortian limestone at depth. The conduits in the Waulsortian bring up warm water to the much jointed and disturbed zone in the Calp above the Waulsortian at a shallow depth. The highest temperature in SG8 was in the upper conduits 21.7°C. The temperature in the disturbed zone was only slightly lower at 21.4°C.

The detailed work by Frank Murphy advanced the knowledge obtained by David Burdon in the early 1980s. David Burdon had thought that the warm water at St Gorman's had come up an E-W aligned fault, whereas Frank Murphy found that it appeared to come up a roughly N-S aligned fault. Frank Murphy did not discount a role for the E-W fault but did not find clear evidence that the main flow was up or along an E-W aligned fault.

As the story of investigations into the geology and hydrogeology advanced, it became obvious that bedrock geology structures added complication to what had seemed to be a simple relationship between pale grey and white Waulsortian limestone surrounded by dark grey limestones and black shales.

2.4.2 The 1990s

By the late 1980s it was becoming obvious that the intense mineral exploration work carried out in Ireland by different companies in the 1970s and 80s had produced new information on the geology of the Carboniferous bedrock in the Irish Midlands.

The initiative to pull together proprietary and open-source information to compile a bedrock map came from Rupert Crowe and others. Murray Hitzman on behalf of Chevron Mineral Exploration Corporation of Ireland and Ivernia West plc, compiled a series of 1:100,000 maps entitled "Bedrock Geological Map of the Carboniferous of Central Ireland". These maps were drawn up by the cartography section of GSI, and then published by the GSI.

Figure 2.8 is an amended extract from the Chevron bedrock map published in 1992. The Rathcore Quarry and St Gorman's Well are marked in red for reference. The Chevron map is very different from the 19th century GSI map in **Figure** 2.3.

There are four different formations shown on the Chevron map. The Waulsortian limestone is the oldest. There is a major, roughly east-west aligned, fault in the north centre of the map, and a second northwest – southeast aligned fault crossing the south centre of the map. In the wedge between them the map shows two anticlines where the older Waulsortian is in the centre of each and the younger Tobercolleen and CPL formations are conformably laid on the flanks. The anticlines are oriented north northeast to south southwest.

Rathcore quarry is located in the Waulsortian, but St Gorman's Spring is located on the feather edge of the Tobercolleen on the western flank of the Waulsortian on or just adjacent to the northwest – southeast aligned fault. On the southern side of this fault is shown the younger CPU formation.

There are no north-south aligned faults shown on the map, but it is interesting that the Tobercolleen and the CPL, north and west of St Gorman's Spring, are perhaps a representation of a north-south feature picked up by the geophysical surveys carried out by Hydro Research and Frank Murphy in the 1980s, and may represent the formation on the western side of the north-south aligned fault inferred by Frank Murphy.

It is also interesting that the Chevron interpretation shows a syncline to the east of the quarry containing Tobercolleen and CPL formations. The boundary between the Waulsortian and the Tobercolleen is to the southeast of the Quarry and not within the area of the quarry excavation, as shown in a later GSI bedrock map in 1999 (described below).

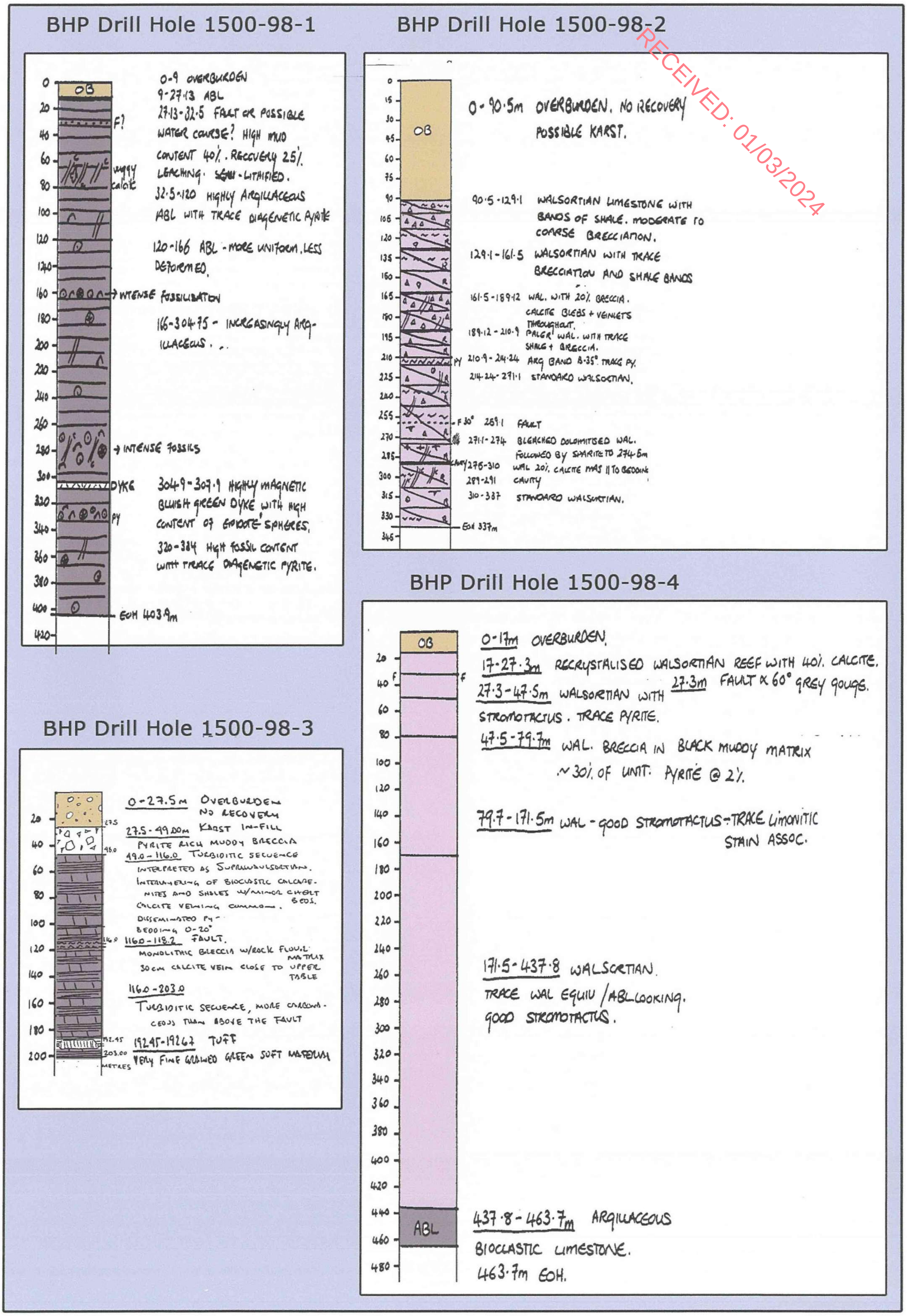
It is perhaps appropriate at this stage in the story to comment on the names of Carboniferous limestone formations that are older, the same age and younger than the Waulsortian Limestone.

The stratigraphy and nomenclature for the lower Carboniferous limestones in Ireland is confusing; even for geologists.

Names for formations have changed and evolved over the past 60 years. Part of the confusion arises because many of the formations appear superficially to be composed of similar lithologies in different proportions; dark grey limestone strata and dark grey or black shale strata. The Waulsortian limestone is distinct because it is generally pale grey and "massive"; (meaning there is little evidence of bedding), unlike the thin beds of shale and limestone in the other formations.

Though the Waulsortian is easy to identify, it is also a cause of some of the confusion because it is not a layer of sediment deposited over a large area at a single moment in geological time. Instead, it is a facies or rock type that arose from the upward growth of calcareous mud mound on the sea floor. It's difficult to describe their growth, but they arose in association with simple organisms (Bryozoa) that grew like a fibrous mat that created a distinct very pure calcium carbonate rich ecosystem. Broken shells, bits of coral and crinoid stems were sometimes caught, or deposited, in these mounds. The Waulsortian limestone usually consists of a great

Figure 2.9 BHP Core Hole Summary Logs (PL Area 1500) 1998



thickness of these mounds that grew one on top of the other and side by side. Meanwhile, at the same time in the same sea, but perhaps at a different depth, where conditions were different, layers of dark grey lime muds and black shales also were being deposited along side the Waulsortian. The Waulsortian mud mounds sometimes grew on top of layers of dark grey limestone and shale. Sometimes, conditions changed and the Waulsortian mud mounds stopped growing and were covered by dark grey limestone and shale. As the dark grey limestones and shales superficially look similar, the only way of determining the age relative to the Waulsortian is by an analysis of the fossils, in particular the microfossils.

From the perspective of the hydrogeology of the quarry and St Gorman's Spring, the names and ages of the dark grey limestones and black shales are less important than the weathering of these rocks and the structural geology on the contact and within the rocks. Therefore, in this report I use the name given by other geologists on maps or in borehole logs. I do not try to reinterpret their maps or logs and try to substitute a new name that is in current usage.

The area of geological interest for this report lies within the Mineral Exploration Licence Area Number PL 1500. When a licence area has been held for a period of time, usually 2 years, the mineral exploration company is expected to produce and file a report on the results of their exploration programme. BHP (Broken Hill Properties) held PL 1500 from the mid 1990s.

BHP carried out airborne and surface Electromagnetic (EM) geophysical surveys in order to identify high conductivity anomalies in the bedrock. Such anomalies might represent zones with a high level of metal mineralisation, in particular pyrite and lead zinc ores which are good conductors.

Four anomalies were core drilled in 1998. The core holes are very deep and the detailed handwritten logs extend for several pages for each core hole.

Figure 2.9 shows the summary logs for each hole. Colour has been added to assist understanding. The location of these core holes is shown in **Figure** 2.10.

The BHP core holes in 1998 are the best record of the bedrock geology after the deep boreholes and core holes at St Gorman's spring.

The findings in the BHP core holes are remarkable. Though all four boreholes were expected to encounter the Waulsortian limestone, two of the holes encountered just dark grey limestones and shales.

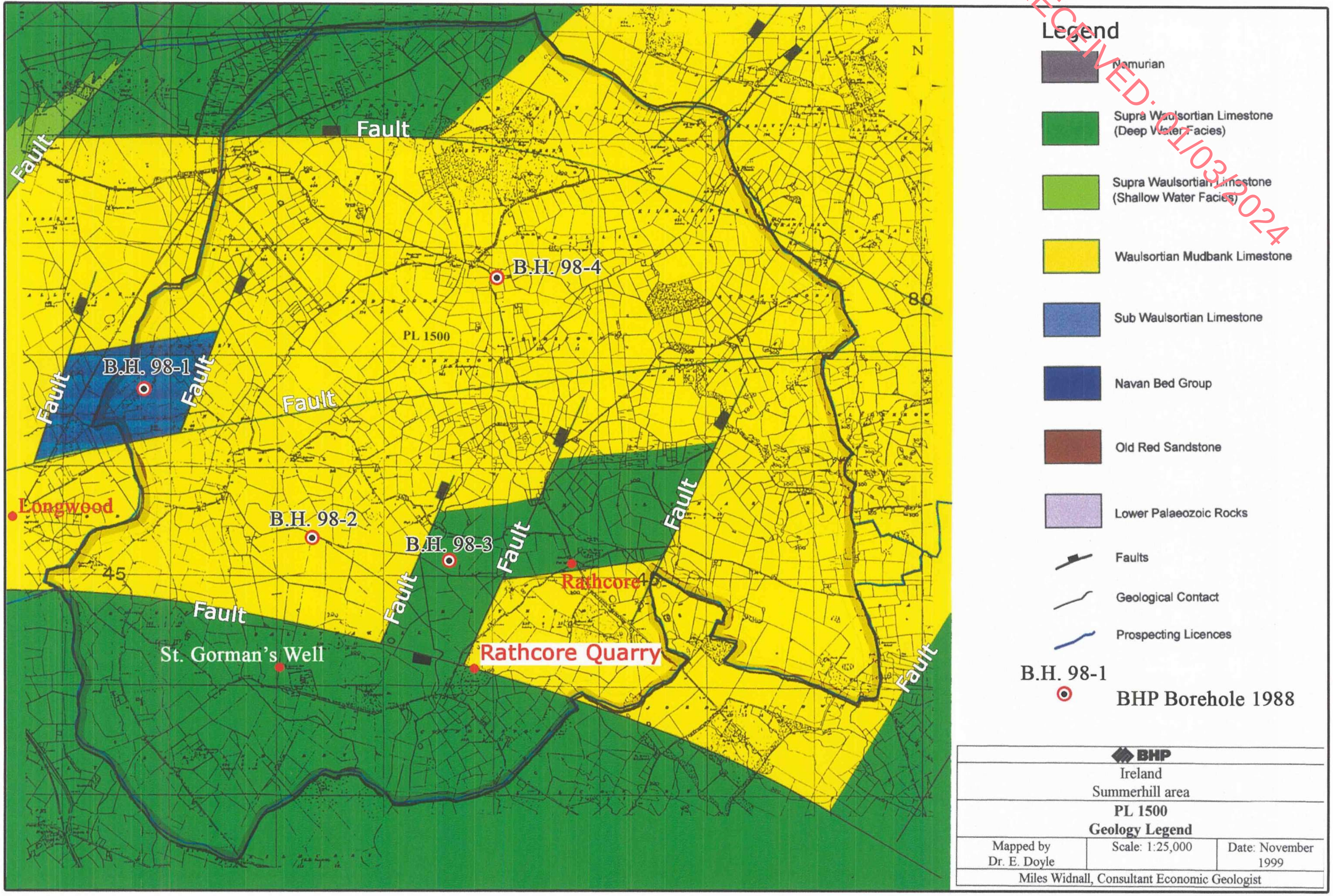


Figure 2.10 BHP Geology Map 1999

Core hole BHP 1500-98-1 went through 400 metres of ABL (Argillaceous Bioclastic Limestone) that was presumed to be older than the Waulsortian limestone, and hence lie below the Waulsortian.

BHP 1500-98-2 is in the valley due north-northeast of St Gorman's Well. It reached a depth of 337m, but remarkably drilled through 90.5 metres of soft unstable overburden that was presumed to be 'karst in-fill'. In other words, at this location, there appears to be a very deep depression, in-filled with probably residual clays and boulders, arising from deep solution weathering of a limestone. Below 90.5 metres the rest of the hole cored through Waulsortian limestone.

The 90m deep karst feature could be a large karst depression, or doline. It is notable that the base of the doline at 90 metres is roughly at the same depth as the large karst solution cavities in the Waulsortian found in boreholes SG4 and SG7 at St Gorman's Well.

The evidence from 1500-98-2 shows that karst solution weathering in the Waulsortian is also deep under areas apart from the St Gorman's spring. Zones of breccia, dolomitisation, bleaching of the rock, faults and a 2 metre size cavity at 289-291 metres depth in the core hole indicate that karst weathering and conduits can be found down to 300 metres below ground level.

BHP 1500-98-3 is in the same valley as 1500-98-2, and to the northwest of Rathcore Quarry. Here there is also deep karst weathering down to 49 metres, but the underlying bedrock is not Waulsortian. Instead it is described as a turbidite sequence of interlayered dark grey limestones and shales referred to as 'Supra Waulsortian'; i.e. a dark grey limestone and shale that is younger, and above the Waulsortian. In other words this is a block of younger rocks that have been faulted downwards amidst blocks of older Waulsortian limestone.

BHP 1500-98-4 is near Summerhill, and to the north east of the area of interest for this report, but it is informative because it encountered 437.8 metres of standard Waulsortian limestone above Argillaceous Bioclastic Limestone (ABL). This core hole shows that the Waulsortian limestone is very thick. It also indicates that the block of ABL found in 1500-98-1 was brought to the surface by a fault that could have seen a vertical movement of 450-500 metres.

The BHP core holes show that the bedrock hidden below the surface in the area probably consists of several blocks of different types of rock, separated by faults with large vertical movements. The core holes also show that karst weathering processes have penetrated to

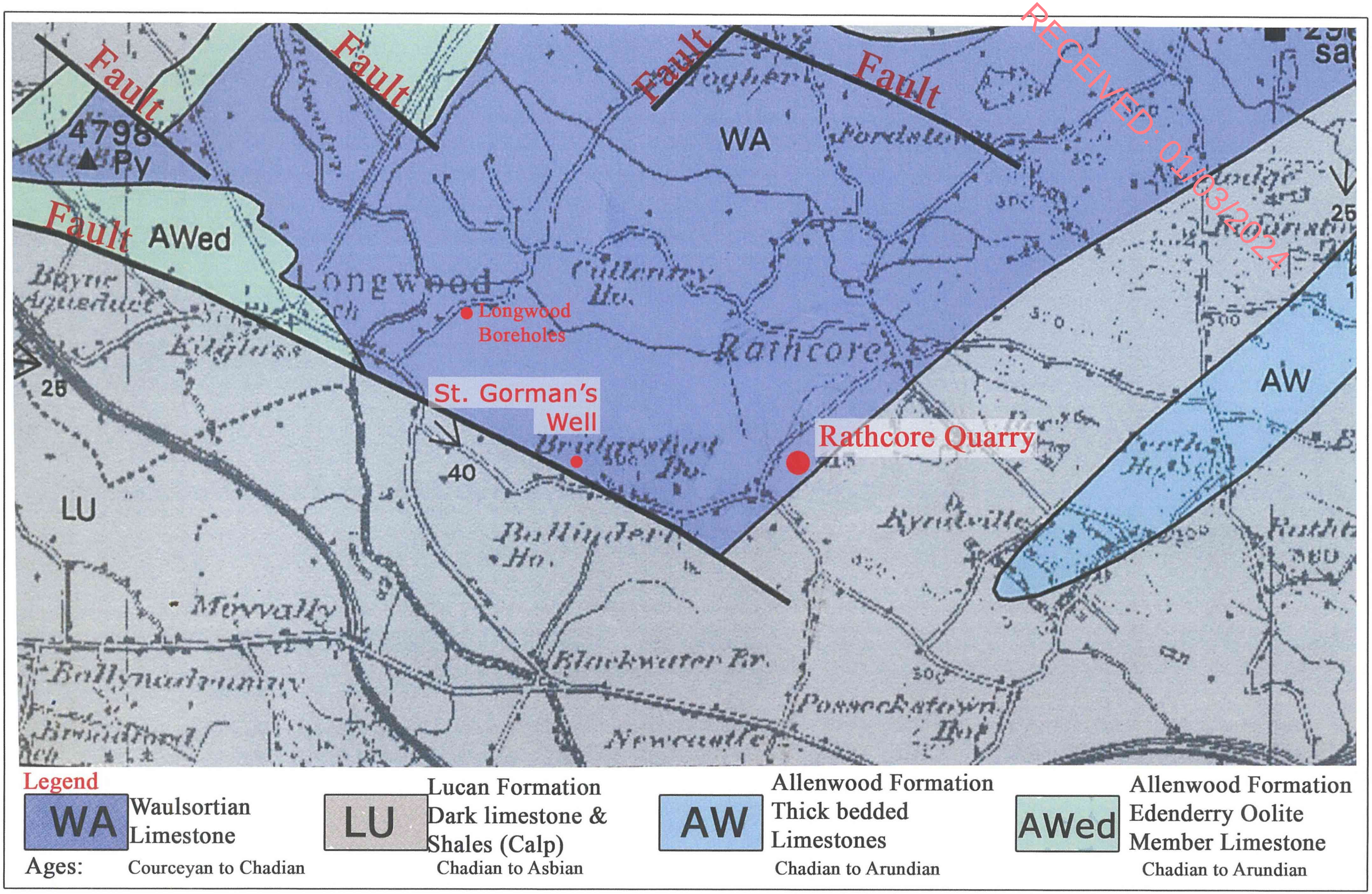


Figure 2.11 Bedrock Map Geological Survey of Ireland 1999

considerable depths in both the Waulsortian limestones and the dark grey limestones and shales.

In 1999 BHP produced a map of the PL1500 area in an interim biannual report. This map is shown in **Figure** 2.10. I have added the locations of the core holes drilled by BHP in 1998, and the position of the quarry and St Gorman's spring for ease of reference.

The Waulsortian is shown in yellow. The dark grey limestones and shales that are younger than the Waulsortian are shown in green, and the older dark grey limestones and shales are shown in dark grey-blue.

The most notable feature of the map is the overall difference from the Chevron map produced 7 years earlier. A second notable feature is a long curving fault running **north** of St Gorman's Well and straight through the centre of the current excavation at Rathcore quarry; in effect indicating that the southern half the quarry is in the dark grey limestone and shale. The exposure in the modern quarry would contradict this, but in 1998-1999, Traceys, the owners of the quarry before Kilsaran, may have not excavated as far south as the present quarry footprint.

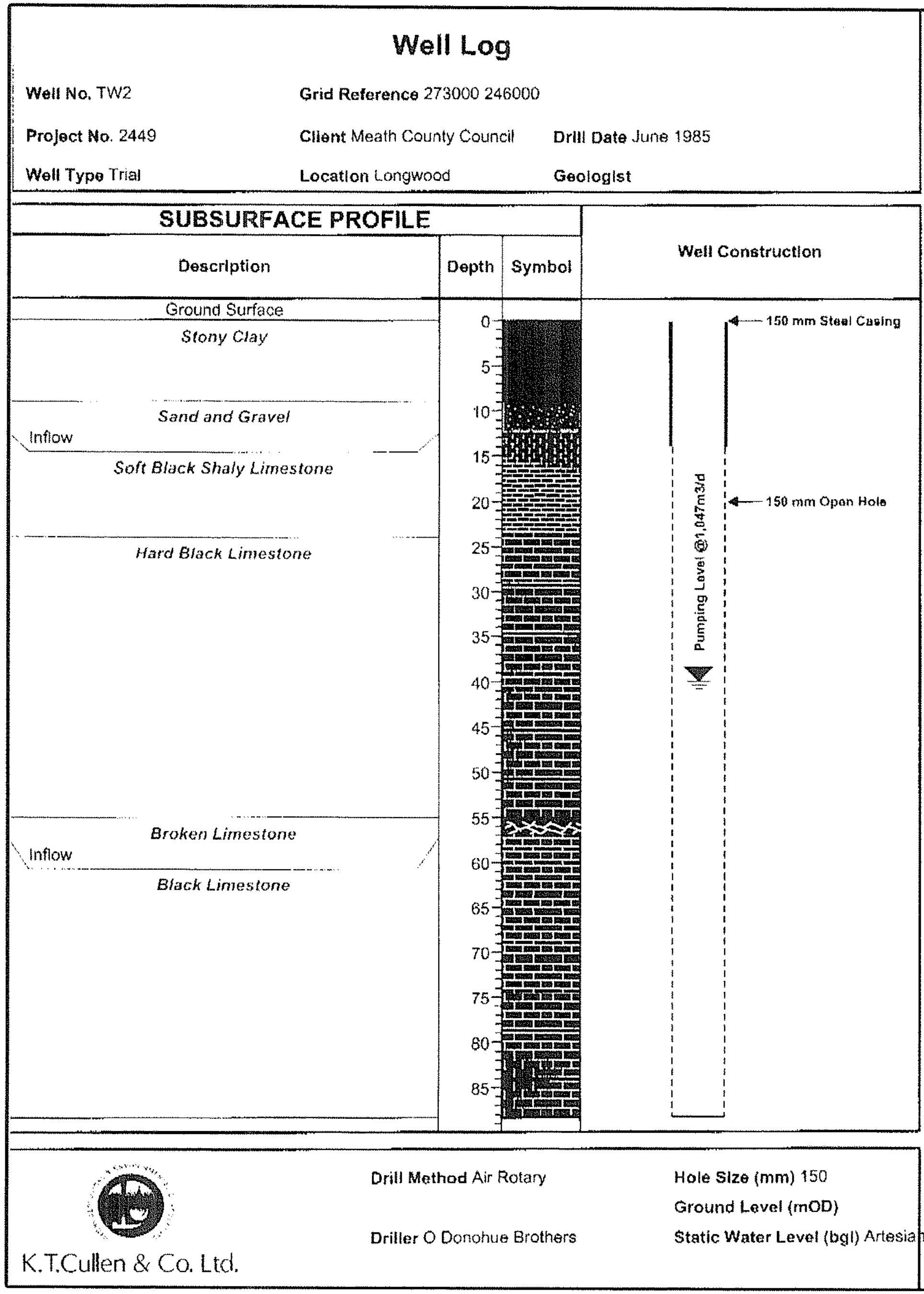
The other notable features of this map are the north-northeast to south-southwest aligned faults dropping down the younger dark grey limestones and shales, and raising up the older dark grey limestones and shales. The alignment of these faults is the same as the alignment of the anticlines in the Chevron map.

It is of note that this BHP map does not appear to refer to, or include, the major fault running through St Gorman's spring, or the presence of Waulsortian anticlines and synclines containing Tobercolleen or CPL formations, shown on the Chevron map produced seven years earlier.

In 1999 the Geological Survey published Sheet 13 in the national series of 1:100,000 scale bedrock maps. The map was published ahead of the explanatory memoir that would normally be published at the same time as the map.

An extract from Sheet 13 is shown in **Figure** 2.11. It shows the same area as the extract from the Chevron map from 1992. I have added again the position of the quarry and St Gorman's Well for ease of reference.

The GSI's bedrock map was a part of a nationwide bedrock mapping project, and therefore information, and an understanding of the Carboniferous limestone stratigraphy from elsewhere outside the area shown in this extract, was probably influential in the drawing of boundaries



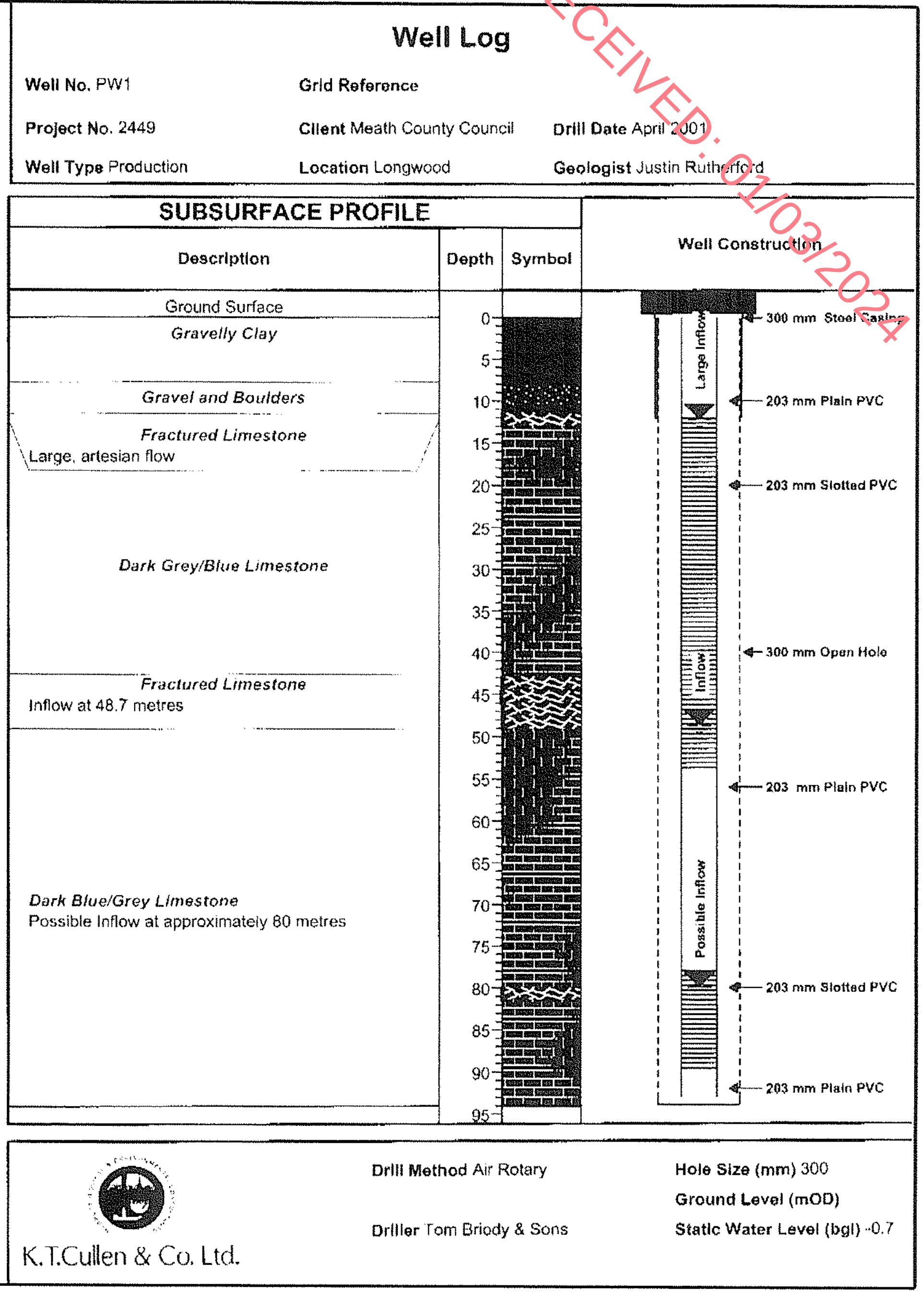


Figure 2.12 Longwood Water Supply Borehole Logs 1985 and 2001

and naming of formations shown in this extract. Also a map at 1:100,000 scale is not a scale that lends itself to showing complex detail.

However, it is apparent that the GSI's bedrock map does not show the interpretation of the bedrock geology and structure put forward in the Chevron map at the same scale and published the GSI in 1992.

Informally, I have asked several of the senior geologists involved in the preparation of both maps, why the Chevron interpretation of the geology had been discounted, or changed by the GSI in 1999. Some did not realise that it had. Others, did not remember the discussions taking place at that time, but do, with sadness, remember that Mike Geraghty, who was the one of the lead authors of the map, and the memoir, was ill and died at the time the map was being finalised and published.

It is also notable that the stratigraphical information gained from the four BHP core holes and the structural interpretation in 1998-9, was not incorporated into the GSI's Sheet 13. It seems likely that the essence of the map had been drawn before the results of the core holes were reported.

So, though a government published map may seem authoritative and impersonal, there may be a personal story behind its compilation and the position of faults and lithologies on the map.

Though the 1999 position of a block of Waulsortian limestone with dark grey limestone and shales to the south, and the boundary passing through St Gorman's spring, is superficially similar to the geological map produced in 1859, the boundary is now shown as a fault. In addition, a non-faulted contact between Waulsortian and overlying dark grey limestone and shales is shown passing through Rathcore quarry. Two areas underlain by the younger Allenwood formation pale grey limestone and Edenderry Oolite member of the Allenwood formation are also shown in the west and east of the map extract.

2.5 21st century Geology Investigations, drilling and mapping outside the quarry

2.5.1 Longwood Borehole 1

A water supply borehole was drilled in 2001 for Longwood village. It was based on the findings of an exploration borehole drilled in 1985. The site of these boreholes is shown on **Figure** 2.11. The logs for both boreholes are shown in **Figure** 2.12. The vertical scale in each log is slightly different.

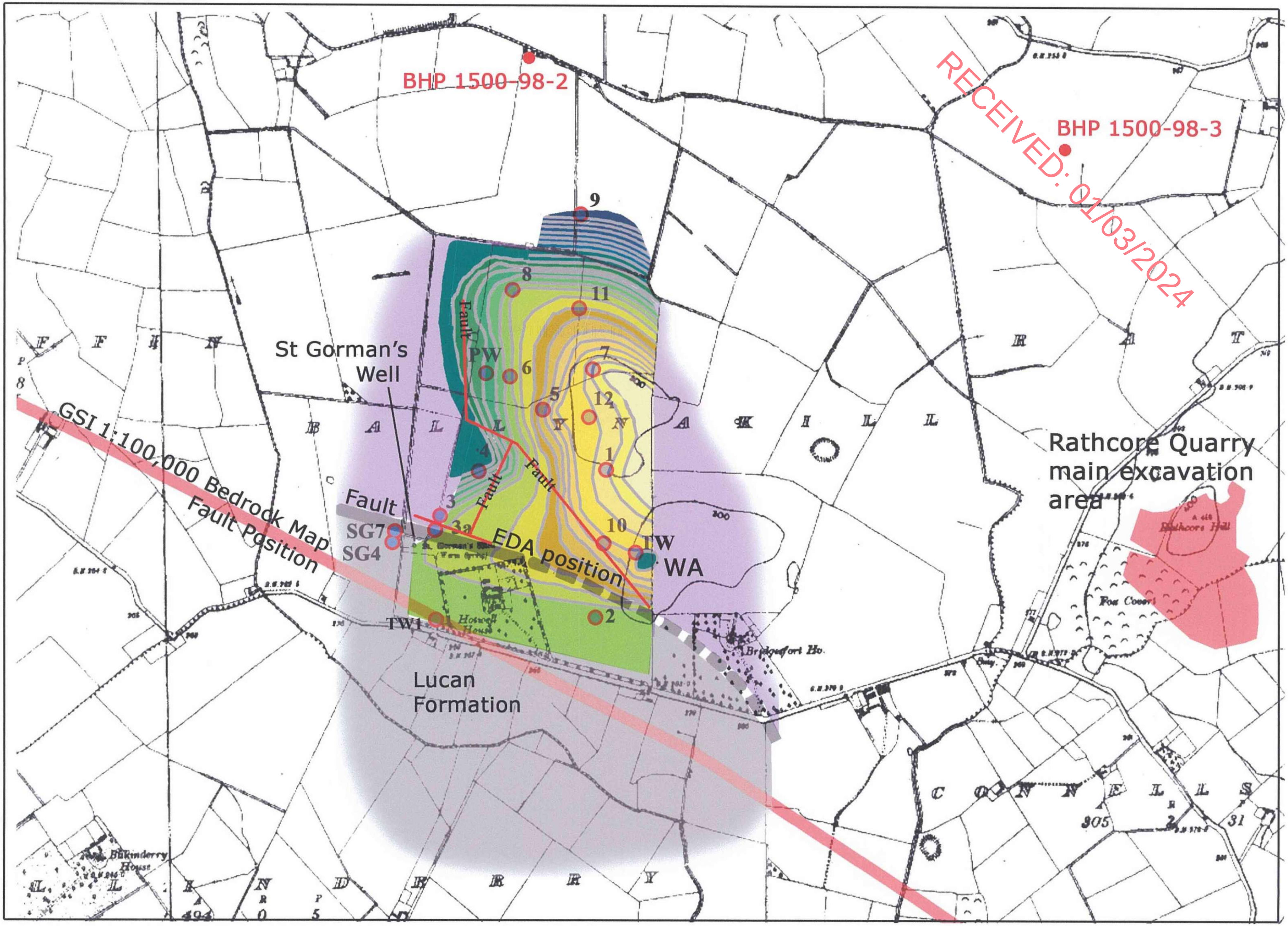


Figure 2.13 Ballinakill Roadstone borehole locations and geology

The first exploration borehole, TW2, was drilled on the side of the road. The later production borehole was drilled about 3 metres away. Both boreholes encountered water under artesian pressure in gravels below boulder clay and in the fractured top of the rock. The boreholes encountered the same black or blue - grey limestone down to a depth of 94 metres. Though the GSI map shows this area as underlain by Waulsortian limestone, there was no evidence of this limestone in these two boreholes. However, there was evidence of water inflows through zones of fracturing or breccia in the dark limestone. This finding was similar to Frank Murphy's observation of fracturing and water flow in the dark grey Calp above the north-south fault at St Gorman's spring. As will be described further below, a second production borehole was drilled under my supervision in 2011 about 45 metres south east of the first production borehole. This borehole went through black limestones then a fault and into the Waulsortian limestone.

2.5.2 Roadstone Exploration of Ballinakill

Following the production of the GSI's bedrock map in 1999, Roadstone (CRH) bought a large area of land to the west and northeast of St Gorman's Well and the associated boreholes. The boreholes and the spring remained on the property of Hotwell House.

Roadstone engaged John Barnett and Associates to prepare planning applications in 2006 for the development of a new limestone quarry on part of the lands. The hydrogeologist Eugene Daly of EDA lead the groundwater investigation team.

They carried out investigations in 2001-2002, and then later in 2006. The team carried out a geophysical investigation followed by core hole and borehole drilling and testing. The information submitted with planning applications, has provided very useful information on the geology of the Ballinakill – St Gorman's Well area.

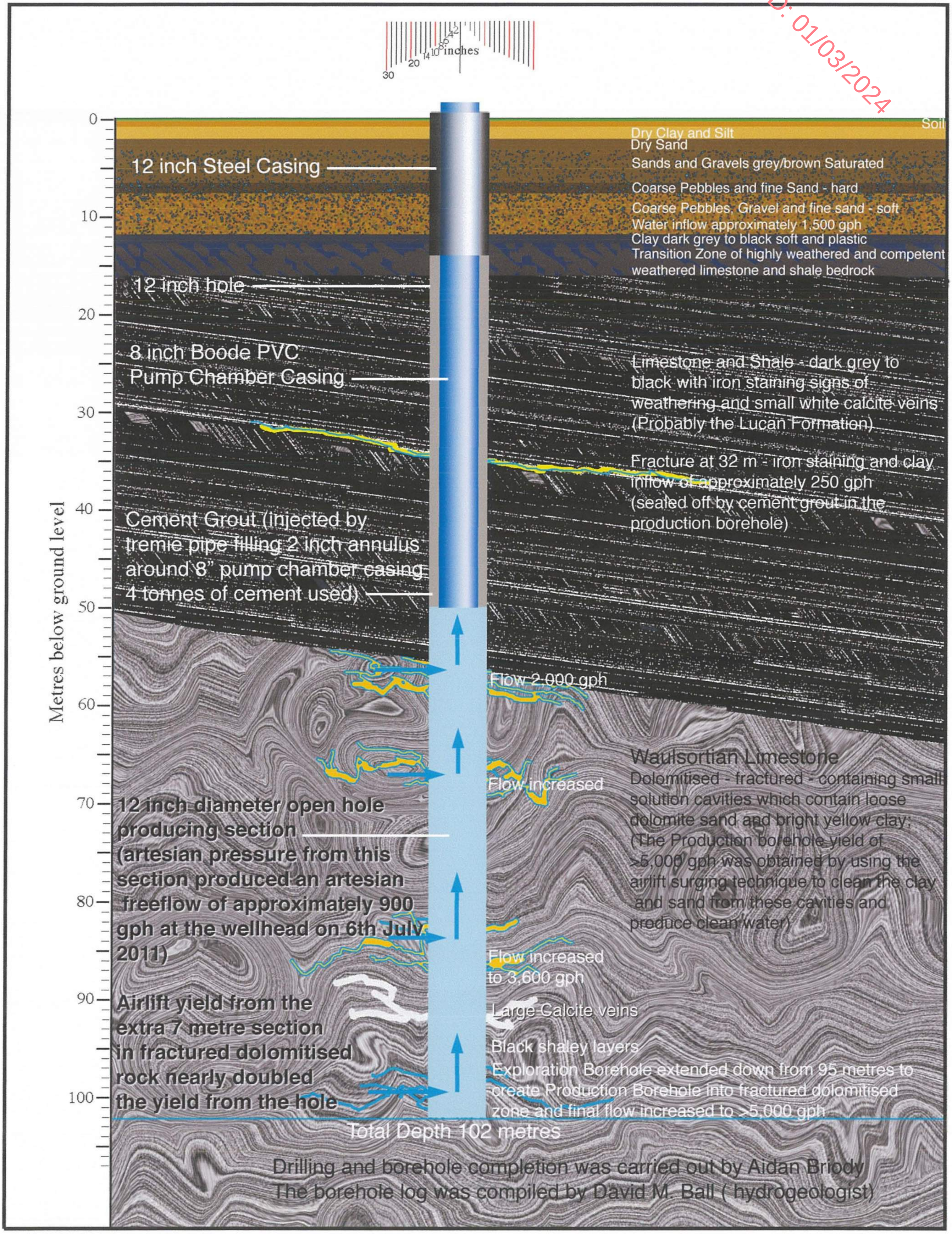
Figure 2.13 is a complex map showing the locations and numbering system for boreholes drilled at Ballinakill by EDA. The location of the main excavation area of Rathcore quarry, the location of two BHP core holes and the locations of SG4 and SG7 next to the spring are also shown. A borehole labelled TWI is believed to be a County Council test well.

The **Figure** also shows original interpretations by EDA transcribed from other figures in their documents, and my processing of borehole data from the EDA borehole logs.

Roadstone borehole 9 in the valley to the north did not reach bedrock. All the other boreholes reached the bedrock. Borehole 2 and borehole 3 penetrated the Lucan formation dark grey limestones and black shales. The remaining boreholes all encountered Waulsortian limestone.

Figure 2.14 Longwood Production Borehole No.2

Longwood Water Supply - Production Borehole No.2 Completion Log
(The final Production Borehole, to a depth of 102metres, was first drilled as a 95metre deep exploration borehole. The exploration hole was reamed out at 12inch diameter. Work took place between the 27th June and 7th July 2011)



Eugene Daly drew a major fault line along an alignment shown in grey in the **Figure**. I have coloured the area north of this fault in mauve to denote presumed Waulsortian limestone, and the area south of the fault in grey, to denote Lucan Formation. The major fault shown on the GSI bedrock map is shown in red for comparison. It is significantly to the south of the EDA fault. Gareth Ll. Jones provided EDA and John Barnett with an assessment of the micro fossils in a sample of the Lucan Formation encountered in Core hole 2. He concluded that the core was from the upper stratigraphic layers of the Lucan formation, and therefore, to bring it down into juxtaposition with the Waulsortian, would have required a down throw movement on the fault of about 500 metres.

The contour map overlying the boreholes in green, brown and yellow shows the topography of the top of the bedrock buried below the sand and gravel till overburden at Ballinakill. The elevations, above Ordnance Datum, are derived from the EDA borehole logs and either the collar height, or ground level.

It appears to show the western part of a buried plateau or large knoll of Waulsortian limestone, with steep sides to the north, west and south. There is no information from the lands adjacent to the east.

The maximum elevation of the top of the Waulsortian is 84 metres O.D. The elevation at core hole 4 is 69 metres. The bedrock at the site of core hole 9 is below 60 metres OD, and the top of competent Waulsortian limestone in BHP core hole 1500-98-2 is -17 metres OD; i.e. below modern sea level. The top of competent rock in BHP core hole 1500-98-3 is 27 metres OD. These data together show that there is a big change in the buried topography of the top of the Waulsortian limestone in this small area.

The flat topped steep sided feature has the appearance of a residual karst feature called a “Hum”, which is the Yugoslav name for the stump of a karst pinnacle, where the top has been planed off; in Meath, presumably planed off by the erosion of successive ice sheets.

The buried deep karst depression encountered in BHP 1500-98-2 may be a single doline (in-filled sink hole), or maybe a larger in-filled depression called a ‘Uvala’. This is again a Yugoslav name. It means a large closed depression; i.e. a flat area surround by limestone hills and with no outlet valley.

2.5.3. Longwood Borehole 2

Though the original production borehole for Longwood was estimated to provide a yield of over 1,500m^3/day, the County Council wanted a second water supply borehole because the first

Figure 2.15 Tellus Conductivity and AMT Resistivity maps from Sarah Blake's Research

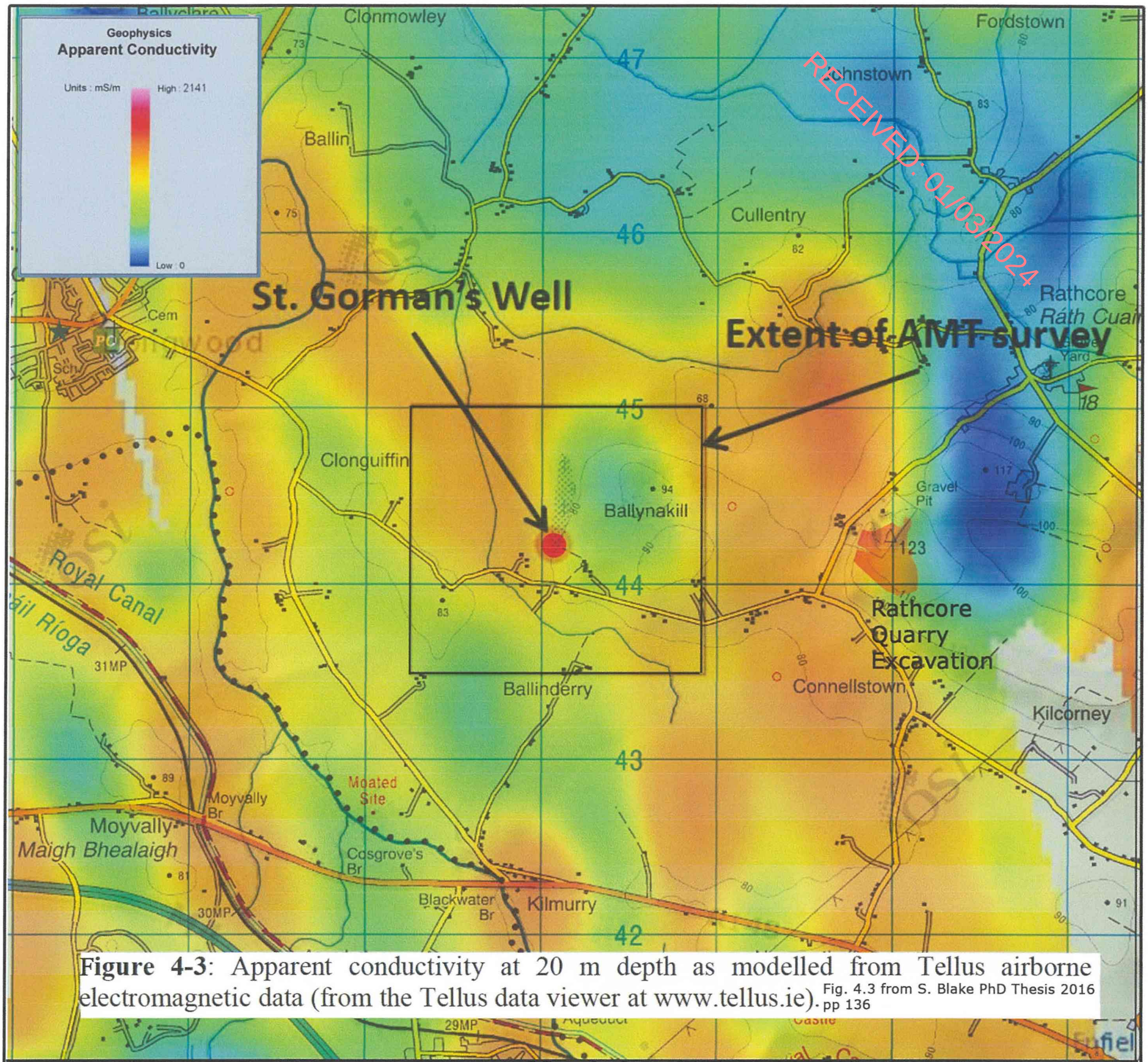
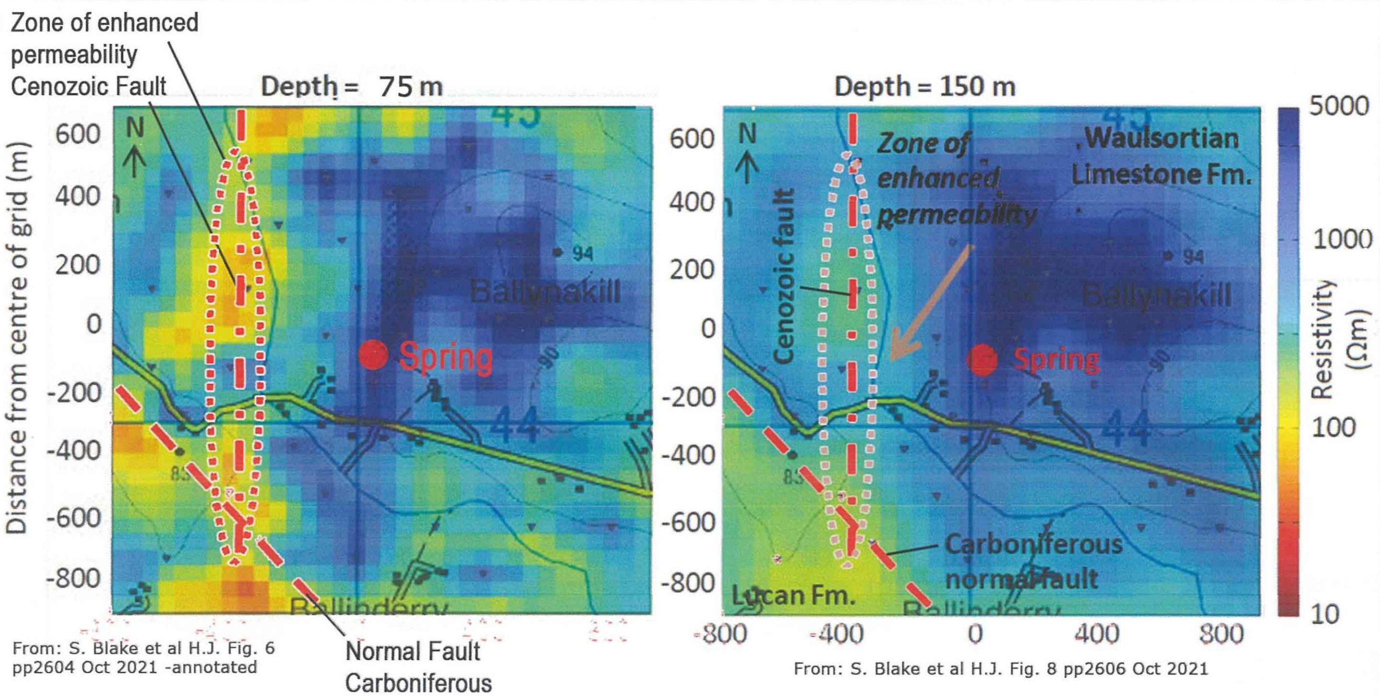


Figure 4-3: Apparent conductivity at 20 m depth as modelled from Tellus airborne electromagnetic data (from the Tellus data viewer at www.tellus.ie). Fig. 4.3 from S. Blake PhD Thesis 2016 pp 136



From: S. Blake et al H.J. Fig. 6 pp2604 Oct 2021 -annotated

From: S. Blake et al H.J. Fig. 8 pp2606 Oct 2021 borehole appeared to have a much lower sustainable yield than expected. In 2011, I supervised exploration and production borehole drilling of a second borehole. The chosen site was 45 metres away from the first hole within the land owned by the County Council. In choosing the site, it was hoped that the borehole would either strike a fault zone, or penetrate the Waulsortian limestone. The dark grey or black limestones encountered in the first Longwood borehole, and shown in **Figure** 2.12, are not on the GSI Bedrock map, which depicts this area as underlain by Waulsortian limestone.

The completion log for Longwood Water Supply Borehole No.2 is shown in **Figure** 2.14. The text on the log describe the findings and the flow rates at different depths.

The borehole went through coarse fluvio-glacial sands and gravels to a depth of 12 metres, then a one metre confining layer of clay, followed by dark grey limestones and shales down to a depth of 55 metres. There were fractures in the dark grey limestones and shales, but the main yield was from solution cavities in the Waulsortian limestone encountered below 55 metres. The contact between the dark grey limestones and the Waulsortian appeared to be a fault.

By 2011, the available information from the mineral exploration boreholes, water supply boreholes and the site investigation boreholes at Ballinakill, were clearly indicating that the buried geology and structures in the area were more complex than shown on the 1999 bedrock map.

2.5.4 Geological Investigations and mapping since 2010

Sarah Blake undertook a PhD entitled “A multi-disciplinary investigation of the provenance, pathways and geothermal potential of Irish thermal springs” through NUIG. Her PhD research focussed on two sites; Kilbrook Spring and St Gorman’s Spring.

Sarah Blake assessed the previous investigations of the geology in the area, but the work carried out for Roadstone by EDA was not available at the time of her research. Sarah Blake described and stressed the importance of understanding structural geology in the context of hydrogeology in the area and karst pathways for the upward flow of warm groundwater.

Sarah Blake referred to an example of structural control on karst in Rathcore quarry where there appears to be an intersection of two faults and the development of a 20metre wide karst depression filled with unconsolidated material.

Sarah Blake has published papers and given lectures and poster sessions on her work on St Gorman’s spring in conjunction with other hydrogeologists, geophysicists and structural geologists. She has shared her thesis, her papers and all her data with me, and, as will be

Figure 2.16 Location of AMT stations and section through final resistivity model

From Sarah Blake et al
Hydrogeology
Journal 2021

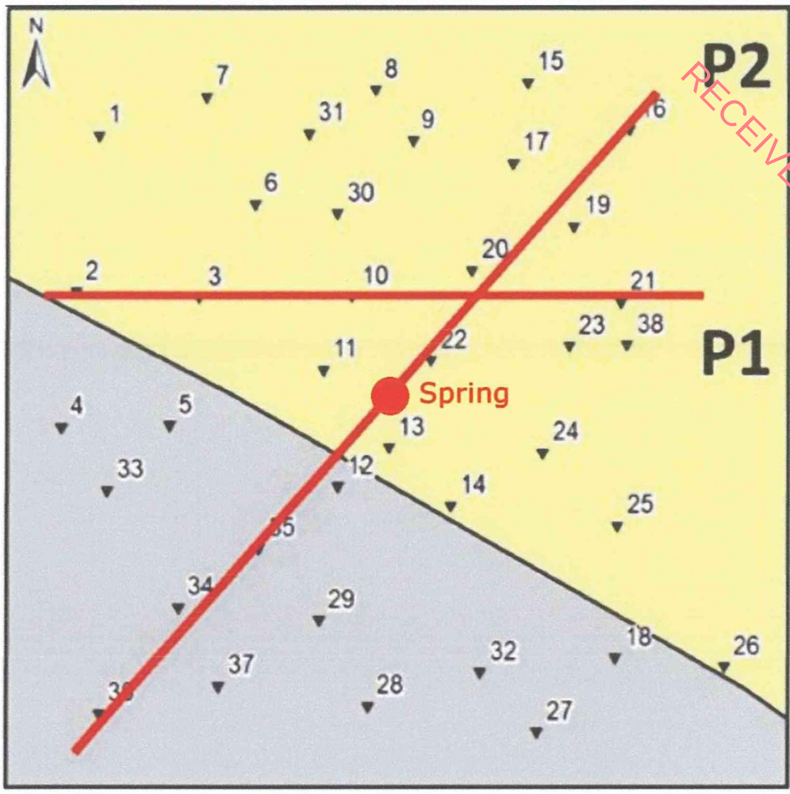


Figure 5 Position of AMT Stations and orientation of sections

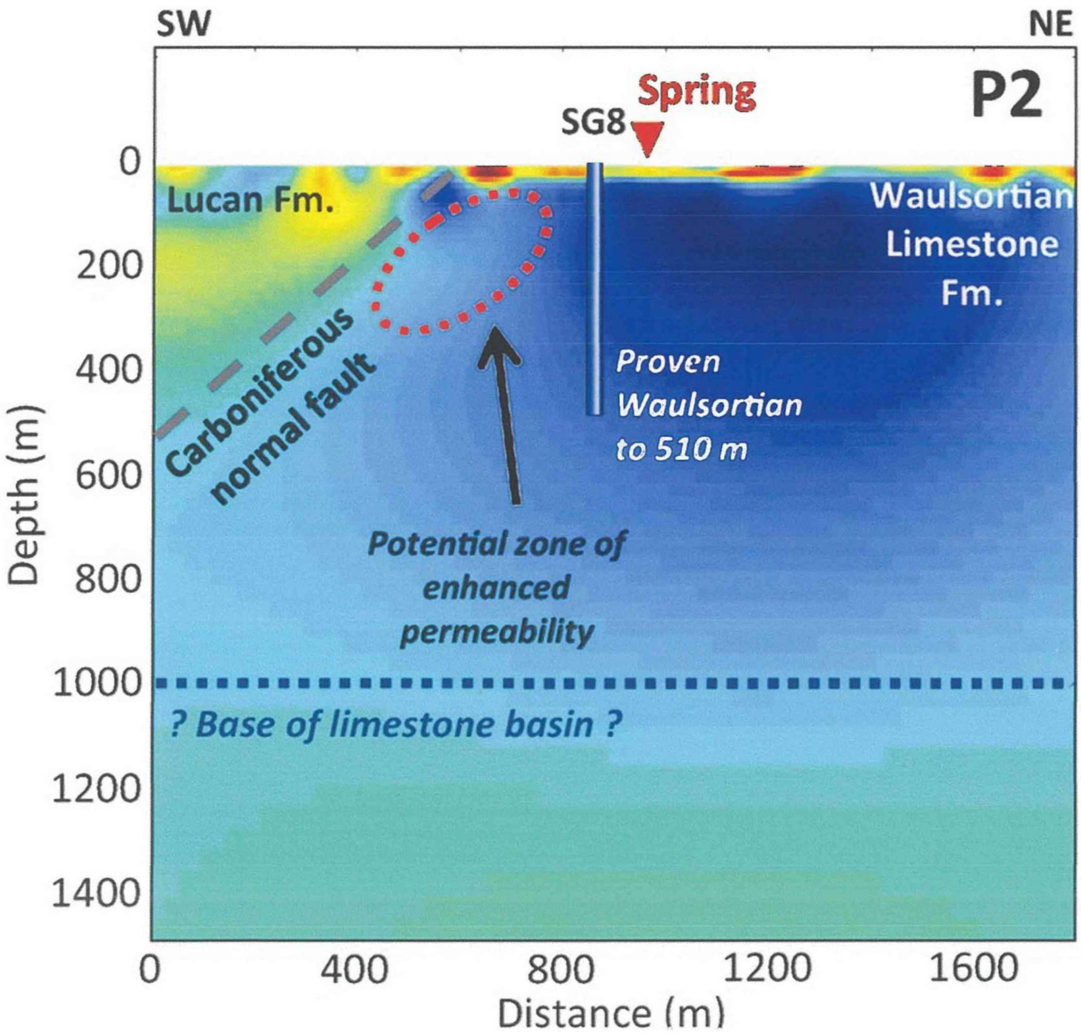


Fig. 8 Vertical profile through the model (P2 in Fig. 5) showing main features of the hydrothermal flow system. SG8 indicates the extent of the 500-m geothermal borehole from Murphy and Brück (1989)

described in detail later, I have carried on taking pressure transducer measurements of water levels in borehole SG4 from the same position as her previous pressure transducer. The data that I have obtained on behalf of Kilsaran is a continuation of her water level and temperature data. The data collected during this study for Kilsaran will be given to the GSI for their records along with this report.

Sarah Blake has added to the geological information on the area by following up on the data coming from the Tellus airborne EM survey of the area that was being carried out during her PhD research.

Sarah Blake followed up the airborne survey by carrying out a ground survey using the AMT (audio-magnetotelluric) method in October 2013.

This is a passive geophysical technique, where simultaneous measurements are made at carefully spaced stations overnight to measure naturally occurring electromagnetic waves. These waves are generated by lightning discharges during storms anywhere in the world. The electromagnetic waves are propagated around the globe, constrained in the space between the earth's surface and the upper boundary of the ionosphere. This space is called the Earth-ionosphere waveguide. The data obtained at the stations can be processed to determine the variations in resistivity in the subsurface.

Sarah Blake spaced 38 stations 200 metres apart in a large grid centered on St Gorman's spring. The spacing was chosen in order to try to determine the best resolution of the resistivity of the subsurface at depths greater than 100 metres below ground level.

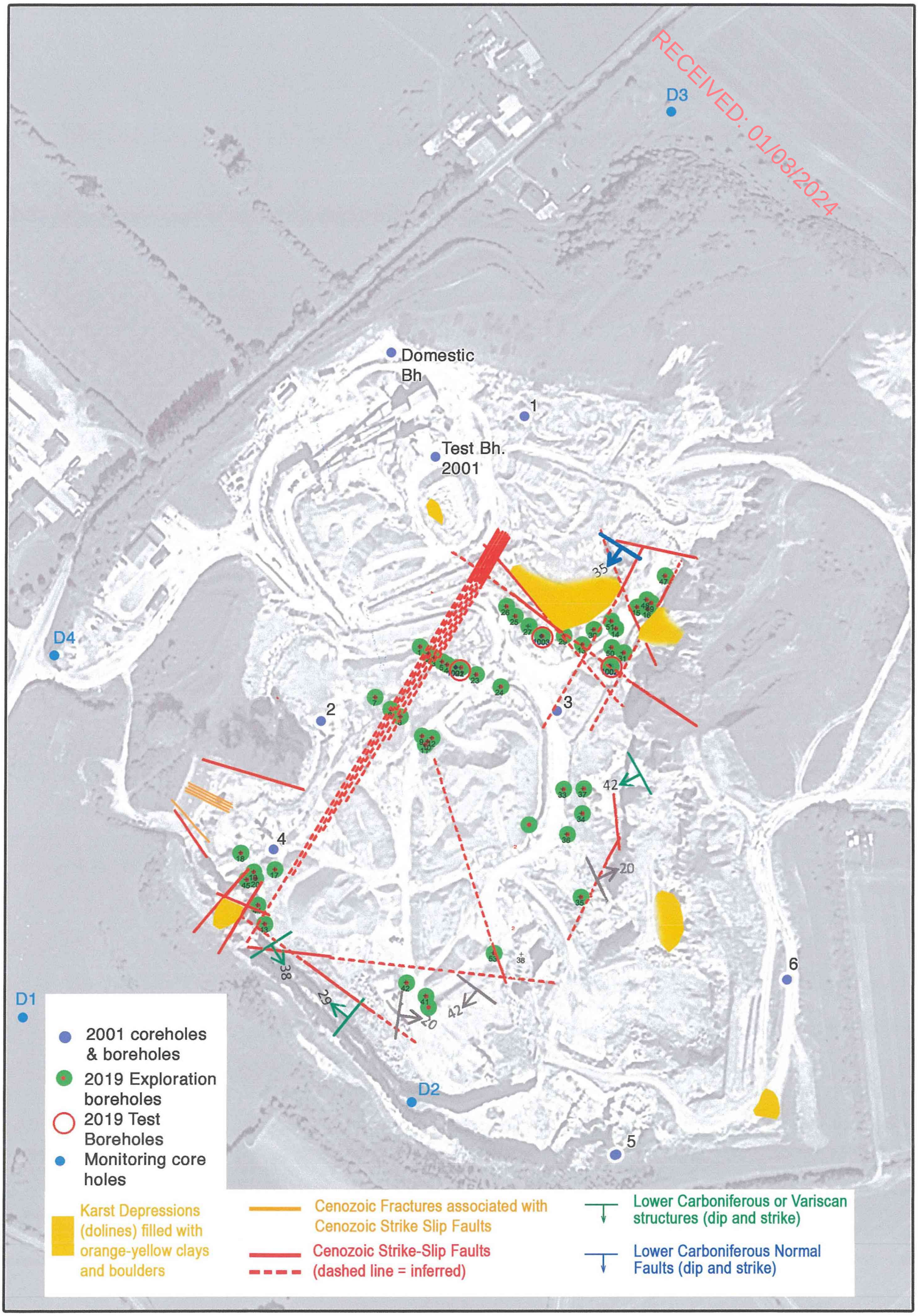
Figures 2.15 and 2.16 are maps and sections selected and combined from Sarah Blake's thesis and subsequent papers. I have chosen them to give a summary of her main findings on the geology of the St Gorman's spring area. I have tried to reference the **Figure** numbers and the source document on each item. I have added text and arrows to highlight certain features.

In **Figure** 2.15, the upper map shows the Tellus airborne geophysics conductivity information for a depth of 20metres below ground level, overlaid on the Discovery Series base map. The upper map shows the outline of the AMT survey area shown in the lower two maps.

The conductivity information in the upper map shows a small low conductivity area to the north east of St Gorman's spring. This is the Waulsortian limestone under the Ballinakill hill shown in **Figure** 2.13. This low conductivity area seems to be isolated from other low conductivity areas, shown in blue, by areas of high conductivity shown in red and yellow. One area of high conductivity is to the west and north of St Gorman's spring. It appears to form a roughly north south aligned area.

It is notable that the area of the Waulsortian limestone in Rathcore quarry is not shown as low

Figure 2.17 Rathcore Quarry Structural Geology and Borehole locations



conductivity. The low conductivity area appears to be offset to the east and north of the quarry. The two lower maps show the processed AMT data. Sarah Blake shows several depth slice maps in her thesis and published papers. The two shown in **Figure** 2.15 are selections for 75 metres and 150 metres depth. Sarah Blake identified a low resistivity (i.e. high conductivity) north-south aligned feature to the west of St Gorman's spring, that appears to fit with the broader area of high conductivity shown in the Tellus conductivity map in the upper part of **Figure** 2.15.

Sarah Blake has interpreted this north-south feature as an 'enhanced permeability Cenozoic age fault'. She has also provided a position for a Carboniferous normal fault with a northwest to southeast alignment about 600 metres southwest of the spring. This is different from the position of the major fault shown on the GSI bedrock map and the position of a fault between the Waulsortian and the Lucan interpreted by EDA and shown in **Figure** 2.13.

It seems that every study of the geology of the area, including Du Noyer's original survey, recognises that there is a boundary between the Waulsortian limestone and a different dark grey limestone with shales somewhere in the vicinity of Ballinakill hill; and St Gorman's Well, but in each study or map it is in a different position and orientation.

The upper map in **Figure** 2.16 shows the AMT station positions and the position of the initial presumed boundary between the Waulsortian and the Lucan formations. The lower part of **Figure** 2.16 shows the AMT section along the alignment P2. The section shows the change in apparent resistivity down to 1,500 metres depth, and the position and depth of SG8, the 510 metre deep core hole drilled during Frank Murphy's work. The distance between the spring and the position of the Carboniferous normal fault appears to be closer to the spring in **Figure** 2.16 than in **Figure** 2.15.

2.6 Early Geological Investigations at Rathcore Quarry

Rathcore quarry appears to have started as a small sand and gravel pit cut back into Rathcore Hill in the 19th century. Tracey Enterprises Ltd operated an aggregate quarry on the site from 1991. Kilsaran acquired the quarry in 2005.

Tracey carried out exploration drilling in 2001 for a planning application. Tracey drilled six exploration rotary core holes. The locations of these holes are shown in **Figure** 2.17.

Two water supply boreholes were drilled. These are both shown on **Figure** 2.17. The water supply borehole for the plant was used for testing, and there is a log for this borehole.

The logs for the six core holes and the test borehole have been summarized and are shown in **Figure** 2.18.

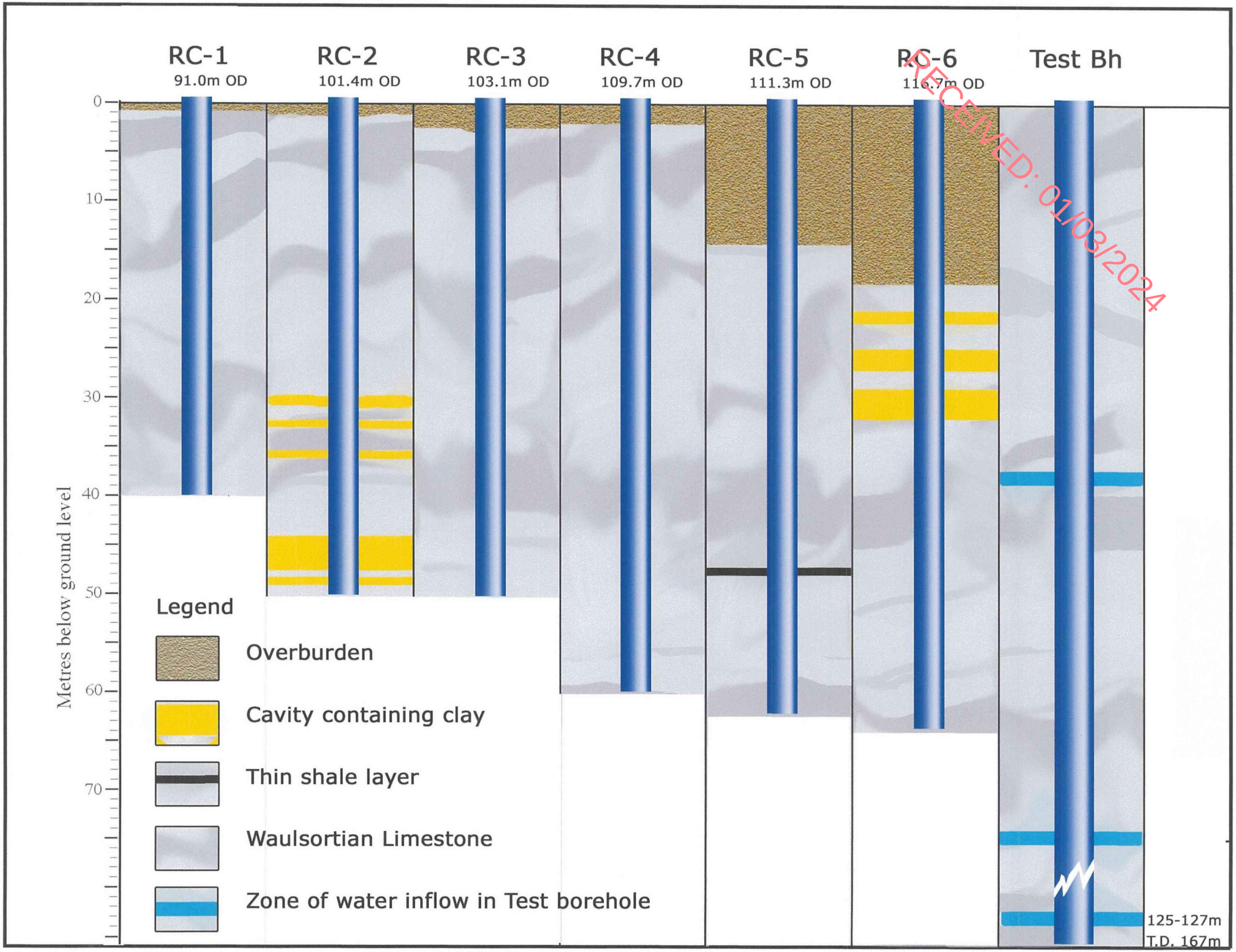


Figure 2.18 Rathcore Exploration Quarry Drilling 2001 Summary Logs

The upper 25-30 metres of rock shown in the logs core holes 2, 3 and 4 has since been removed during the development of the quarry.

All the core holes encountered massive Waulsortian limestone, but each one also encountered individual fractures, or groups of fractures, in the rock that were stained with iron oxide and, or, thin deposits of yellow clay. Thus indicating that, at some point in time groundwater has moved through these fractures.

Core hole 2 is notable for encountering at least five large karst cavities containing yellow clay. Whereas, core holes 1, 3, 4 and 5 did not encounter large cavities.

Core holes 5 and 6 are on the southern and south eastern perimeter of the quarry. The thick over burden encountered by both indicates that the hard Waulsortian bedrock forming the core of Rathcore hill has steep sides buried under soft more recent material. Neither of these holes encountered the dark grey limestone and shale of younger Lucan formation that is shown to be overlying the Waulsortian in this location on the GSI bedrock map.

Core hole 6 encountered large cavities containing clay. This indicates that the outer slope of the Waulsortian core has been dissolved by karst weathering.

The borehole used for carrying out a pumping test in 2001 and used as a water supply for the fixed quarry plant did not encounter cavities containing clay. The hole was low yielding and appear to gain water from three distinct zones of minor fractures.

The Tracey planning application referred to a large vertical solution cavity open at the surface, just south of the test well and the plant. It's location can be seen on **Figure** 2.17.

This cavity was wide at the top and tapered with depth. It was clay sided, and it was possible to see water at its base. The cavity has since been filled in for safety reasons. I have been told that before it was filled, an employee with cave diving experience, went down into the cavity and along a sub-horizontal cave at its base. He managed to feel his way along the cave under water for about 25 metres. He did not reach the end of the cave because there was zero visibility and it was not safe to explore further.

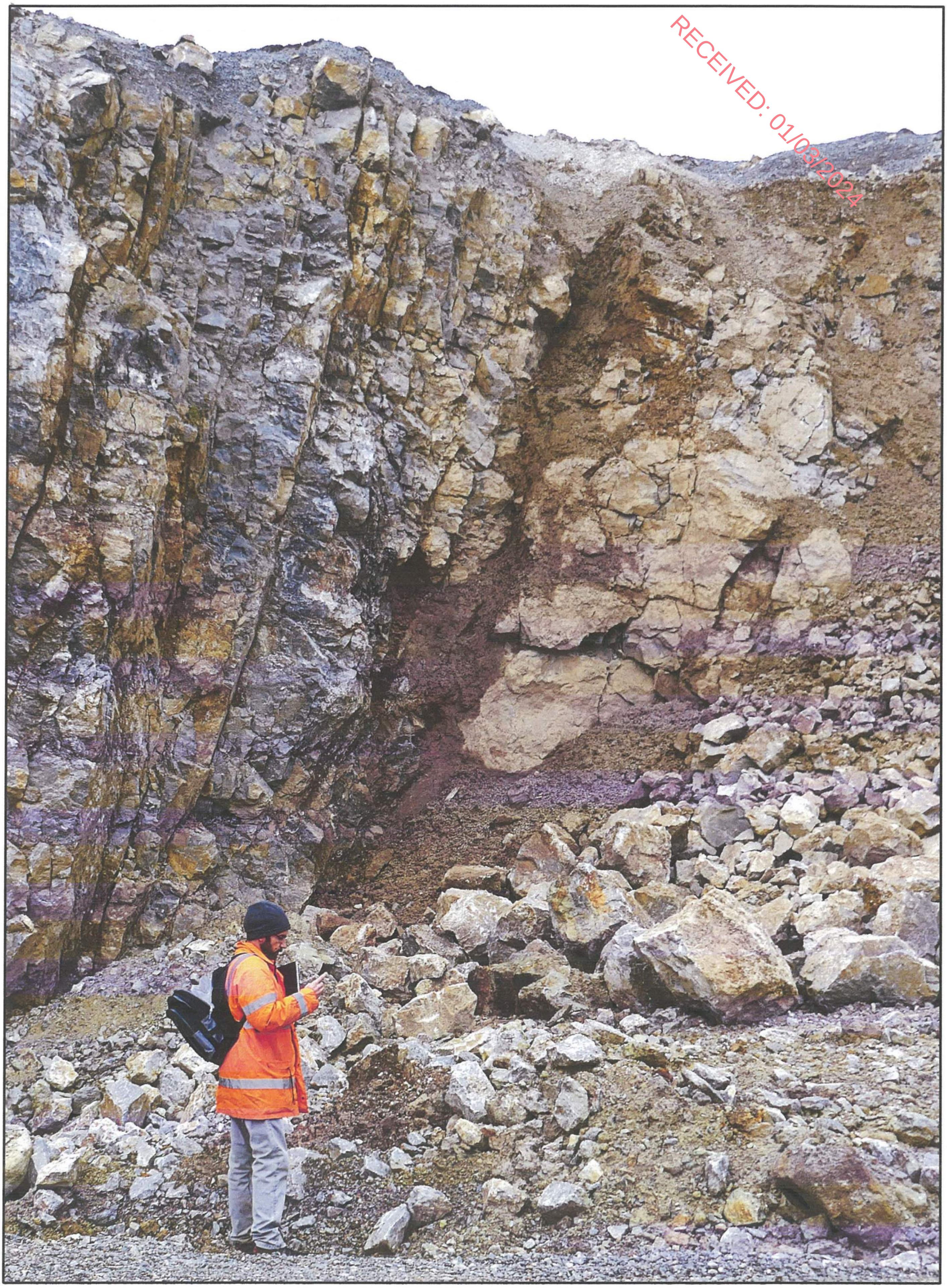
An EIAR prepared in 2016-7 by Kilsaran. It included the requisite sections on the geology and hydrogeology of the area and the quarry, but no new drilling was carried out to explore the bedrock below the quarry.

2.7 Geological Investigations at Rathcore Quarry for the current study

2.7.1 Site surveys and structural geology

I carried out a site visit in late 2018. The floor of the quarry had been lowered by 25-30 metres from its level in 2001. It was apparent that the current quarry floor is below the winter groundwater level, but above the groundwater level during a dry summer. There was no

Figure 2.19 J.P. Moore measuring the orientation of fault alignments in the quarry in 2019



The structures on the left are Cenozoic strike-slip faults. The broken rock and clay on the right are the edge of an infilled karst depression in the north of the quarry anecdotal evidence of springs or major inflows from karst cavities in the quarry walls. It was evident that if the quarry were to obtain permission to excavate the rock further, it was incumbent on Kilsaran to investigate the hydrogeology below the existing quarry floor.

My first objective was to try and find out whether there was evidence that a karst groundwater flow system might exist below the quarry. It had been assumed that below the quarry floor the Waulsortian limestone was essentially a large solid block containing occasional cavities filled with ancient clay. Kilsaran needed to know whether there was a groundwater flow system below the quarry floor, and its characteristics, in order to assess whether the quarry could be economically dewatered, and most important, to assess whether dewatering the proposed excavation could have an effect outside the quarry. In other words, find out whether any groundwater flow system below the quarry might connect the quarry to a groundwater flow system in the area around.

I specifically use the term groundwater flow system rather than aquifer, because groundwater does not flow through the solid rock. The solid rock is not an aquifer. Instead, groundwater can only flow through the cracks, faults, or solution widen conduits in the rock, which break up the rock. These breaks have to be linked up into a network or system of interconnected openings for flow to take place.

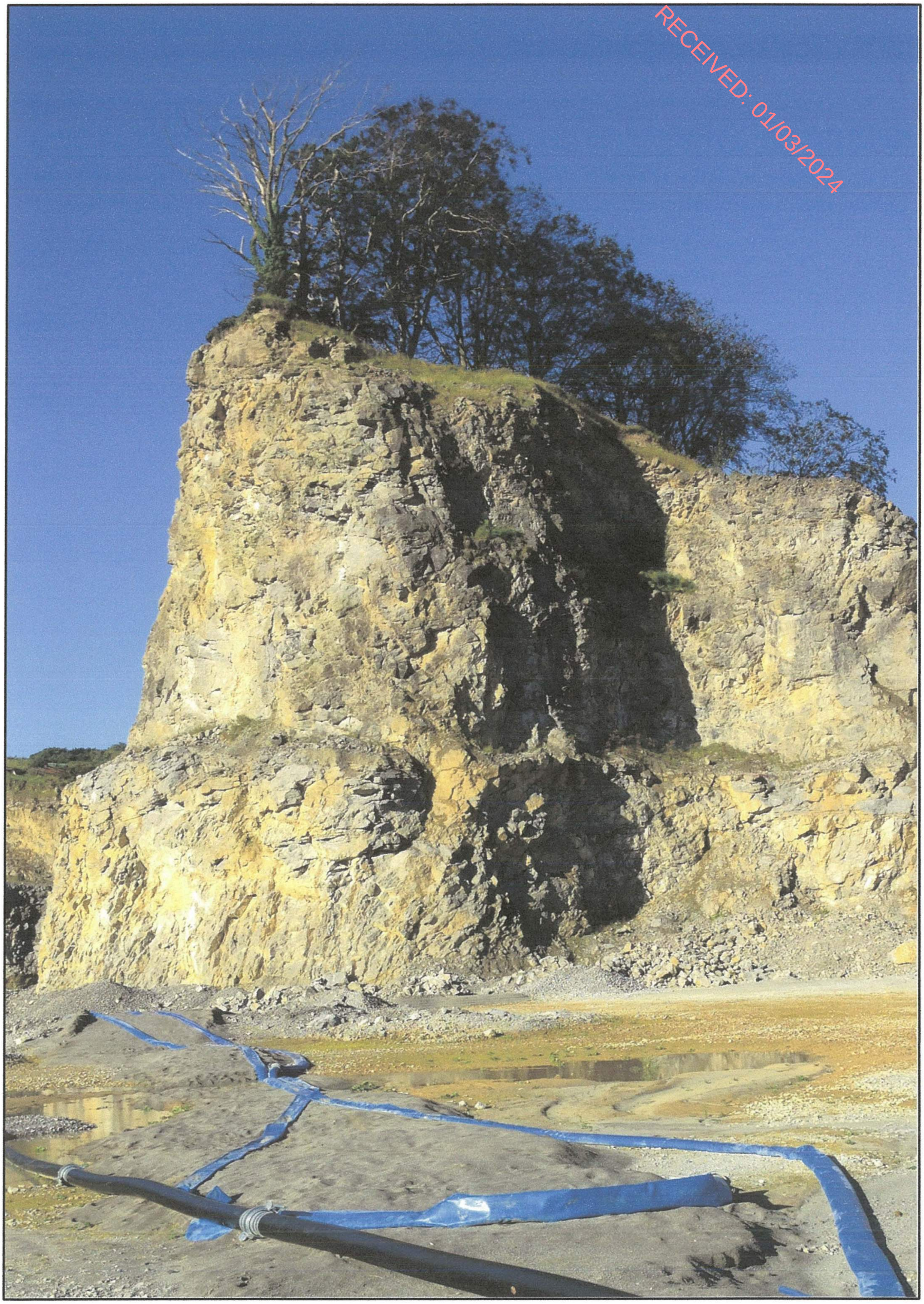
On my first visit to Rathcore quarry, I recognised that there were geological structures visible in the quarry walls that if projected downwards might indicate the development of karst conduits deeper in the bedrock. I recognised that there appeared to be karst solution depressions infilled with clay and weathered rock visible at the edge of the quarry excavation.

I realised that I needed expert assistance to map and understand these structures. Kilsaran engaged John Paul Moore. John Paul qualified first as a hydrogeologist, but since 2011 had been training as a structural geologist working within ICRAG (Irish Centre for Research in Applied Geosciences) in UCD, and carrying out very detailed research for a PhD on faults and fracture systems in Irish bedrock and their implications for groundwater flow. He has published several papers on the subject, and also been one of several co-authors in Sarah Blake's papers on St Gorman's spring.

John Paul and I carried out several site surveys of the structures evident within the quarry.

Most of the structures that he identified were Cenozoic strike-slip faults. The Cenozoic era refers to the last 66 million years in geological history. Other structures that we were looking for were Carboniferous age structures. Faulting took place in the early Carboniferous, as the limestones were being deposited, but there was further deformation and faulting at the end of the Carboniferous period during the Variscan mountain building period.

Figure 2.20 Massive Waulsortian Limestone Outcrop on western side of Rathcore Quarry



John Paul's research has found that the Carboniferous normal faults are now usually tight or closed, and generally not zones of enhanced groundwater movement, unless they have been opened by karst solution processes. In contrast, the more recent faults created during the Cenozoic era are more open, and more likely to have become precursors of palaeo- and modern karst solution weathering, and hence zones of preferential groundwater flow. A summary of his findings is shown in a block diagram in Figure 2.48 at the end of this chapter.

John Paul has found, through his field work throughout Ireland, that zones of intense karst cavity development also often occur at the intersection of the old Carboniferous and the younger Cenozoic faults.

Figure 2.19 shows a section of the quarry wall where John Paul Moore identified a zone of intense, northeast to southwest, aligned Cenozoic strike-slip faults, next to a large infilled karst depression. This site is on the northern edge of the current quarry floor, and the location can be seen in **Figure** 2.17. He also identified a lower Carboniferous normal fault at the north eastern edge of the large karst depression. This normal fault was the only clearly identifiable Carboniferous age normal fault exposed in the quarry, at that time. There may be a late Carboniferous (Variscan) strike-slip fault on an alignment of 280° exposed in 2022 along the southern wall of the quarry.

By contrast with the clay and rubble filled karst depression, **Figure** 2.20 illustrates the competency of the majority of the rock in Rathcore quarry, which is unbroken Waulsortian limestone. The photograph is of a buttress of massive limestone on the western side of the quarry.

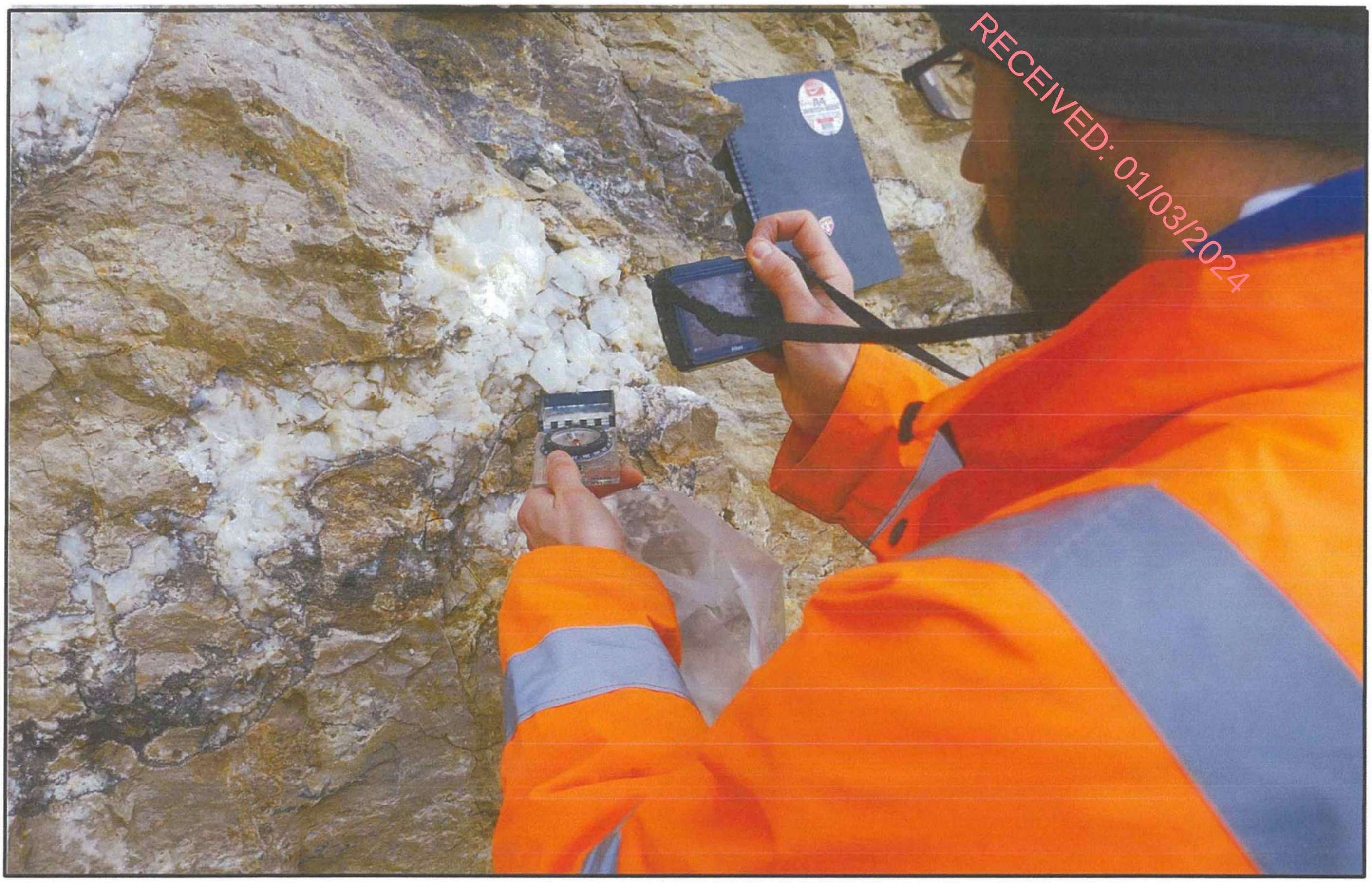
The photograph in **Figure** 2.21 shows a close up of a fresh exposure of typical Waulsortian limestone. This photograph was chosen because it also shows a pale brown dolomite alteration along a small fracture that also contains a calcite vein. Even though there is no open crack now, it can be identified as a past fracture by the inclusion of a fragment of darker limestone sealed in the calcite and dolomite.

Dolomitisation probably took place either shortly after the Waulsortian was lithified or a few tens of millions of years later, during the Variscan orogeny. Thermal fluids rich in magnesium made their way up narrow cracks in the limestone and altered the limestone minerals from predominantly calcium carbonate to calcium-magnesium carbonate. Though there are many zones of dolomitisation in the quarry, the change in limestone mineralogy does not alter the value, or potential uses of the rock excavated from the quarry.

The geological and structural geology site visits revealed small and large scale features. **Figure** 2.22 contains two photographs. The upper photograph is an opportunistic 'snap' over John

Figure 2.21 Fresh exposure of Waulsortian Limestone containing a zone of dolomitisation

Figure 2.22 Rathcore Quarry - geological and structural mapping of exposures



a) J.P.Moore recording the orientation of a calcite vein in pale brown dolomitised Limestone

b) East wall of the quarry: one of the few sites where bedding and curved cross-bedding can be seen in the, otherwise, massive Waulsortian limestone

Paul's shoulder as he steadies himself to photograph both his compass-clinometer and an outcrop showing a large sparry calcite vein in a matrix of dolomite.

The lower photograph shows the quarry wall in the south east in 2019 with a rare example of the curved cross-bedding associated with Waulsortian mud mounds. This section of the quarry has since been excavated.

The GSI bedrock maps have shown that the eastern side of the quarry should consist of Waulsortian limestone overlain by dark grey limestones and black shales of the younger Lucan Formation, but no evidence of the Lucan has been found. Instead it appears that the Waulsortian forming the core of Rathcore Hill drops away rapidly on the east, south and south west sides. The top of this core and the steep sides have been heavily dissolved. The rock is loose and irregularly shaped. There are many cavities in the rock.

Figure 2.23 is a photograph taken at the top of the east wall of the quarry. On the left is the top edge of the limestone the outer edge of which plunges steeply to the right under a rich brown clay that changes into a bright yellow-orange clay. The clay is very compact. In most cases, a hammer is needed to break it. The clay appears to extend at a gentle dip to the east and above it is a layer of very tough dark grey-brown glacial till or boulder clay, seen on the right in the photograph. The boulder clay appears to be a lodgement till compressed by the weight of the ice sheet under which it was laid. It contains numerous cobble size fragments of both Waulsortian and dark grey limestone. The boulder clay varies in thickness but appears to be a sub-horizontal layer. In the distance in the photograph, it is possible to see a thick layer of light brown sandy till that lies above the boulder clay. This sequence of orange clay followed by boulder clay then topped by sandy till is found on the flanks of the limestone core to the east and south forming the tail of the 'Crag and Tail' feature identified in the digital terrain model shown in Figure 2.1. The core of Waulsortian limestone dips away more steeply to the west but it appears to be still covered by clays, boulder clay and gravels.

The nature and imposing thickness of the dark boulder clay can be seen in the photograph in **Figure** 2.24. This photograph was taken looking east at the eastern side of a square cut at the northern end of the quarry. The quarry wall in the centre is a large karst depression or doline infilled with orange clay and rubble. John Paul Moore identified a Cenozoic northeast to southwest aligned strike slip fault at the foot of the quarry wall and a second Cenozoic fault forming the right hand side of the doline. The contrast between the orange clay in-fill and the overlying thick bed of black boulder clay can be seen clearly.

The orange clay on the outer edge of the Waulsortian core appeared initially to be a residual clay formed, in situ, by the prolonged solution weathering of the pure limestone. It appears that