Abstract

As the population of Ireland's capital increases a more advanced solution is required to treat its wastewater. The Wastewater Treatment Works (WwTWs) at Ringsend currently has the capacity to treat 1.6 million P.E. (population equivalent) but is required to enlarge operations to process 2.4 million P.E. to comply with E.U. guidelines. A long sea outfall tunnel, discharging treated wastewater into Dublin Bay at a distance sufficient to dilute it in compliance with the Water Framework Directive, was deemed the most appropriate solution for the upgrade due to space restrictions onsite. Ground-work investigations for this tunnel were undertaken on behalf of Dublin City Council and twenty-three offshore and two onshore boreholes have been drilled along two trajectories extending eastwards from the Ringsend site. This thesis aims to provide a comprehensive account of the subsurface geology of Dublin Bay. Detailed lithological logs, including important tectonic features, were produced for each of the twenty-five boreholes. Boreholes were largely dated using biostratigraphy with the exception of borehole M22 for which U-Pb detrital zircon analysis was undertaken. The lithological logs were digitized using Adobe Illustrator and from these a geological map and cross section of Dublin Bay were created. This thesis has proven that Carboniferous interbedded limestones, calcareous mudstones and calcarenites underlie the majority of the Dublin Bay area. It has also shown the presence of post-Early Cambrian meta-sedimentary rocks (the Bray Group) near the eastern edge of the study area underneath the Burford Bank and immediately to the west. Furthermore it has conclusively proven that the easternmost borehole (M23) is Early Jurassic in age thus constraining the position of the Dalkey Fault that bounds the Kish Bank Basin.

Acknowledgements

Firstly, I must thank Koen Verbruggen for his enthusiasm for my previous work on Dublin Bay and his suggestion to undertake this research project. The funding from the INFOMAR (through the Geological Survey of Ireland and the Marine Institute) is gratefully acknowledged. Secondly I wish to thank CDM for their assistance, especially Amy O'Connell and Deaglan Gibbons. Thanks are also due to the dedicated technicians of Trinity College who showed extreme patience with my endless requests. Francis Hendron has been invaluable to me over the course of this project as an aide and a friend. Mags Duncan has showed continued and unending support as always. My husband Risteard Sheridan has been my rock and has shown enthusiasm like no other. Thanks are also due to my long-suffering father who has unquestioningly helped, whenever asked, with anything. Lastly, to my supervisors Dr. David Chew and Prof. George Sevastopulo who have endured my alternative approach to research and who have guided me so warmly through my work I offer my biggest thank you of all.

Muireann McDonnell

1.1 Introduction

The growing population of Dublin has put considerable pressure on the waste-water treatment works (WwTWs) at Ringsend. The plant, which was completed in 2003, currently has the capacity to treat 1.7 million PE (population equivalent) to a tertiary level (ultraviolet disinfection). There are plans to expand the WwTWs to treat 2.4 million PE. Waste-water from the WwTWs discharges into Dublin Bay. However, the River Liffey Estuary is classified as a sensitive water body under the Water Framework Directive (WFD) and in conjunction with the Urban Wastewater Treatment Directive it has led to strict guidelines on the quality of wastewater being discharged into the estuary. To cope with the increased capacity and E.U. guidelines numerous treatment methods were considered (biological nutrient control, etc.). The WwTWs site is currently so restricted that the plant is unique in operating its single batch reactors over two storeys. Owing to this areal constraint 'a long sea outfall discharging beyond the sensitive waters' was deemed the most appropriate solution for Ringsend (Gaudes, CDM website). The pipe will be 5m in diameter and will extend approximately ten kilometres eastwards across the bay from the WwTWs at a depth of 50 – 60m beneath the seabed.

CDM Smith has been contracted by Dublin City Council (DCC) to manage the project. CDM Smith is an international engineering, construction and operations firm with several water-based projects throughout Ireland. For this project large-scale ground investigation works have been carried out to establish the most suitable trajectory for the tunnel across the bay. This included twenty-five boreholes along two alignments; a northern line running east-west and a second, southerly line running southeast-northwest. The majority of the boreholes drilled were offshore. All of the boreholes encountered bedrock with an average depth of 70 – 90m and a maximum depth of 106m below the seabed. The boreholes shall be discussed in stratigraphic order beginning with the oldest, the Lower Palaeozoic rocks to the east.

(Two drilling platforms in Dublin Bay, photo courtesy of David Ball April 2011)

1.1.1 Aims and Objectives

This thesis has several aims. These include:

1. to describe comprehensively the bedrock geology of Dublin Bay.
2. to log in detail all twenty-five boreholes.
3. to digitize all the field logs using Adobe Illustrator and to produce a summary log for each borehole.
4. to produce a geological map of Dublin Bay from the data gathered from the logging
5. to integrate the existing knowledge of the regional structural geology of the Dublin region with the data from this thesis to create a geological cross section for Dublin Bay.

1.2 Geological Framework of the Dublin Region

The bedrock geology of Dublin Bay is poorly known. To date geological investigations within the bay have been focussed on the recent soft sediment Quaternary geology with programmes like INFOMAR producing an abundance of new data.

The INFOMAR programme is the successor of the National Seabed Survey run by the GSI and the Marine Institute. Encompassing a diverse array of maritime projects the survey has gathered data on over 125,000km^2 of Ireland's inshore waters. With regard to Dublin Bay surveys have been carried out since 2003 focusing on the mouth of the bay from Dun Laoghaire eastwards including work on the Kish Bank Basin. However, surveys of the inner, shallow waters only begun in 2009. These surveys have elucidated the nature of the seabed topography and the soft sediments but yield no indication of the characteristics of the underlying bedrock. This synopsis on the bedrock geology of the Dublin Bay region is derived primarily from the onshore geology where outcrops, road cuts, quarries etc., have been extensively studied over the last century. A comprehensive description of the regional geology of the Dublin Bay region is given by Sevastopulo and Wyse-Jackson (2009)

Fugro have also constructed logs for each of the boreholes. These logs describe in detail the overburden with information on matrix type and clast grain size and the bioclastic and lithoclastic content. According to these logs the unconsolidated soft sediment usually reaches depths of approximately 25m grading through clays to sand and gravel at depth. The description of the bedrock is focused primarily on structural details such as fractures, styolites and veining. Bedrock is typically referred to as argillaceous limestone extending from the Quaternary/bedrock interface to the end of each hole with sparse additional information.

Below (Fig.1) is a map of the geology of the Dublin region. It comprises Lower Palaeozoic rocks (including the Bray Group), the Leinster Granite and several Carboniferous formations to the south. The central region is dominated by what is commonly referred to as 'Calp' limestone with two inliers of Lower Palaeozoic rocks at Balbriggan and Portraine. To the north again are more Lower Palaeozoic rocks. A small fault-bounded inlier of Bray Group is also found on the Howth peninsula along with Waulsortian limestone. Faults within the Dublin region trend northeast-southwest with the most notable faults being the Rathcoole Fault which bounds the Leinster granite and the Howth Fault which passes through Balscadden Bay on the Howth peninsula. The rocks encountered along the two lines of boreholes are mainly Carboniferous in age with only two Lower Palaeozoic boreholes and one Jurassic borehole at the eastern end of the northern transect. It is noted that the tunnel will only encounter Carboniferous rocks and shall not extend as far east as the Lower Palaeozoic holes. The bedrock geology shall be discussed below in stratigraphic order.

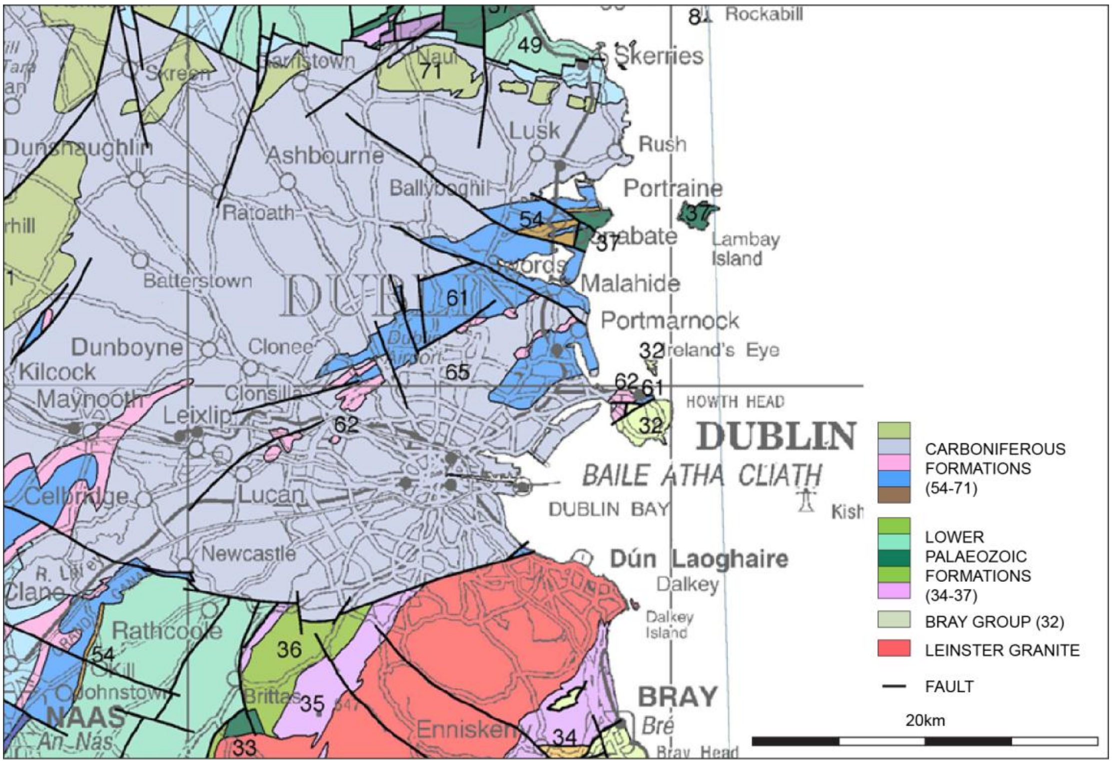

Figure 1. Geology of the Dublin region, showing the distribution of the Leinster Granite, the Lower Palaeozoic Bray Group, other Lower Palaeozoic formations and the Carboniferous (based on the 1:750,000 geological map of Ireland (1928) published on line by the Geological Survey of Ireland).

1.3 Bray Group

The Cambro-Ordovician Bray Group comprises a succession of interbedded grey, green, purple and red slates and greywacke siltstones and sandstones considered to be proximal turbidites (Holland, 2009) that are 'preserved at a low metamorphic grade, despite local structural complexity' (BGS, 1995). The section dips and youngs northwards and reaches maximum thicknesses of 4,500m. Thick pale-pink quartzites, up to 100m in places, are also present and often form topographical highs within the landscape (Bray head, the Sugar Loaf Mountains, etc.). Clear sedimentary structures like lamination, cross-bedding and grading typical of deep-sea fans are commonly found and several trace fossils (*Oldhamia, Arenicolites* and *Skolithos*) are also present in the succession. During the Late Silurian and Early Devonian, contemporaneously with the emplacement of the Leinster Granite, sinistral transcurrent faulting and north-westerly directed thrusting (Max et al., 1990) is believed to have deformed the Cambro-Ordovician rocks.

On Howth head the Bray Group is faulted against dolomitized Carboniferous carbonates (Waulsortian) with ferruginous staining along the fault line and with a well-developed fault breccia in Balscadden Bay. Trace fossils (*Oldhamia)* within these rocks suggest they formed in marginally shallower water than those of Bray Head.

1.4 Silurian Rocks of the Dublin Region

The distribution of Silurian rocks in the Dublin region is limited to the North County Dublin coastline on a section south of Balbriggan and at also Portrane. The basal Silurian rocks south of Balbriggan are Rhuddanian in age, dated by the presence of the graptolite *acuminatus*, and are faulted against Ordovician rocks. They consist of dark graptolitic mudstones (Rickards, Burns and Archer, 1973). On top of the basal sequence lie the rocks from the latter part of the Telychian stage which comprise largely greywackes. The Telychian cycle is overlain by rocks of Wenlock age, dominated by graptolitic mudstones with lesser greywackes. This section south of Balbriggan is comparable to the rocks of the Lake District in Northern England.

The rocks of Portrane are located between Dublin City and Balbriggan and are best exposed on the coastal section with few exposures inland. The sequence is composed of greywackes, siltstones and mudstones (Holland, 2009). These rocks can be seen in tectonic contact with the older Ordovician rocks at the northern end of the section. The Portrane rocks have been dated as Silurian based on lithological comparisons with the Balbriggan rocks as no diagnostic fossil assemblages are present.

1.5 Carboniferous Formations of the South Dublin Region

The Carboniferous is divided into the Mississippian and the Pennsylvanian sub-systems. Only the Mississippian sub-system is encountered in the Dublin Region and thus will be discussed below. Tournaisian rocks include the Malahide Formation. Rocks from the Viséan are more widespread and include the Waulsortian, Tober Colleen, Lucan and Clondalkin Formations.

Series	Stage	SUBSTAGE	FORMATION	THICKNESS (m)
MISSISSIPPIAN (PART)	SERPUKHOVIAN			
MISSISSIPPIAN (PART)	VISEAN	BRIGANTIAN	BELGARD FORMATION	300 +
MISSISSIPPIAN (PART)	VISEAN	ASBIAN	CLONDALKIN FORMATION	250 +
MISSISSIPPIAN (PART)	VISEAN	ASBIAN, HOLKERIAN, ARUNDIAN	LUCAN FORMATION	300 - 800
MISSISSIPPIAN (PART)	VISEAN	LOWER VISEAN	TOBER COLLEEN FORMATION	50 - 200 +
MISSISSIPPIAN (PART)	TOURNAISIAN		WAULSORTIAN LIMESTONE	0 - 200
MISSISSIPPIAN (PART)	TOURNAISIAN		MALAHIDE FORMATION	300 +

Figure 2. Stratigraphical age and total known thickness of the Carboniferous formations in south County Dublin. Those formations likely to be encountered in tunnelling along the line of the Northern Alignment are shown in red. Thicknesses are adapted from Nolan (1986, 1989).

1.5.1 Malahide Formation

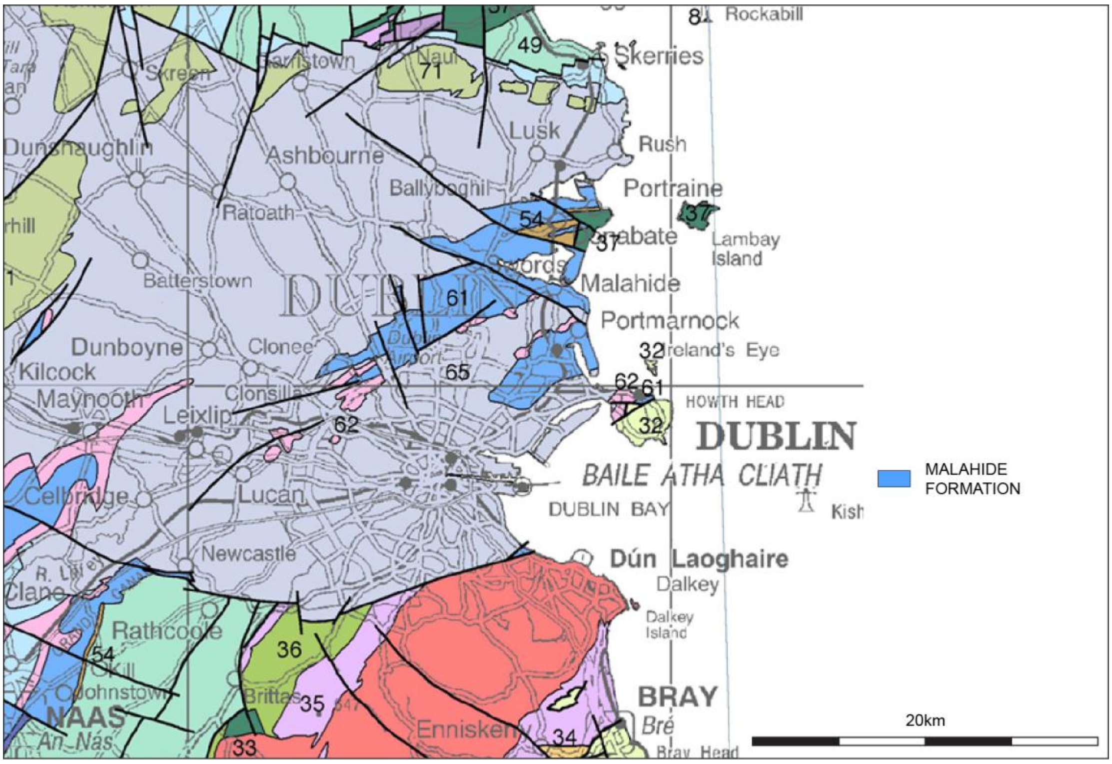

Figure 3. The distribution of the Malahide Formation subcropping beneath Quaternary deposits in the Dublin Region. Adapted from the 1: 750,000 Geological Map of Ireland (GSI, 1928).

The Malahide Formation encompasses the limestone and shale successions from the basal clastics seen at Donabate to the Waulsortian Limestones seen at Feltrim Quarry. They are best studied on the coastal section at Malahide, north County Dublin as the only outcrop in south County Dublin is now built on. The base of the formation begins with up to 40m of basal 'birds-eye' micrites and oncolites (Marchant, 1978) typical of tidal flat micrites and identical to those of the Longford-Down Massif. Above are interbedded argillaceous biomicrites, biomicrites and biosparites with thicknesses of over 150m. The top of the formation is dominated by calcareous muds and shales comparable to the Cover Shales at Feltrim Hill and the Tober Colleen Formation (formerly the Rush Slate Formation). Throughout, the section is considered variably bioturbated and also contains *syringopora* with colonies varying in size from a few centimetres to sixty centimetres. There are 'nodules' that characterize the Malahide Formation which are micritic and are thought to have formed by 'early diagenetic nucleation around the burrows' (Marchant, 1978).

Within the Malahide coastal section there are numerous faults along which dolomitization is prevalent. These faults also act as conduits for mineralising fluids that have led to sphalerite, galena and chalcopyrite being commonplace.

The Malahide Formation is late Courceyan (Upper Tournaisian) in age base on its conodont assemblages (Marchant, 1978).

1.5.2 Waulsortian Limestone

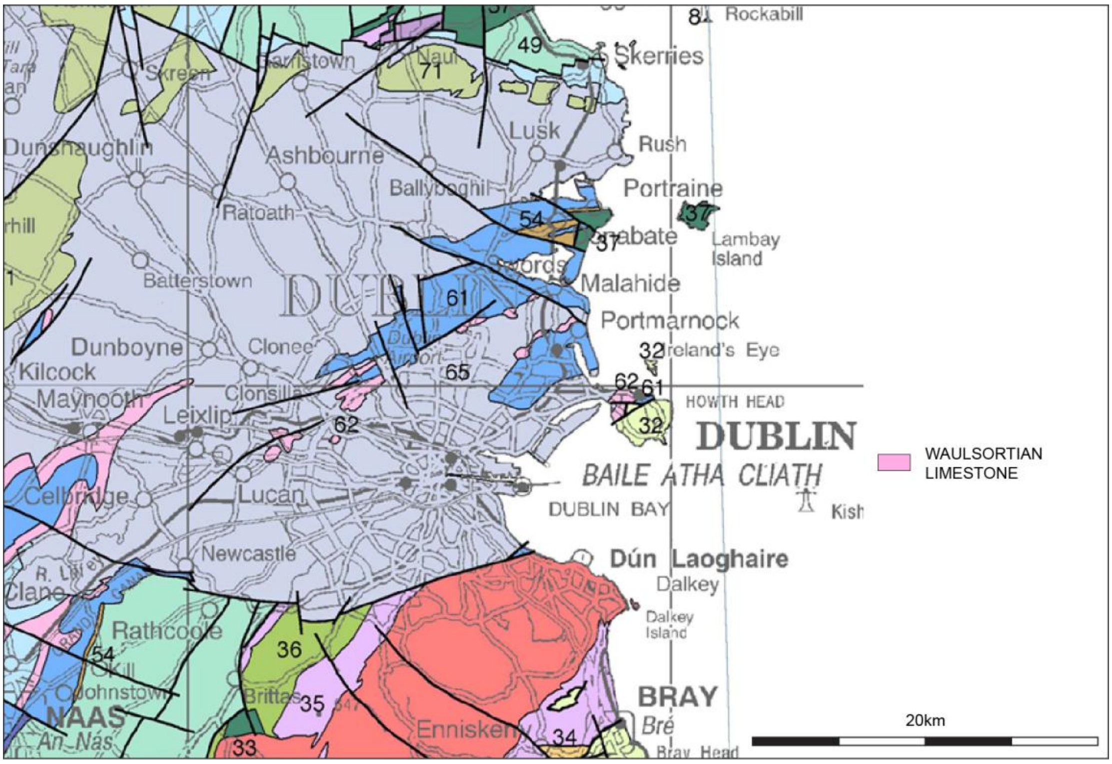

Figure 4. The distribution of the Waulsortian Limestone in the Dublin region. Adapted from the 1: 750,000 Geological Map of Ireland (GSI, 1928).

Waulsortian limestone is characterized by massive heterogeneous micrite with conspicuous sparry masses, stromatactis cavities and a fossil assemblage including bryozoans, corals and shells. The heterogenous micrite is thought to have formed from several generations of carbonate mud. Its locality for the Dublin Basin is Feltrim Hill Quarry in north County Dublin. There are no contemporaneous examples of such phenomena but they are believed to represent mounds on the seafloor composed of carbonate mud and skeletal grains. Within the Dublin Basin the Waulsortain limestone is referred to as the Feltrim Limestone Formation (Jones et. al., 1988). In north County Dublin the Waulsortian is discontinuous and varies greatly in thickness from 0 – 200m over short distances reflecting its mound-like nature. It may be seen in the geological map as a series of small isolated occurrences to the southwest of Portraine. It is susceptible to dolomitisation, most notably in proximity to faults (such as on the Howth peninsula). Karstification is also common due to pronounced jointing. Pyrite is abundant in the overlying Tober Colleen Formation and it may have contributed to karstification as pyrite when oxidized acidifies groundwater. However the Waulsortian Limestone itself does not typically contain pyrite.

Based on research by Hudson, Clarke and Sevastopulo (1966) the Waulsortian Limestone of the Dublin Basin has been assigned to the Upper Tournaisian.

1.5.3 Tober Colleen Formation

The Tober Colleen Formation represents a period of uninterrupted sedimentation and has its type section south of Rush on the north County Dublin coast. The formation is largely comprised of cleaved mudrocks of Late Ivorian age, usually with little carbonate, and rare boulder beds containing Tournaisian material. The mudrocks are slightly calcareous, becoming more so towards the top of the formation, and contain small micritic nodules and a number of allochthonous limestone blocks throughout the formation (Marchant, 1978). Theses limestone blocks vary in composition with Marchant (1978) describing one as a Waulsortian limestone and another as “a slumped conglomerate of limestone clasts”. Bioclasts are not common but include crinoids, bryozoan, solitary corals and ammonoids. Detrital siliciclastic grains may account for up to 15% with non-skeletal grains such as intraclasts and ooids making up to 17.5% (Kalvoda et al., 2011). The thickness of this formation ranges from 50 – 250m.

1.5.4 Lucan Formation

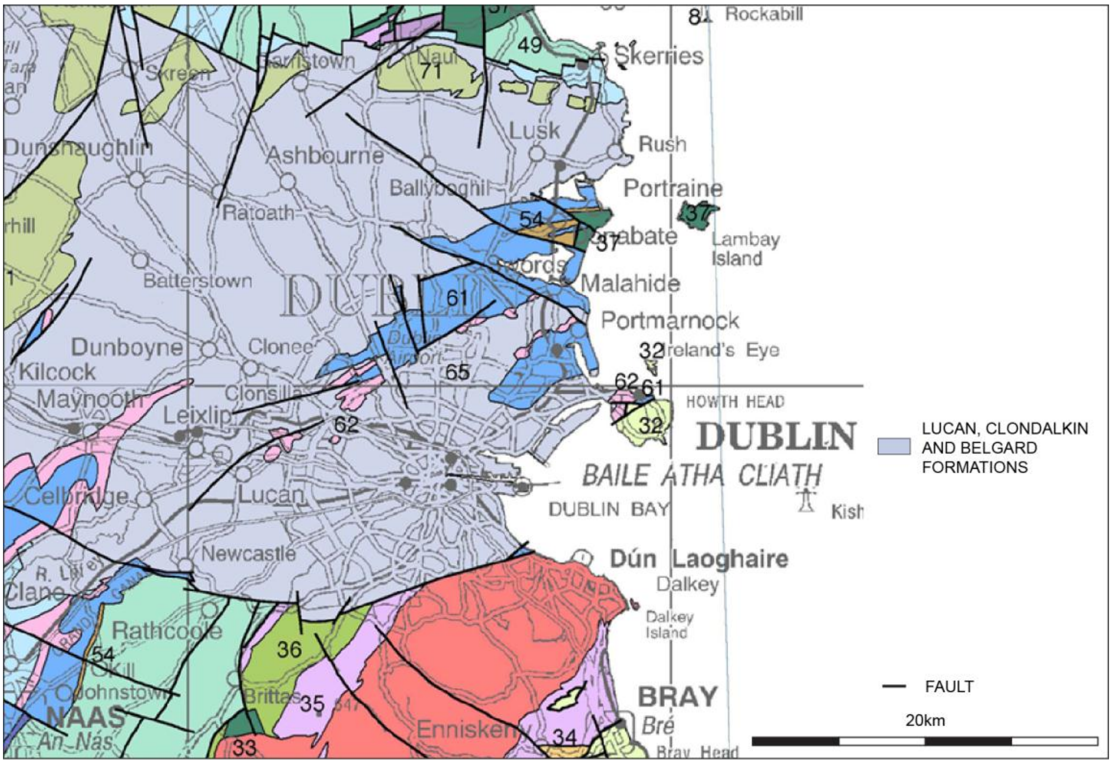

Figure 5. The distribution of the Lucan and younger formations in the Dublin region. Adapted from the 1: 750,000 Geological Map of Ireland (GSI, 1928).

The Lucan Formation is comprised deep marine mudstones and siltstones which represent distal turbidites. The main lithologies are dark argillaceous limestones, shales and calcareous mudstones with some skeletal units and common chert and pyrite. The shallow water material is thought to originate from the western margin of the Balbriggan Shelf. This formation is widely known as the Calp Limestone and is locally referred to as the Upper Dark Limestone and has long been a source of building materials and aggregate for Dublin. The thickness varies from 300 – 1123m. The formation consists of four megacycles (Sevastopulo and Wyse-Jackson, 2009) the lowest two being of Arundian age, followed by an Holkerian cycle and finally a cycle beginning in the Holkerian and terminating in the Asbian, Each cycle commences with beds containing coarse detrital material and passes upwards into a thick succession of basinal limestones and shale.

1.5.5 Clondalkin Formation

The Clondalkin Formation is up to 500m thick and is best exposed at a number of quarries known as the Clondalkkin Quarries in the Red Cow Townland. The formation comprises three main lithotypes

(Browne, 1965). The first lithotype is comprised of biomicrites (calcarenites) with crinoids, foraminifera and occasional corals and brachiopods. Quartz, muscovite and pyrite are found in small quantities as both detrital and authigenic grains. The second lithotype is a coarse, grain-supported biosparite (calcarenite) containing foraminifera, crinoids brachiopods and corals. The last lithotype is a micrite (calcisiltite) containing foraminifera interbedded with shales up to 0.15m thick. Bedding is regular within this formation with bed thicknesses largely unvarying and sharp contacts between consecutive beds. Dating of fossils has established that the Clondalking Formation is Asbian in age.

Chert is found throughout the Clondalkin Formation and may occur in up to 50% of beds in any particular outcrop (Browne, 1965). The chert typically occurs as bands, most notably in the less argillaceous, bioclastic layers. Slumped beds containing large lithoclasts of Leinster Granite and Lower Palaeozoic slate and greywacke characterize the middle and top of the formation and are associated with turbidity currents thought to have been triggered by movement of the Silurian-Carboniferous Rathcoole fault that bounds the formation to the west.

Replacement dolomitization is widespread through the Clondalkin Formation and is associated with a north-south trending fault which follows the Dublin – Naas road and the Rathcoole fault where the rocks are also locally mylonitized. There are also several locations noted by Browne (1965) where dolomitization had occurred without any obvious faulting.

1.6 The Kish Bank Basin

The Kish Bank Basin is a north-westward dipping half-graben (Jenner, 1981) thought to be located approximately 20km off the coast of County Dublin. It has three bounding faults; the Bray Fault to the south-west, the Dalkey Fault to the north-west and the Lambay Fault to the north-east. The Dalkey and Lambay Faults are bisected by the large dextral strike slip Codling Fault (trending northwest – southeast) with an offset of up to 9km. To the south the basin is bounded by the Mid-Irish Sea High which separates it from the Central Irish Sea Basin. The basin is elongated northeast – southwest with total dimensions of 32 x 48km (Naylor et al., 1993) and is generally thought to have formed part of a larger Permo-Triassic basin that dominated the majority of the northern Irish Sea region (Dunford, Dancer & Long, 2001).

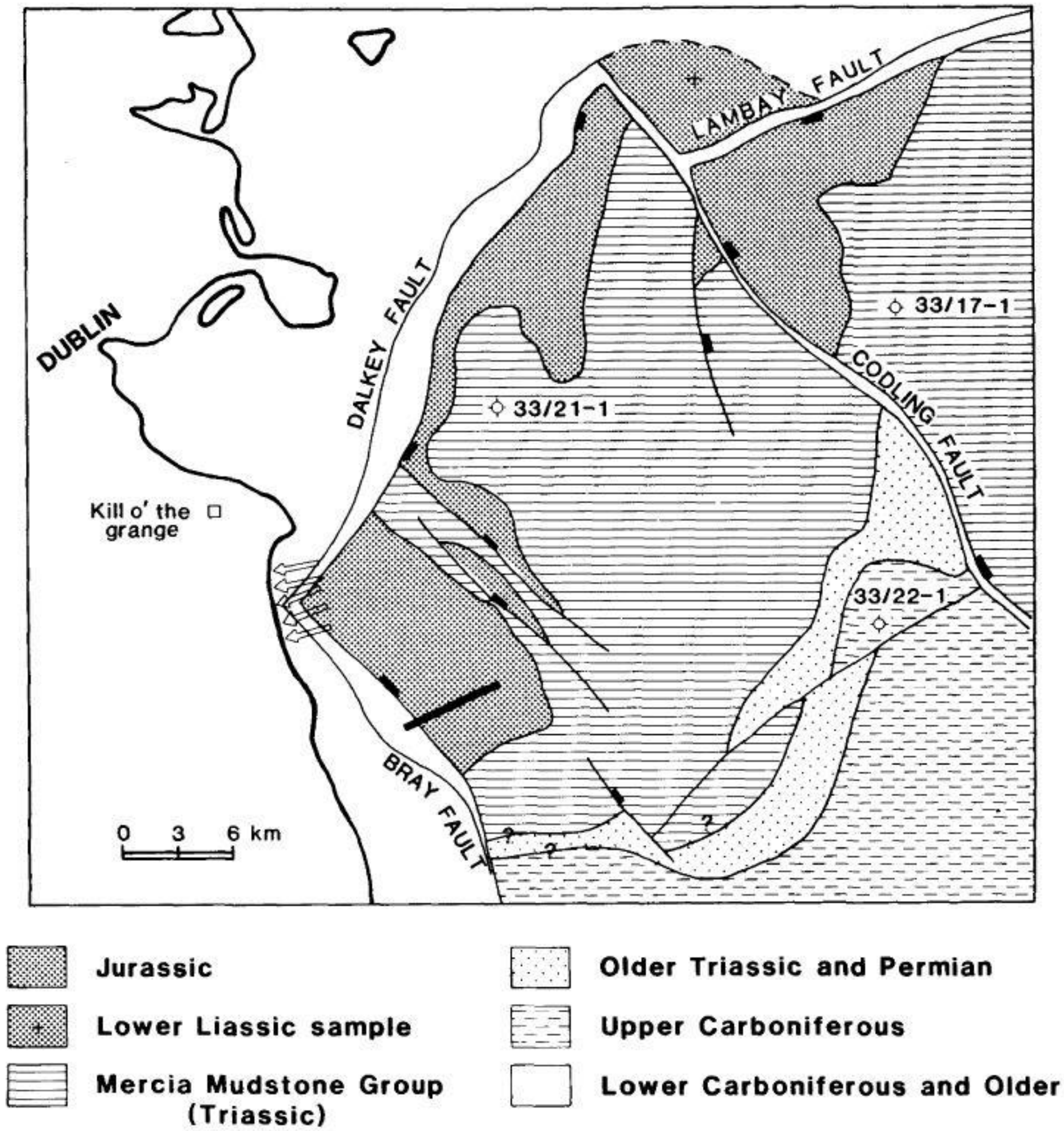

Fig. 6 Location and pre-Tertiary geology of the Kish Bank Basin with respect to Dublin Bay (Figure from Broughan, Naylor and Anstey, 1989). The cross to the north of the Lambay Fault shows the location of the grab sample taken by Dobson and Whittington, 1977.

There have been four wells drilled in the Kish Bank Basin (Amoco 33/22-1, Shell 33/21-1, Fina 33/17-1 and Enteprise 33/17-2A). The Amoco hole at the south-eastern boundary of the basin encountered a thick Carboniferous succession unconformably overlying Lower Palaeozoic rocks. The other three holes only encountered the Permo-Triassic basin fill (Naylor et al., 1993) without reaching its base but it is accepted that the basin fill is over 2000m thick and lies unconformably on the Carboniferous rocks beneath (Naylor and Shannoon, 2009). The general stratigraphy of the Kish Bank Basin consists of the Permian Collyhurst Sandstone; friable sandstones, overlain by an Upper Permian interval of interbedded calcareous claystones, siltstones and sandstones. Above this interval are over 2000m of Triassic sediments including the Triassic Sherwood Sandstone Group (up to 1035m recorded in the Fina 33/17-1 well) and the Triassic Mercia Mudstone Group which comprises marls containing thick halite units. The Mercia Sandstone thickness ranges from 535.2m (Fina 33/17-1 well) to up to 1122m (in the Shell 33/21-1 well), this in conjunction with halite units being more prevalent in the wells west of the Codling Fault suggests that the basin was deeper in the west and was fault controlled (Naylor and Shannon, 2011).

Our knowledge of the structure and stratigraphy of the basin has relied mainly upon seismic data. Etu-Efeotor (1976) was the first to suggest the presence of Jurassic sediments in the basin. Using geophysical information and limited rock sampling surveys he concluded that within the thick Permo-Triassic sediments lay “a thin Jurassic sequence”. In 1977 a grab sample taken on the upthrown side of the northern Lambay Fault (53º18’N 05º45’W) proved to be Lower Liassic dark carbonate mudstone and finely crystalline limestone (Dobson and Whittington, 1977) containing an Early Jurassic microfauna. Using seismic mapping techniques Broughan et al. (1989) inferred the presence of 2,700m of Jurassic sediment against the Dalkey/ Lambay Faults. Dunford et al. (2001) suggested that this Jurassic sediment may have been deposited within an adjacent sag basin when the faults described the above were not bounding faults of the Kish Bank Basin. Broughan et al. (2001) also discuss the presence of fossils in boulder clay at Kill o’ the Grange (originally decribed by Lamplugh et al., 1903) as being Liassic in age and most likely derived from the Liassic of the Kish Bank area. No Jurassic rock has been discovered in exploration wells of the Kish Bank Basin (Naylor and Shannon, 2011) and there is no evidence of pre-Tertiary strata that is younger than the late Liassic.

1.6.1 Jurassic Rocks

The Jurassic is divided into the Lower and Middle-Upper Jurassic by the Cimmerian event (Naylor and Shannon, 2009) which marks the beginning of a phase of extensional tectonism in the earliest Middle Jurassic as Gondwana separated from Laurasia.

The Jurassic rocks of the British Isles and Ireland were typically deposited under marine conditions with occasional input from shelf carbonate sequences (Broughan, Naylor and Anstey, 1989) and are represented as interbedded calcareous mudstones, calcisilts and limestones with common bivalves and ammonites (BGS, 1995). They lie conformably on the Triassic sediments beneath. In Ireland the only onshore outcrops of Liassic rocks are confined to Northern Ireland along the County Antrim Coast and comprise only the Lower Liassic with no Middle or Upper Liassic rocks recorded. This may reflect a hiatus in deposition or their erosion during a mid-Cretaceous interval before the deposition of the Upper Cretaceous. It is believed that a more complete Jurassic succession existed in Northern Ireland but again due to the mid-Cretaceous erosion it has been subsequently removed. Evidence for this is given by Wilson and Manning (1978) who noted 'derived blocks of shale containing Middle Liassic fossils have been found near Ballintoy and Murlough Bay'. All of the Liassic rock of Northern Ireland is assigned to one group; the Waterloo Mudstone Formation with a type location at Waterloo Bay near Larne. The Liassic succession in Northern Ireland is markedly thicker at other sites across the British Isles; For example the thickness of the *planorbis* biozone at Waterloo Bay is up to double the thickness of the same strata in Somerset.

Much of our knowledge of the Jurassic stratigraphy in the Irish Sea region has been obtained from the Mochras borehole at the northern end of Cardigan Bay, Wales. This borehole was drilled through 1305m of thinly interbedded light and dark grey calcareous mudstones with more massive siltstones and towards the base of with a sequence of bioturbated limestones towards the base (Naylor and Shannon, 2011). The rocks have been dated as Lower Liassic (Hettangian to Upper Toarcian). Seismic studies of the same area suggest up to 1800m of Lias Group rocks are present (BGS, 1995) and the total thickness of Jurassic rocks in the Cardigan Basin is estimated at up to 3800m (Broughan, Naylor and Anstey, 1989)

In the St. George's Channel Basin, off the southwest coast of Britain, Lower Liassic shales and Upper Liassic limestone rock samples have been collected from the seabed with three gravity cores confirming the presence of Lias rocks in the basin. The Lower Liassic shales have been dated as Lower Pleinsbachian and are described as laminated with calcareous and carbonaceous material and are comparable to shales found in the Kish Bank Basin and those in the Mochras borehole. The

Upper Liassic limestones were dated as Upper Toarcian and comprise crinoidal packstones with rare shell fragments and scattered echinoid and bryozoan material (Broughan, Naylor and Anstey, 1989).

1.7 Tectonic Structure of the Dublin Region

The Lower Palaeozoic rocks of the Dublin Region were deformed during the Caledonian Orogeny (Nolan, 1989) and were subsequently intruded by the Leinster Granite (405±2Ma). The areas intruded by the granite formed positive blocks during the Dinantian, such as the Balbriggan block north of the Dublin region and the Leinster Massif to the south. The central area subsided more rapidly leading to the development of the Dublin Basin.

Evidence for syn-sedimentary tectonics during the Carboniferous is discussed by Nolan (1989) who notes the presence of ‘angular unconformities and overlap relationships’. He also notes the presence of boulder beds in the North Dublin region. The boulders are believed to represent reworked Carboniferous and pre-Carboniferous basement rocks that were derived from within the Dublin Basin as a result of local tectonics. Nolan (1989) also describes the main phases of syn-sedimentary tectonics that developed the Dublin Basin during the Dinantian and early Namurian. These include a Chadian period of faulting and associated tilting of fault blocks in the south of the basin and a second, renewed period of faulting and associated tilting of the fault blocks in the south/southwest of the basin during the Asbian (Nolan, 1989).

The next major tectonic event to affect the Dublin region was the Variscan Orogeny caused by the closure of the Rheic Ocean to the south. Although this orogeny began in the Devonian its effects were not felt in Ireland until the Middle to Upper Carboniferous (Landes et al., 2005) with the intensity of the deformation decreasing northwards from the source (Graham, 2009).

In the Dublin region the maximum shortening direction was northwest-southeast with estimates of up to 10% regionally and up to 30% locally (eg. Loughshinny). Variscan faults trend northeast-southwest, perpendicular to the regional shortening direction (Corfield, 1996). Faults within the basement rocks underlying the basin were reactivated to accommodate the deformation (Graham, 2009). LeGall (1991) suggests that it is this reactivation of tectonic structures within the basement rocks that has influenced the Variscan structures of the Dublin Basin. Fold development is controlled mainly by lithology, with fold axes trending east-northeast to northeast within the Dublin Basin, with the majority of the axial planes dipping steeply south. The most notable example of folding may be seen at Loughshinny in North County Dublin where *en echelon* chevron folds are clearly visible.

Fig. 7 Coastal section at Loughshinny, Co. Dublin showing chevron folds of Brigantian age (photo by David Chew)

1.8 Depth to rock head

Information on the topography of rockhead (depth to bedrock) is poorly constrained outside of the main River Liffey channel. The most comprehensive study of depth to rockhead is by Naylor (1965) shown in Fig 8 below. Naylor's study collates pre-existing records including information gained from past coring programs to produce a contoured map of the near shore area at Ringsend. The figure illustrates a deep channel at the mouth of the River Liffey in line with the drilling lines.

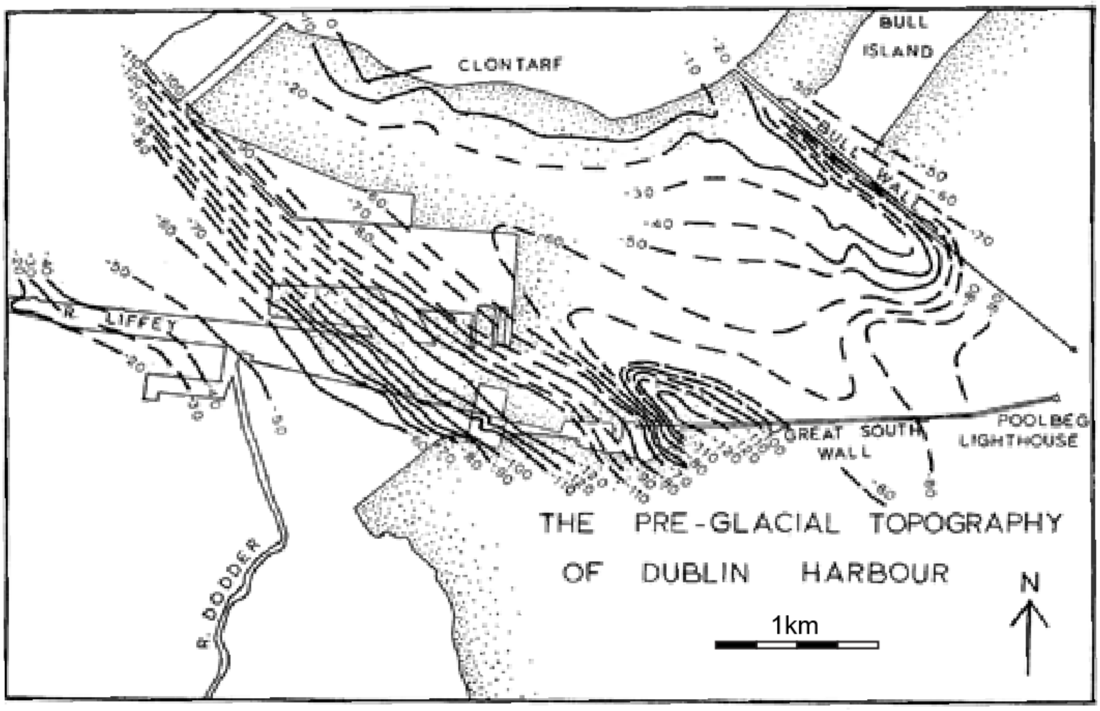

Figure 8. Depth to rock head in the Dublin Port area (adapted from Naylor 1965). Contours in feet below Dublin Port Datum, which is 0.436m below OD.

1.9 Materials and Methods

It should be noted that significant quantities of core from some core boxes had already been removed for geotechnical analysis prior to undertaking the logging in this project. This has led to large gaps in the logs and, in some cases, minor complications in establishing the exact depths of units.

The lengths of the logged intervals were measured using a steel measuring tape with graduations in millimetres. Total depths of the logged intervals were calculated using these measurements in conjunction with the depth information written on the core boxes.

Rock head was easily identified in a number of boreholes with soft sediment and/or pebbles and cobbles lying directly on coherent bedrock. In some boreholes rockhead was harder to identify due to the presence of large blocks close to the bedrock – sediment interface. It was hence uncertain if these blocks represented overburden or disrupted bedrock. Rockhead in these instances was determined by measuring whether the orientations of the strata, veins and fractures of the blocks were consistent with unequivocal bedrock at depth. For a small number of boreholes, samples had been previously removed at the probable depth of rockhead and in such instances rockhead is taken as the value recorded by the drillers. In all cases rockhead is assumed to be accurate to 0.5m..

Rock type was identified by colour, grain size, composition and whether samples effervesced with 10% hydrochloric acid (HCl). A number of thin sections have been made and examined confirming the lithotypes of some units but no detailed petrographical study has been carried out to date.

Pyrite was identified in hand sample using a hand lens but the abundances discussed do not account for the microscopic, framboidal pyrite content.

Chert and silicification were identified based on examination by hand lens, hardness, the ease with which it was or was not scratched by a steel blade and the lack of effervescence with (10%) HCl.

Dolomite was identified using a hands lens and a lack of effervescence with 10% HCl.

Dips for bedding, fractures and veins were recorded relative to core normal using a clinometer. Bedding dips are predominantly very low angle and this combined with a curved core surface made exact measurements difficult.

Alteration within these logs refers to deep weathering including both colour alteration and weakening of the rock. It does not refer to dolomitisation or tectonism.

Part II. Geology of the Boreholes of the Northern Alignment Drilling Line

2.1 Summary information from the Boreholes of the Northern Alignment

2.1.1 Location of Boreholes

The northern alignment comprises sixteen boreholes; two onshore, three in the intertidal zone and the remaining eleven offshore. The location of each borehole is marked below on Fig. 9. The boreholes shall be discussed in stratigraphic order beginning with the oldest, the Lower Palaeozoic rocks in the east of the bay.

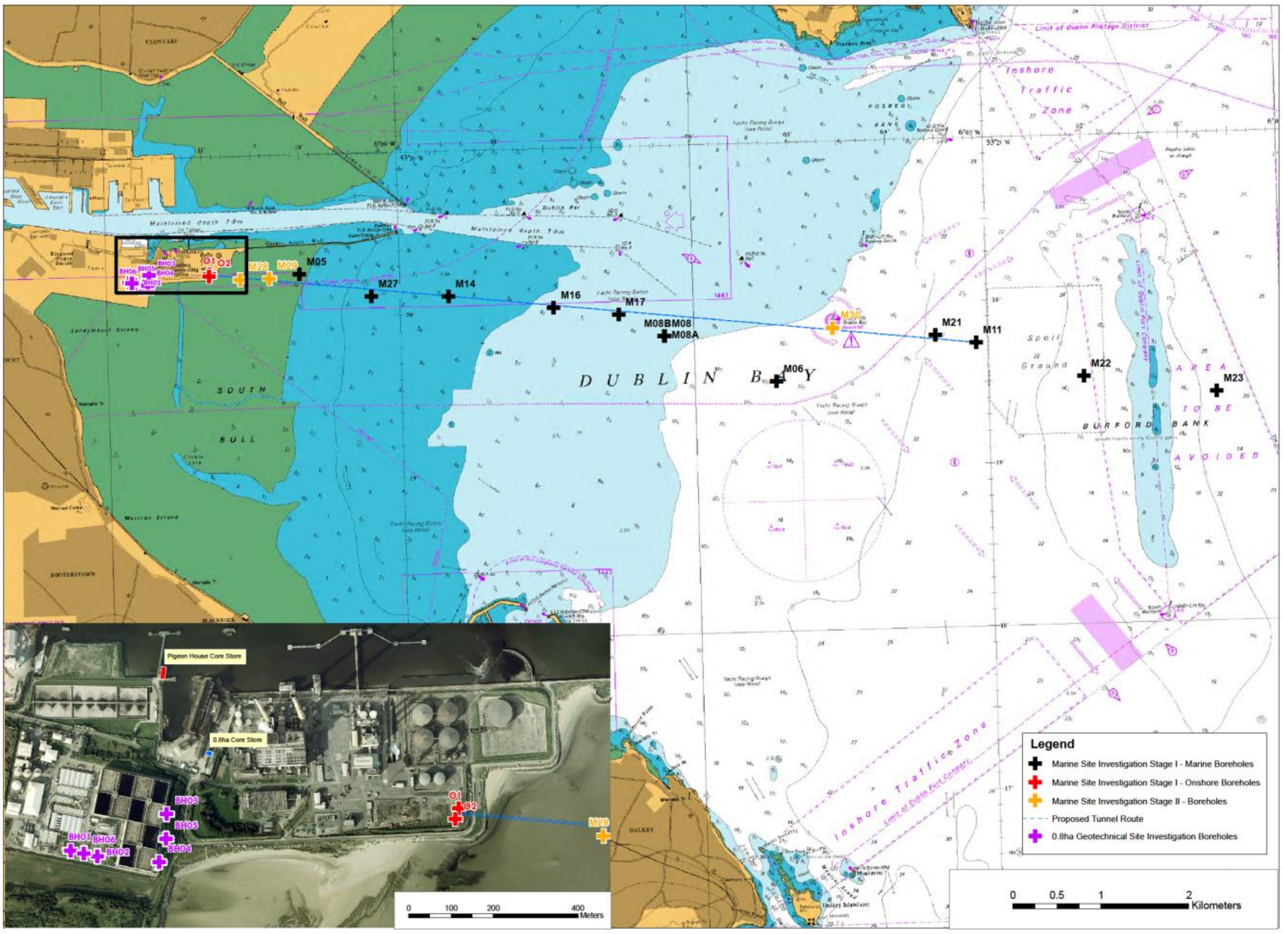

Figure 9. Location of the boreholes relevant to the Northern Alignment (modified from a map supplied by CDM Smith).

2.1.2 Key to Symbols Used in the Summary Logs

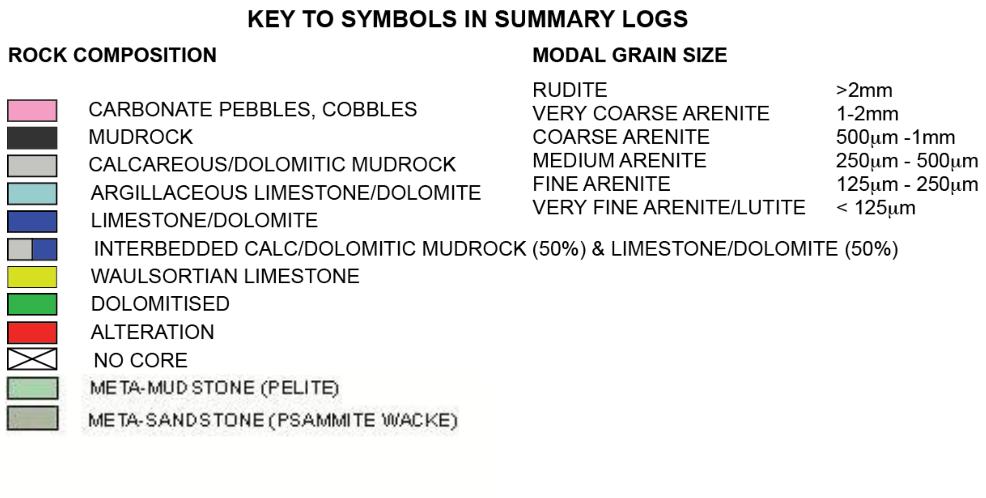

Figure 10. Key to symbols used in summary logs

2.2 Summary Logs

2.2.1 Borehole M22

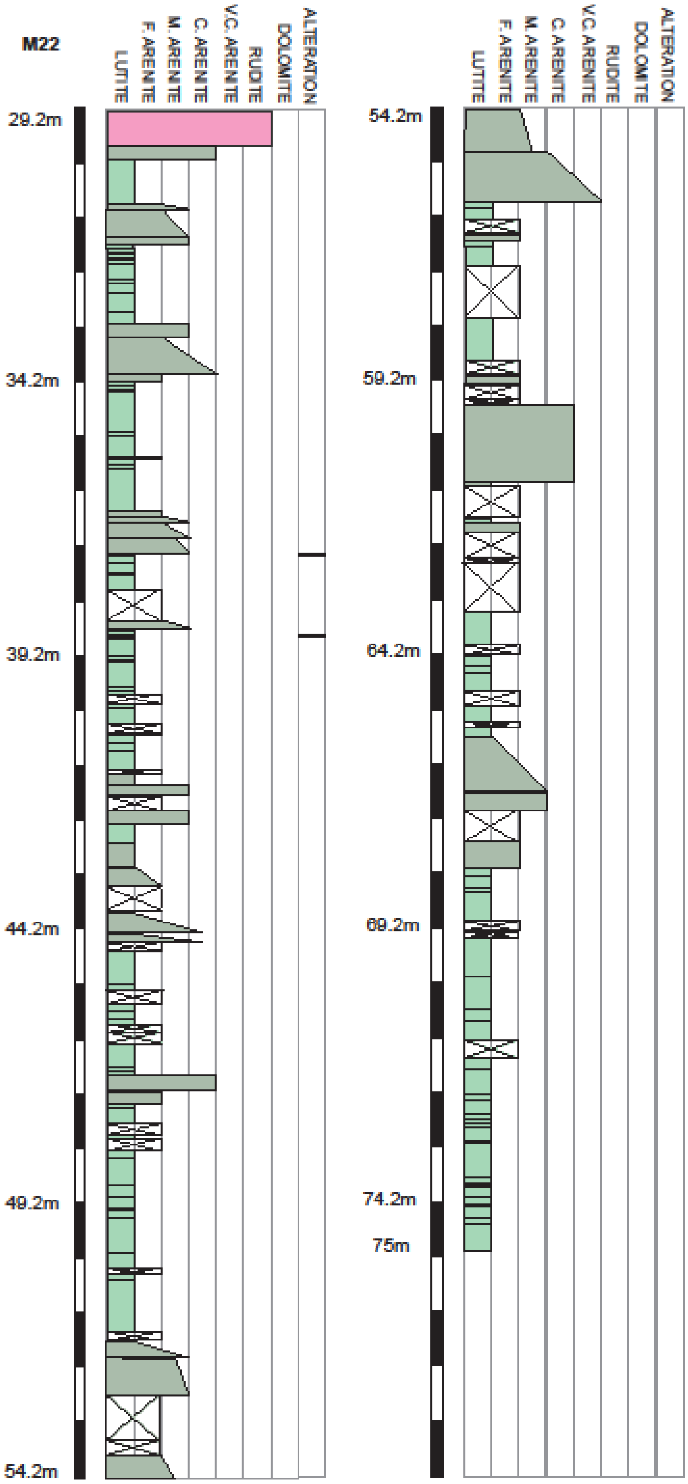

Fig. 11 Summary log of M22

Borehole M22 is located approximately 500m west of the Burford Bank and 1500m east-southeast of borehole M11 (Fig 9). The lithologies of M22 and M11 are entirely different with markedly different inferred ages (Lower Palaeozoic versus Tournaisian) and thus a fault has been inferred to lie between them. The summary log is illustrated above in Fig. 11 with the detailed log given in Appendix 1.

2.2.1.1 Formation

Using zircon dating (section 4.2.4) the rocks of M22 have been assigned to the Lower Palaeozoic Bray Group (see section 1.3).

2.2.1.2 Rock Head

Rockhead has been recorded at 29.85m. The top unit is comprised of angular rubble of coarse meta-sandstone (psammitic wacke) with a plastic mud coating above which lies the overburden of clay and pebbles.

2.2.1.3 Lithological succession

The lithological succession is largely uniform throughout. It comprises predominantly meta-mudstone (pelite) beds, with frequent mudstone wisps, interbedded with meta-sandstones (psammitic wacke). The majority of the meta-sandstone beds are graded.

2.2.1.4 Chert

Chert was not identified in this borehole

2.2.1.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

Pyrite is only present in trace quantities with rare exceptions. At 68.14m a meta-mudstone bed is recorded with pyrite nodules $<1cm^2$. Chlorite however is commonly found throughout the length of borehole M22, most notably on fracture surfaces. The crystals appear striated (possibly due to slip on the fractures) and are very dark green.

2.2.1.6 Dolomite

Dolomite was not identified in this borehole.

2.2.1.7 Structural features: tectonic dip

The tectonic dip within the M22 borehole ranges from a minimum of 10° to a maximum of 70°. The average dip for the rocks of this borehole is 40°. Steep dips are visible in the photo beneath (photo 1).

2.2.1.8 Structural features: veins

Veins are uncommon in M22. They are all composed of quartz with the majority appearing 'rusted'. The dip of the veins varies from 0° to 30°.

2.2.1.9 Structural features: fractures

Borehole M22 is highly fractured throughout. The dips of these fractures range from 40° to 70° with no dominant dip. The bulk of the fractures have chlorite present and a large proportion have highly polished surfaces, and likely represent slip surfaces. Films of pale green (2.5Y/7/4) clay are also common on the fracture surfaces.

2.2.1.10 Alteration

M22 shows no major alteration. There is minor colour alteration from the characteristic pale greens (such as GL1 5/1/5G) of the borehole to pale purple on some surfaces but its cause is uncertain.

Photo 1. Core box containing a section of borehole M22.

2.2.2 Zircon Dating

Detrital zircon dating was undertaken on a psammitic wacke sample from the M22 borehole. The sample preparation techniques, analytical method and techniques and results are given in section 4.2.4 and are very briefly summarized here. Detrital zircons separated from the M22 borehole yield U-Pb detrital zircon spectra characteristic of an Avalonian provenance with prominent peaks at 550 - 630 Ma and minor peaks at 1200 Ma, 1500 - 2200 Ma and 2500 - 2900 Ma (Fig. 47). Several concordant zircons cluster at c. 520 - 530 Ma, while the youngest detrital zircon is a solitary concordant analysis at 490 Ma (Fig, 48).

2.2.2 Borehole M11

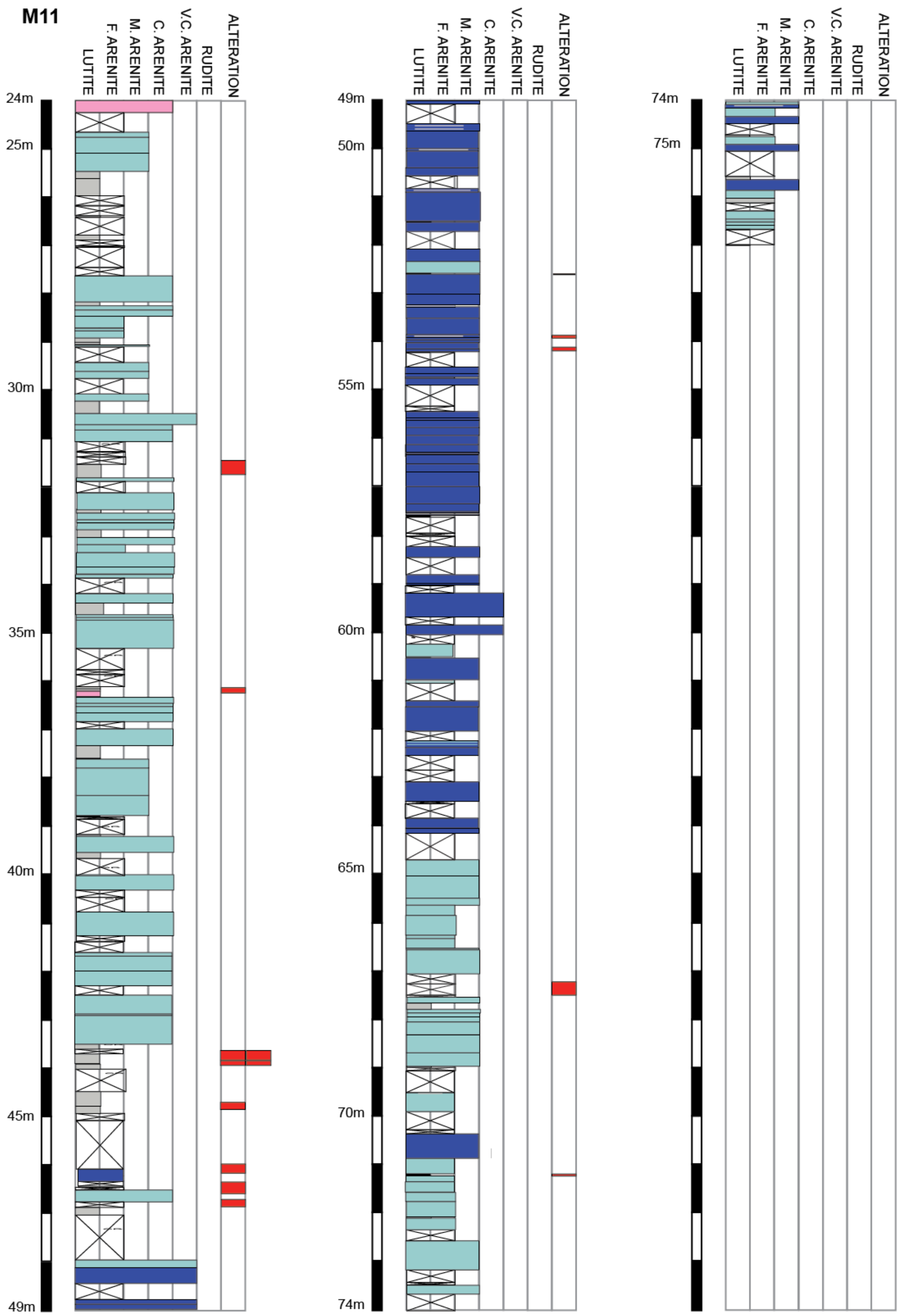

Fig 12 Summary log of M11

Borehole M11 is located approximately 1500m west-northwest of M22 and 500m east-southeast of M21 (Fig 9). The summary log of M11 is illustrated above in Fig 12 and the detailed log is given in Appendix 1. As discussed previously a fault is believed to lie between M22 and M11 while the contact between M11 and M21 is believed to be stratigraphic.

2.2.2.1 Formation

Using biostratigraphy (section 4.3) and lithostratigraphic correlation the borehole M11 has been assigned to the Malahide Formation of Tournaisian age (see section 1.5.1 of this thesis).

2.2.2.2 Rock Head

Rockhead was not precisely determined in the borehole M11. A geotechnical sample was taken from 24.64 – 25.00m prior to this phase of logging and is assumed to have contained rockhead. Above this stratigraphic level lies overburden of brecciated limestone cobbles and pebbles in a clay matrix. This overburden is believed to be Quaternary in age.

2.2.2.3 Lithological succession

The uppermost section of the borehole M11, from 25.00 – 49.00m, is overwhelmingly dominated by coarse calcarenites (90%). These calcarenites are largely (90%) argillaceous. Interbedded with the argillaceous calcarenites are minor calcareous mudstones (10%). Below 49.00m to the end of the hole the lithology consists entirely of calcarenites (50% argillaceous). They are largely medium grained (70%) and are interbedded with minor fine grained calcarenites (30%).

2.2.2.4 Chert

Chert is only found in small quantities in the basal 20m of the borehole M11. It is seen as bands <40mm thick (at 61.92m and 57.60m) and as granular chert < 20mm (at 60.46m). Minor silicification of bioclasts is also seen.

2.2.2.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

Pyrite is common and moderately abundant throughout the M11 borehole. It occurs most notably in the calcareous mudstones but is also found in the calcarenites and within the calcite veins. Oxidised pyrite is also present in association with gypsum. A particularly gypsiferous section is seen from 69.45 – 69.85m.

2.2.2.6 Dolomite

No dolomite was identified in this borehole.

2.2.2.7 Structural features: tectonic dip

The tectonic dip of M11 ranges from 0° to 5° although occasionally dips of 20° are encountered. The general dip for this borehole is taken to be less than 5°.

2.2.2.8 Structural features: veins

There are two main vein sets in M11; approximately 70° and bed parallel. Throughout the borehole veins are thin, mostly <1mm with very occasional veins >10mm. They are all composed of calcite with occasional pyrite.

2.2.2.9 Structural features: fractures

As with the veins there are two main orientations of fractures; 70° - vertical and bed parallel. Bed-parallel fractures are closely spaced whereas the steep fractures are widely spaced and with clay films.

Stylolites are prevalent throughout the core length. The preferred orientation is horizontal but many stylolites are steeply inclined representing horizontal shortening.

2.2.2.10 Alteration

Alteration in M11 is minor and sporadic. Alteration is seen mainly in the leaching of the calcareous mudstones leaving them weak and friable in some instances leading to the formation of muds which are plastic in appearance.

At 36.40m a possible cavity was noted. A unit of 0.2m length is recorded as consisting of pebbles of limestone with patina.

2.2.3 Borehole M21

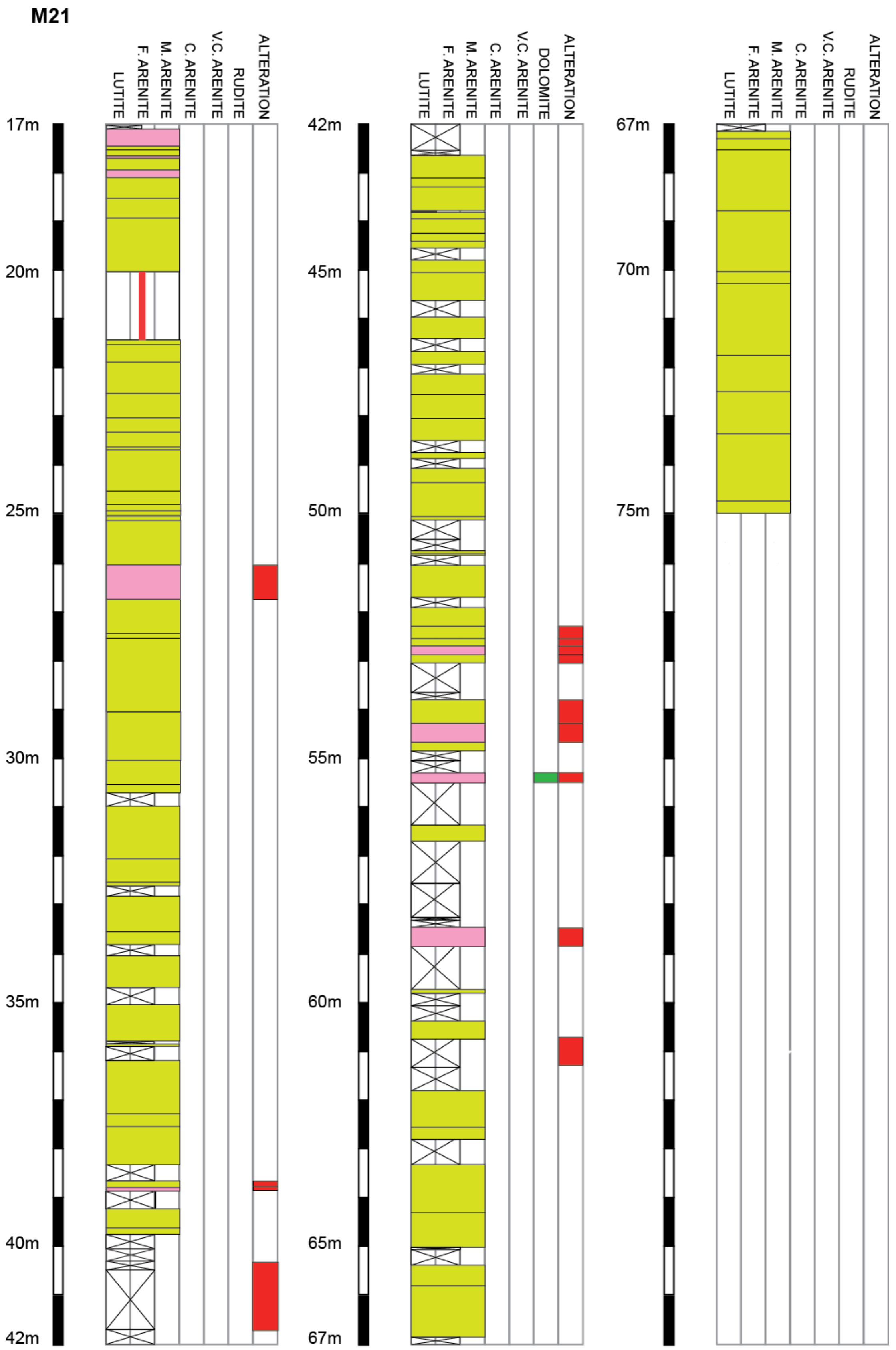

Fig 13 Summary log of M21

Borehole M21 lies 500m east-northeast of M11 and approximately 1100m east of M30 (Fig. 9). The summary log of M21 is illustrated above in Fig 13 and the detailed log is given in Appendix 1. As discussed above the contact between M21 and M11 is stratigraphic and a similar stratigraphic contact is inferred to exist between M21 and M30.

2.2.3.1 Formation

Borehole M21 is assigned to the Waulsortian Limestone Formation (see part 1.5.2)

2.2.3.2 Rock Head

Rockhead is taken to be at 17.00m, the top of the highest limestone unit, as the drillers have recorded a zone of core loss (AZCL) from 17.00-17.10m. No rock is present in the core box above the indicated AZCL.

2.2.3.3 Lithological succession

Borehole M21 is comprised entirely of the distinctive Waulsortian Limestone. It is comprised of calcilutite throughout containing characteristic stromatactis cavities and fossil assemblages. The Waulsortian Limestone Formation is discussed in detail in section 1.5.2 of this thesis. Due to the poor condition of the core surface, little in depth facies analysis was possible. Where the core surface was smoother geopetal fills were observed. In one case, in boxes 31 and 32, the geopetal fills suggest that the core oddly youngs downward. This would mean that M21 was upside down. This is extremely unlikely and human error must be assumed as at other levels in the borehole geopetal structures show the section younging upwards as would be expected.

2.2.3.4 Chert

Chert was not identified in this borehole.

2.2.3.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

Pyrite was not identified in this borehole.

2.2.3.6 Dolomite

Only one minor horizon of dolomitisation was recorded at 56.25m.

2.2.3.7 Structural features: tectonic dip

Due to the mound-like nature of Waulsortian Limestones depositional and tectonic dips are both present. To establish tectonic dips geopetal structures must be recorded. Within M21, based on geopetal fills, the tectonic dip is approximately 0°.

2.2.3.8 Structural features: veins

Veins are widespread throughout M21. Their dips range from 0° to 80° with a large number of anastomosing veins. Thicknesses vary from <1mm up to 30mm. The borehole seems to have multiple phases of veining with rust coloured veins cross-cutting white veins of calcite. There also appears to be minor occurrences of dolomite within some veins (box 18). Veining may be seen in the photos below (photo 2 and 2a).

2.2.3.9 Structural features: fractures

Fractures are common throughout M21 with the dominant set ranging in dip from 70° to sub-vertical and a secondary set dipping at 45° . Clay films and infills are prevalent. Substantial quantities of quartz sand was recorded along fractures found between 21.90 and 22.50m and at 58.45m, suggesting that at some stage there was a connection with the surface. The fracture at 58.45m passes downwards into a significant amount of quartz sand and this is interpreted to represent an infilled cavity.

Stylolites are abundant along the length of M21 with up to fifteen recorded within 1.5m of core. Their dips range from 0° – 45° with 30° being the dominant dip.

2.2.3.10 Alteration

Alteration occurs at several discrete levels within the M11 borehole. Alteration is manifested mainly as colour changes but between 54.25 – 54.60m there is a section of brecciated limestone within a clay matrix.

Photo 2. Core box containing a section of borehole M23.

Photo 2b. Core box containing a section of borehole M23.

2.2.4 Borehole M30

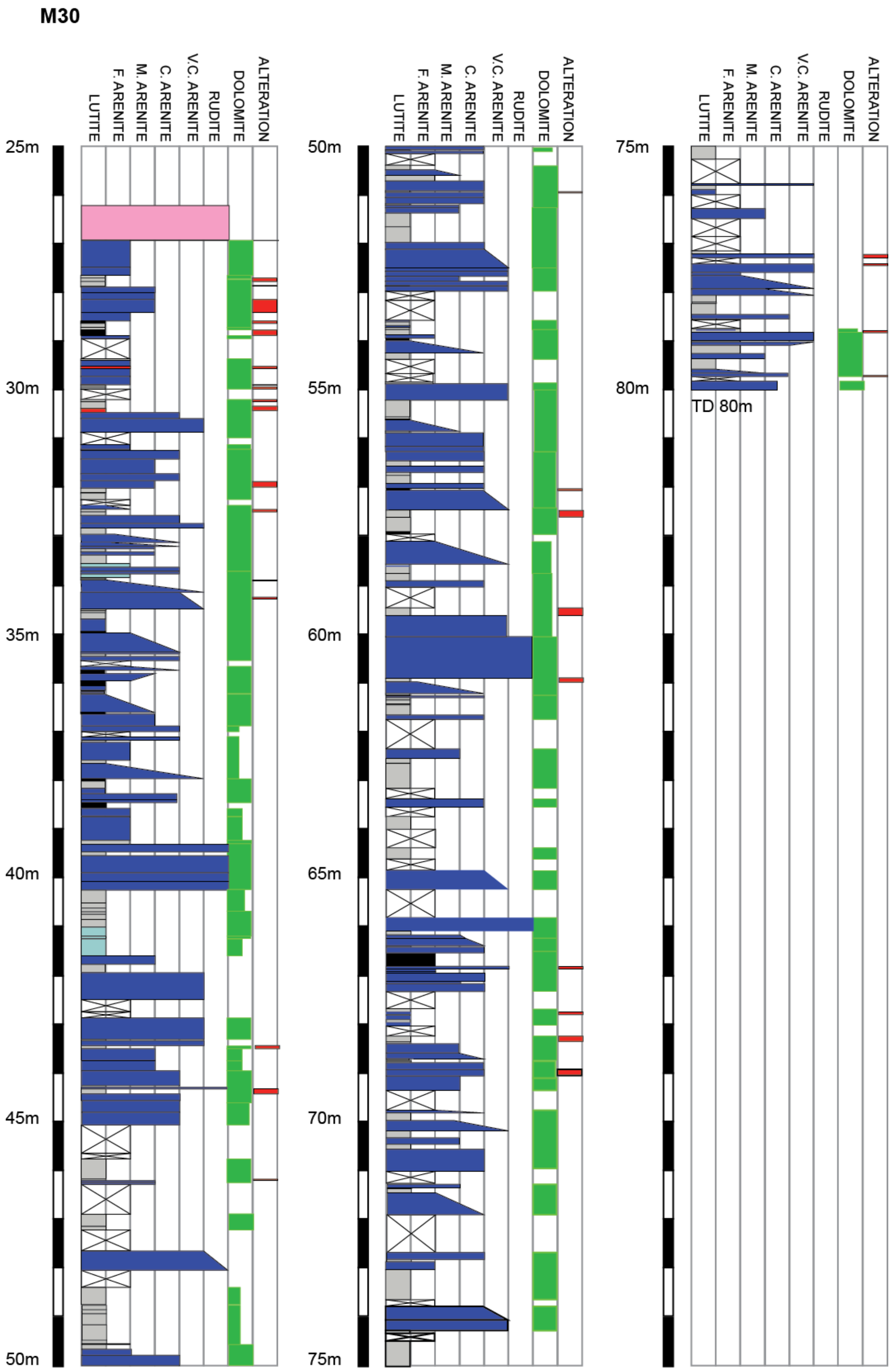

Fig 14 Summary log of M30

Borehole M30 lies 1100m west of M21, approximately 1800m east of M08 (A&B) and just less than 1000m northeast of M06 (Fig 9). The summary log for M30 is illustrated above (Fig 14) with the detailed log is given in Appendix 1. As discussed above the contact between M30 and M21 is believed to be stratigraphic. Due to the distances from M30 to M06 and M08 (A&B) there is not thought to be any overlap of the strata in the two boreholes.

2.2.4.1 Formation

Borehole M30 is assigned to the Lucan Formation (see Part 1.5.4)

2.2.4.2 Rock Head

Rockhead was recorded at 26.90m at the top of a fine grained laminated dolomite above which lies rubble (<80mm) of very fine to coarse dolomite. The structural features and dips of the rubble are inconsistent with those of the bedrock.

2.2.4.3 Lithological succession

The borehole is dolomitised throughout (see section 2.2.4.6). The pre-dolomitised lithologies would have consisted predominantly of calcarenites (70%) interbedded with calcirudites, calcareous mudstones and calcilutites.

2.2.4.4 Chert

Chert is abundant and is mainly encountered within the calcarenites. M30 has the most abundant chert of any borehole within the Lucan Formation.

2.2.4.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

Pyrite occurs in small quantities, mainly in the finer grained lithologies. Gypsum was also recorded.

2.2.4.6 Dolomite

The majority of the M30 borehole is dolomitised but its distribution and nature are variable. The basal 1.2m is entirely dolomitised and is overlain by 4.5m of undolomitised rock. Above this is 24m of entirely dolomitised rock which is then overlain by 25m of partially dolomitised rock. The uppermost

10m is, again, entirely dolomitised. Dolomite ranges from vuggy, coarse grained zebra dolomite to fine grained dolomite.

2.2.4.7 Structural features: tectonic dip

Within M30 dips are mainly below 10° although one dip of 45° was recorded. This high dip is attributed to a slumped unit. The average dip is taken as 10°.

2.2.4.8 Structural features: veins

Veins are not particularly frequent in borehole M30. Calcite veins are encountered in the undolomitised zones and dolomite veins are more abundant in the dolomitised regions. The main vein set dips steeply from 70° to vertical with less common bed-parallel veining also present.

2.2.4.9 Structural features: fractures

Fracturing is not intense but as with the veins the main fracture set is steep, dipping from 70° to vertical. There are however a number of zones where fracturing is intense with a spacing of approximately 20mm. Orthogonal vertical faults have been recorded as well as sets of fractures dipping at 70° diverging from each other at 30°. Clay films on fracture surfaces are common.

2.2.4.10 Alteration

The majority of alteration occurs within the finest grained lithologies with the mudstones and shale sometimes experiencing leaching and colour alteration occasionally resulting in a plastic clay. There are some coarser grained sections that have been reduced to rubble (such as at 29.50m and at 43.40m).

2.2.5 Borehole M06

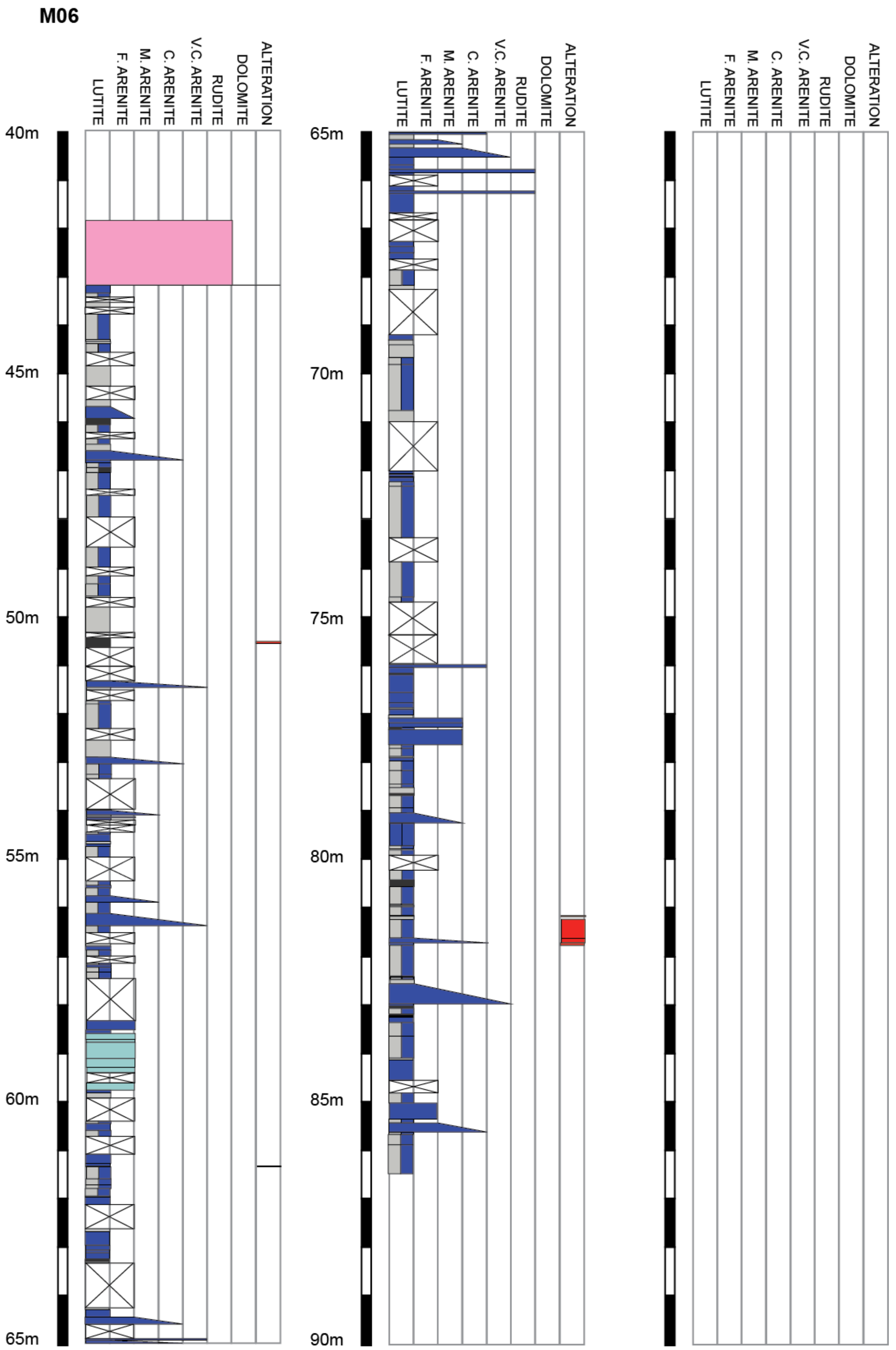

Fig 15 Summary log of M06

Borehole M06 lies just less than 1000m southwest of M30 and approximately 1250m southeast of MO8 (A&B) (Fig 9). Borehole M06 does not lie exactly on the northern alignment drilling line but 500m to the south of it. The summary log for M06 is illustrated above in Fig 15 and the detailed log is given in Appendix 1. As previously discussed, there is not thought to be an overlap between the sequences in M06 and M30 nor is it believed that an overlap exists between

2.2.5.1 Formation

Borehole M06 is assigned to the Lucan Formation (see part 1.5.4)

2.2.5.2 Rock Head

Rockhead was established at 43.89m where a coherent unit of calcisiltite was recorded. Above this unit are pebbles and cobbles of limestone and one of sandstone.

2.2.5.3 Lithological succession

The lithologies within borehole M06 are largely uniform. They consist of interbedded calcisiltites and calcareous mudstones (80%) with sporadic calcarenites and calcirudites. A large portion of the coarser beds are graded (70%). Borehole M06 more closely resembles borehole M08 (A&B) than M30 but no correlation is proffered.

2.2.5.4 Chert

Chert is present throughout borehole M06. It occurs most commonly as nodules but it is also present as bands and as zones of chertification.

2.2.5.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

Pyrite is common through the length of borehole M06. It is most frequently found in the finer grained lithologies, the calcareous mudstones and calcisiltites.

2.2.5.6 Dolomite

Dolomite was not identified in this borehole.

2.2.5.7 Structural features: tectonic dip

The tectonic dips within borehole M06 range from 0º to 50º. The steeper dips are associated with slumped units. The modal dip is 10 º and is thus taken as the tectonic dip for borehole M06.

2.2.5.8 Structural features: veins

Calcite veins are found throughout M06 but are infrequent and thin (<1mm). The majority of veins dip steeply - between 70º and vertical. Bed-parallel veins are also present.

2.2.5.9 Structural features: fractures

Borehole M06 is not particularly fractured. The fractures have dips between 70º and sub-vertical with many having clay films.

2.2.5.10 Alteration

Alteration occurs at a number of horizons along the length of borehole M06. Alteration is generally minor and largely constrained to the calcareous mudstones and calcareous shale. However between 81.00m and 82.00m a more significant zone of alteration is observed. This consists of colour alteration in both the calcareous mudstones and limestones resulting in the rock becoming weak.

2.2.6 Borehole M08 (A&B)

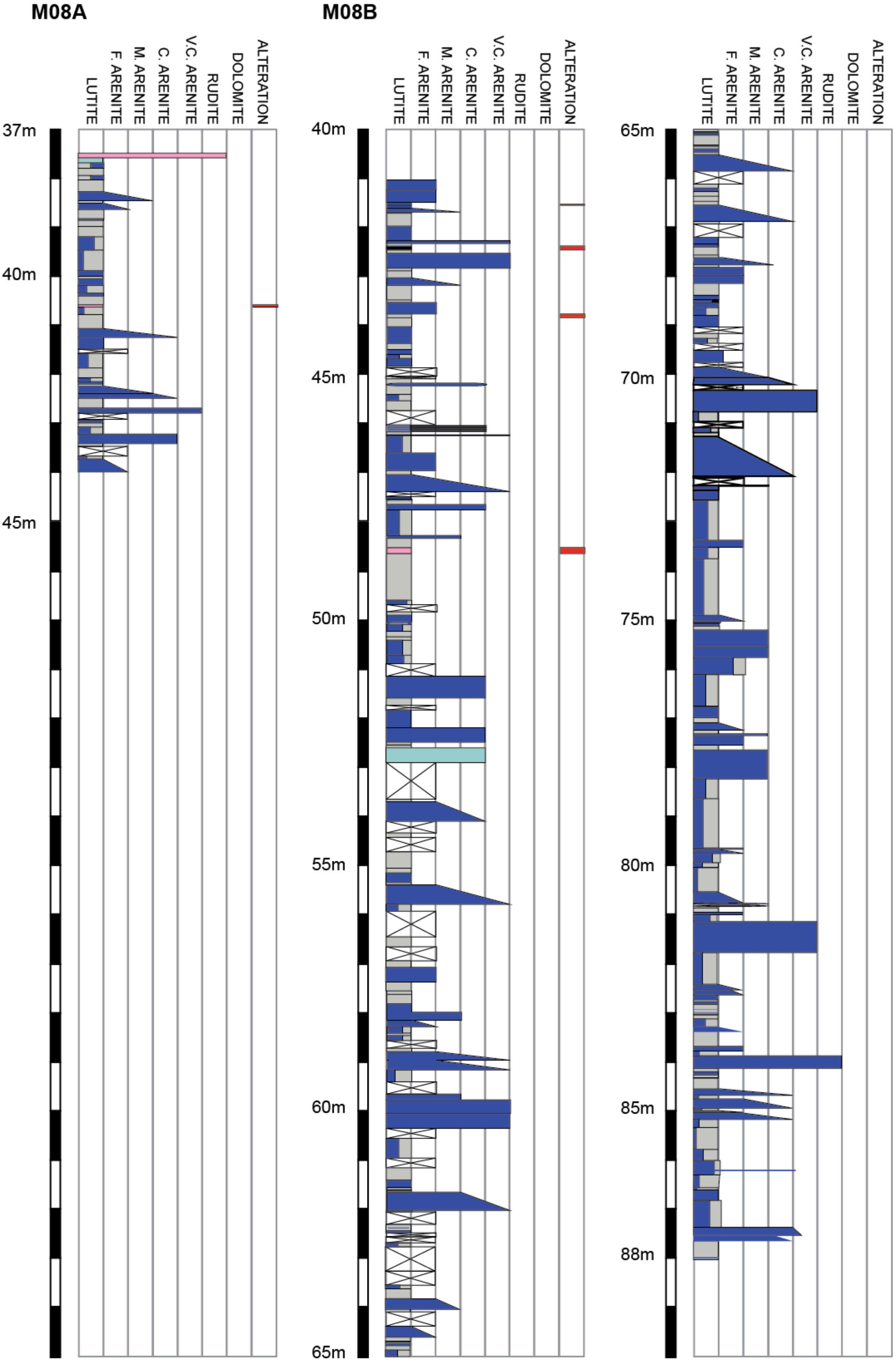

Fig 16 Summary log of M08 (A&B)

Borehole M08 A & B are two boreholes which were drilled very close together (<5m) but the exact correlation of strata between the two boreholes is not obvious. M08 (A&B) lies 1250m northwest of M06 and just over 500m southeast of M17. The summary log of M08 (A&B) is illustrated above in Fig16 and the detailed log is given in Appendix 1. There is not thought to be any overlap between M06 and M08 (A&B). However given the low dips of both the M08 (A&B) and M17 boreholes and their proximity to one another it is possible that there is an overlap of between the sequences.

2.2.6.1 Formation

Borehole M08 (A&B) is assigned to the Lucan Formation (see part 1.5.4)

2.2.6.2 Rock Head

Rockhead was established at 37.58m where a pyritc, graded calcilutite is recorded overlain by pebbly gravel and mud.

2.2.6.3 Lithological succession

Borehole M08 (A&B) is dominated by interbedded calcareous mudstones and calcisiltites (60%) and calcarenites. The calcarenites are largely coarse to very coarse in grain size and a significant proportion of the calcarenite beds are graded. At 64.60m there is a notable unit containing exotic pebbles of schist and quartzite.

Although no direct correlation of strata is inferred between M08 (A&B) and M17 the general sequence of lithologies and the ratio of calcareous mudstone to calcarenite are similar.

2.2.6.4 Chert

No chert has been identified in this borehole.

2.2.6.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

Pyrite and gypsum are commonly found within borehole M08 (A&B). Pyrite is found as laminae and as small nodules. It occurs most frequently in the calcareous mudstones.

2.2.6.6 Dolomite

No dolomite has been identified in this borehole.

2.2.6.7 Structural features: tectonic dip

Tectonic dips within borehole M08 (A&B) range from 0º to 40º with steeper dips recorded within slumped units. The modal dip is <5º and this is taken as the tectonic dip for borehole M08 (A&B).

2.2.6.8 Structural features: veins

Calcite veins are seen throughout M08 (A&B) but are only minor veins (<1mm) with few exceptions. The dips of these veins range from 70º to vertical. Bed-parallel veins are also present throughout.

2.2.6.9 Structural features: fractures

Fractures within M08 (A&B) are widely spaced and their dips range from 60º to sub-vertical. Several fractures have clay films.

2.2.6.10 Alteration

Alteration is most prevalent towards the top of M08 (A&B) with the calcareous mudstones most widely affected. The alteration manifests itself as weakening of these calcareous mudstones which in some instances results in their reduction to a plastic mud. Colour alteration of the calcareous mudstones is also seen.

Alteration and dissolution of the limestones has led to zones of sub-rounded pebbles (such as at 48.50m). This may be due to either leaching of the limestone by weakly acidic waters or pressure solution.

2.2.7 Borehole M17

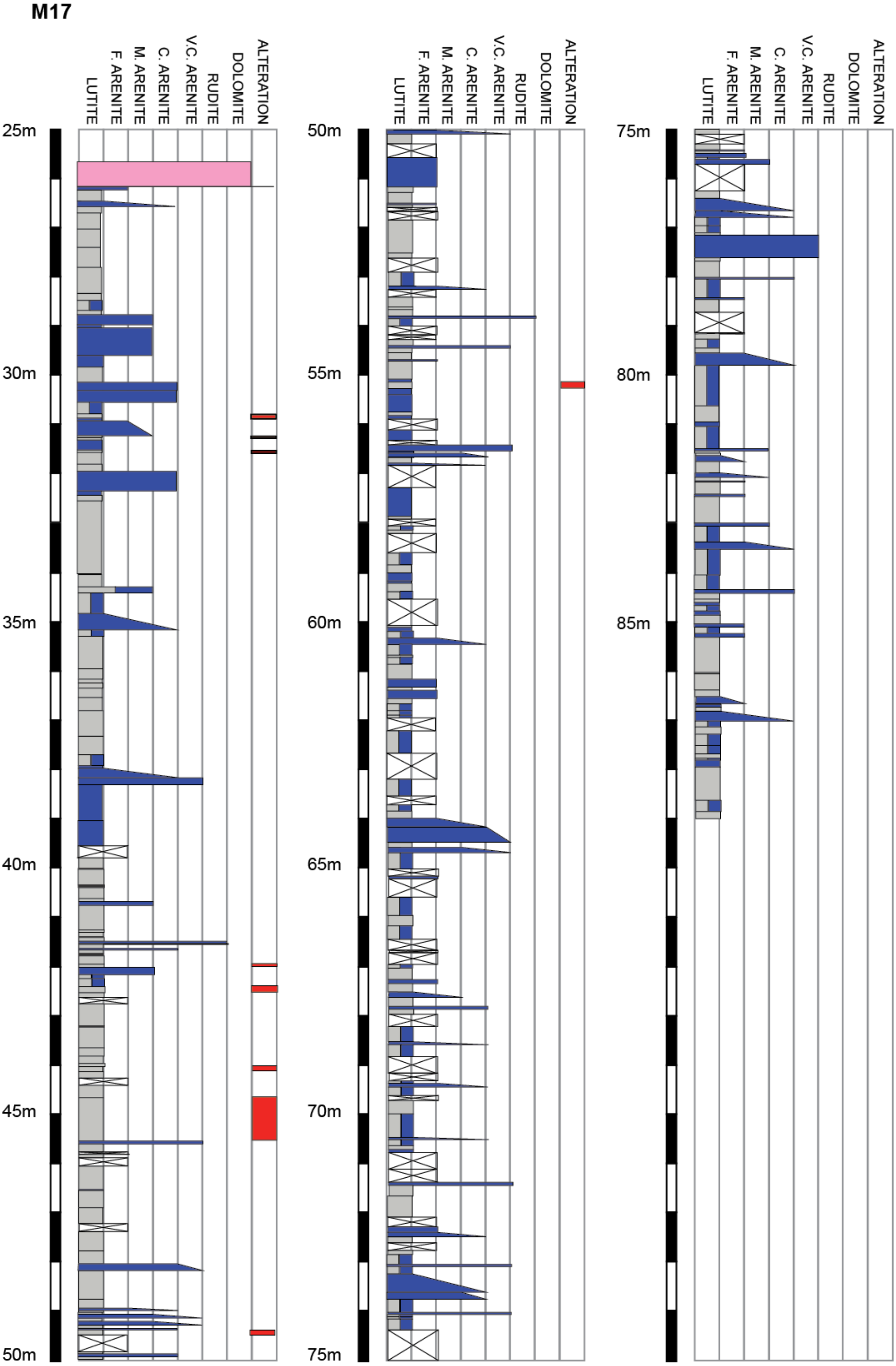

Fig 17 Summary log of M17

Borehole M17 was drilled approximately 500m northwest of M08 (A&B) and 750m east of M16 (Fig 9). The summary log for M17 is illustrated above in Fig 17 and the detailed log is given in Appendix 1. As previously discussed (section 2.2.6) there may be an overlap between M08 (A&B) and M17. Given the low dips and proximity to M16 it is also likely that there will be an overlap between M17 and M16.

2.2.7.1 Formation

Borehole M17 is assigned to the Lucan Formation (see part 1.5.4)

2.2.7.2 Rock Head

Rockhead was established at 26.14m where a very fine calcarenite is overlain by angular pebbles and clay and a boulder of mudstone 28cm in diameter.

2.2.7.3 Lithological succession

Borehole M17 is dominated by calcilutites (80%), most commonly calcareous mudstones. Calcarenites are also present (20%) and are largely coarse-grained, a high percentage of which are graded. There is no direct correlation with borehole M17.

2.2.7.4 Chert

No chert was identified within this borehole.

2.2.7.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

Pyrite is found throughout the M17 borehole. It is found predominantly within calcareous mudstones but it also occurs sporadically in the limestones. When pyrite does occur, it is often abundant.

2.2.7.6 Dolomite

No dolomite was identified within this borehole.

2.2.7.7 Structural features: tectonic dip

Dips within borehole M17 range from 0º to 40º. The modal dip is 5º and this value is taken as the tectonic dip for borehole M17.

2.2.7.8 Structural features: veins

Calcite veins are present throughout M17 but are predominantly thin veins (<1mm). The dips of the veins range from 70º to vertical. Bed-parallel veins are also present. Fluorite is seen within several calcite veins in borehole M17.

2.2.7.9 Structural features: fractures

Borehole M17 is not highly fractured. Fractures that are found have dips between 70º and vertical. Steep orthogonal fractures and conjugate fractures which diverge at 30º to each other are also recorded. Several fractures surfaces have clay films.

2.2.7.10 Alteration

Alteration is sporadic within the M17 borehole. It occurs mainly in the upper half of the core and is manifest as weathering of calcareous mudstones and calcareous shale.

2.2.8 Borehole M16

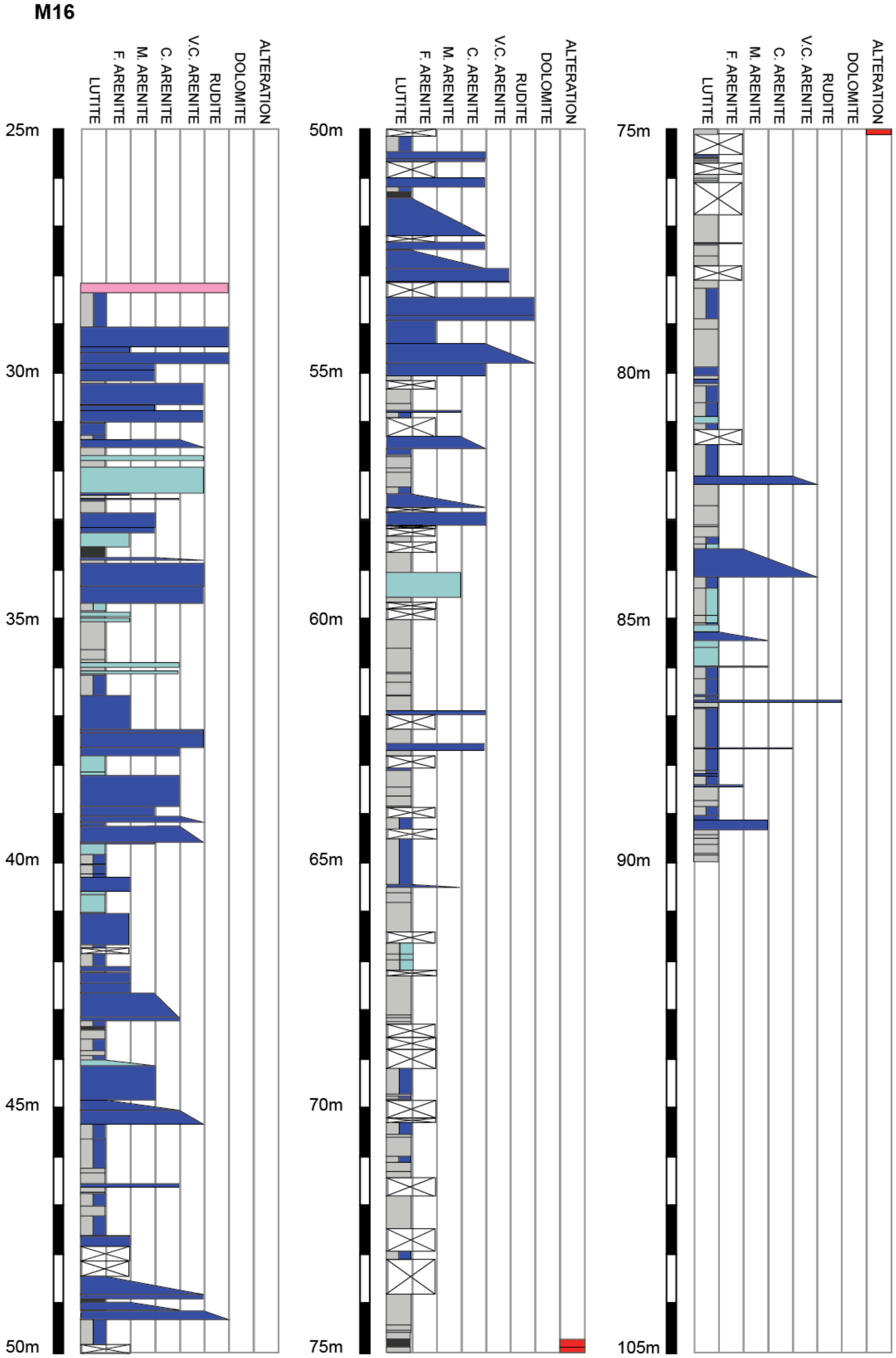

Fig 18 Summary log of M16

Borehole M16 was drilled 750m west of M17 and 1200m east of M14 (Fig 9). The summary log of M16 is illustrated above in Fig 18 and the detailed log is given in Appendix 1. As previously discussed (section 2.2.7), there is likely to be a stratigraphic overlap between M16 and M17 due to their proximity to one another and their low dips. The distance between borehole M16 and M14 and the steep dips (~15º) encountered within borehole M14 make a stratigraphic overlap between these two boreholes unlikely.

2.2.8.1 Formation

Borehole M16 is assigned to the Lucan formation (see part 1.5.4)

2.2.8.2 Rock Head

Rockhead was established at 28.35m where a unit of interbedded coarse calcarenite and calcareous mudstone was encountered. The core box is empty above this unit.

2.2.8.3 Lithological succession

Borehole M16 can be divided into three main sequences. The basal sequence from 90m to 77.50m consists predominantly of interbedded calcareous mudstones and calcisiltites with rare argillaceous calcilutites and calcarenites. The second sequence is from 77.50m – 60.00m and is comprised largely of calcareous mudstones (90%) with three thin calcarenite beds. The third sequence is from 60.00m to rockhead and is dominated by calcarenites (80%). The grain size of the calcarenites ranges from medium to coarse with occasional calcirudites present. A number of the calcarenite beds are graded.

2.2.8.4 Chert

There are only two occurrences of chert in borehole M16. At 44.60m a calcarenite unit shows signs of chertification while chert nodules were found at 38m.

2.2.8.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

Pyrite is rare in borehole M16.

2.2.8.6 Dolomite

No dolomite was identified in borehole M16.

2.2.8.7 Structural features: tectonic dip

Almost all the dips in borehole are <5º with one unit dipping at 30º. The dip of borehole M16 is thus taken as <5º.

2.2.8.8 Structural features: veins

Veins within borehole M16 are mainly <1mm and are rare. The veins dip mainly from 70º to vertical. Bed-parallel veins are also present. Fluorite occurs in one vein at 61.35m.

2.2.8.9 Structural features: fractures

Borehole M16 is not highly fractured. Fractures dip from 70º to vertical with many having clay films.

2.2.8.10 Alteration

Alteration is evident at only one horizon (75m) where a pyritic shale has become weak and is bounded by fractured calcareous mudstone which has undergone colour alteration.

2.2.9 Borehole M14

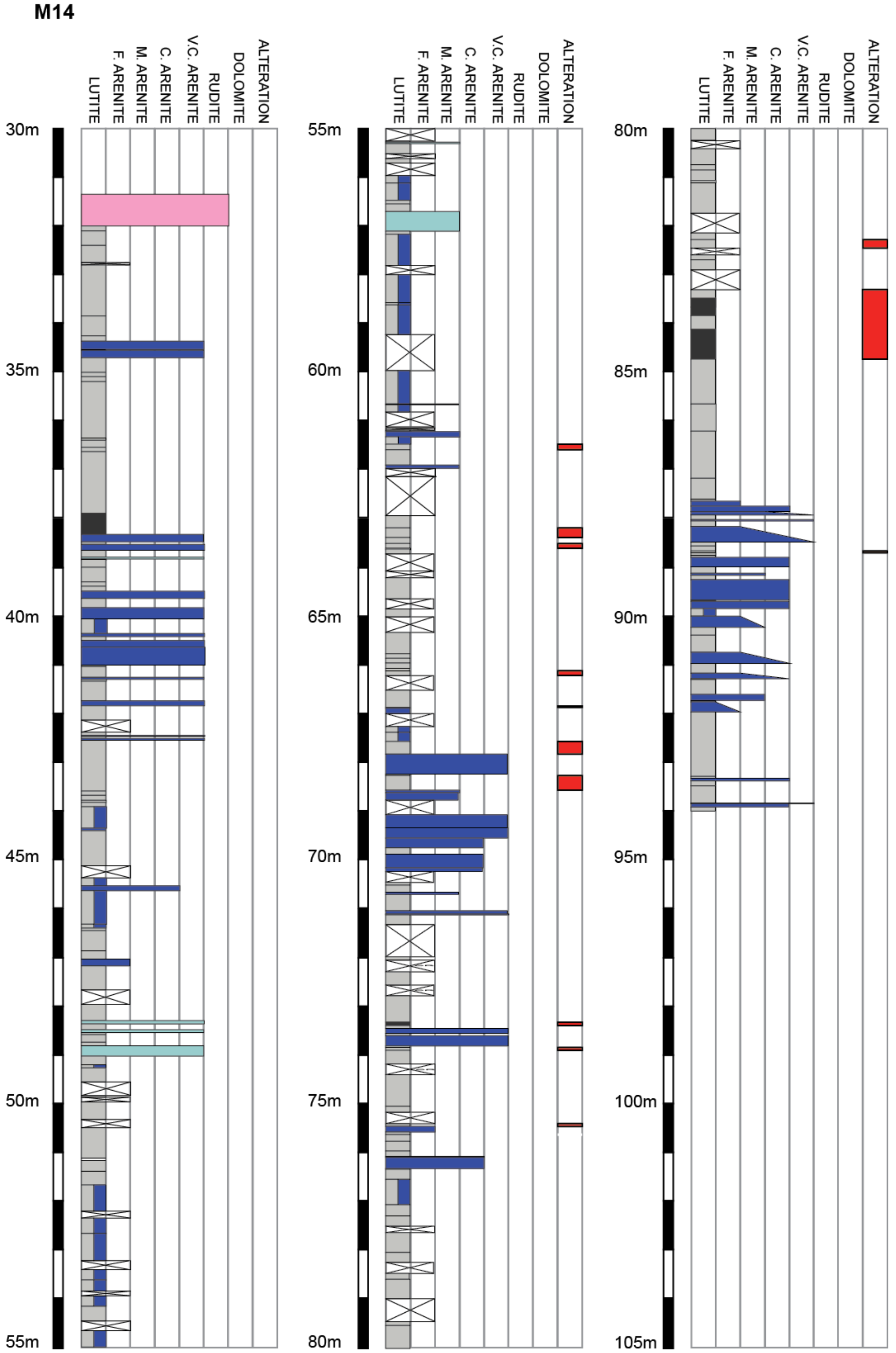

Fig 19 Summary log of M14

Borehole M14 was drilled 1200m west of M16 and 900m east of M27 (Fig 9). The summary log for M14 is illustrated above in Fig 19 and the detailed log is given in Appendix 1. As previously discussed in section 2.2.8 it is not thought that there is a stratigraphic overlap between M14 and M16 due to their difference in dips and their distance from one another. There is not thought to be an overlap between M14 and M27 for similar reasons.

2.2.9.1 Formation

Borehole M14 is assigned to the Lucan Formation (see part 1.5.4)

2.2.9.2 Rock Head

Rockhead was established at 31.90m where the uppermost unit of bedrock is a highly fractured calcareous mudstone. Above this unit lies a gravel consisting of mainly rounded limestone clasts with some foreign pebbles (chert) within a plastic mud matrix

2.2.9.3 Lithological succession

Borehole M14 may be divided into several sequences. The basal sequence from 94.00 – 87.50m is dominated by coarse-grained calcarenites (60%) interbedded with calcareous mudstones. Above this, from 87.50 – 76.00m, the core comprises entirely calcareous mudstones. From 76.00 – 68.00m there is a succession of calcilutites (50%) interbedded with coarse-grained calcarenites. From 68.00 – 42.50m the section is again dominated by interbedded calcilutites but within this part of the succession the associated calcarenites (10%) are argillaceous. The penultimate succession, from 42.50 – 38.00m, comprises very coarse-grained calcarenites (50%) interbedded with calcareous mudstones. The uppermost portion of the section from 38.00m to rockhead is almost entirely composed of calcareous mudstones with one thick bed of very coarse-grained calcarenite.

2.2.9.4 Chert

No chert was identified in this borehole.

2.2.9.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

No macroscopic-pyrite was identified in borehole M14 but gypsum was recorded at several levels and is most probably formed from the oxidation of pyrite. The gypsum is commonly found in association with alteration.

2.2.9.6 Dolomite

No dolomite was identified in borehole M14.

2.2.9.7 Structural features: tectonic dip

The tectonic dip in borehole M14 ranges from 0º to 30º. The dip values cluster from 10º to 15º and hence a value of 12.5º taken as the representative dip for borehole M14.

2.2.9.8 Structural features: veins

Veins within borehole M14 are infrequent and minor (<1mm). The majority of veins dip between 70º and vertical but bed-parallel veins are also present.

2.2.9.9 Structural features: fractures

Borehole M14 is not highly fractured with the exception of the uppermost 3m. The fractures have dips ranging from 70º to vertical with many having clay films.

2.2.9.10 Alteration

Alteration is minor and only occurs below 62m. In all cases the altered lithology is calcareous mudstone and/ or shale. These rocks have become weak and in some cases have become a plastic mud. Colour alteration is also recorded within these units.

2.2.10 Borehole M27

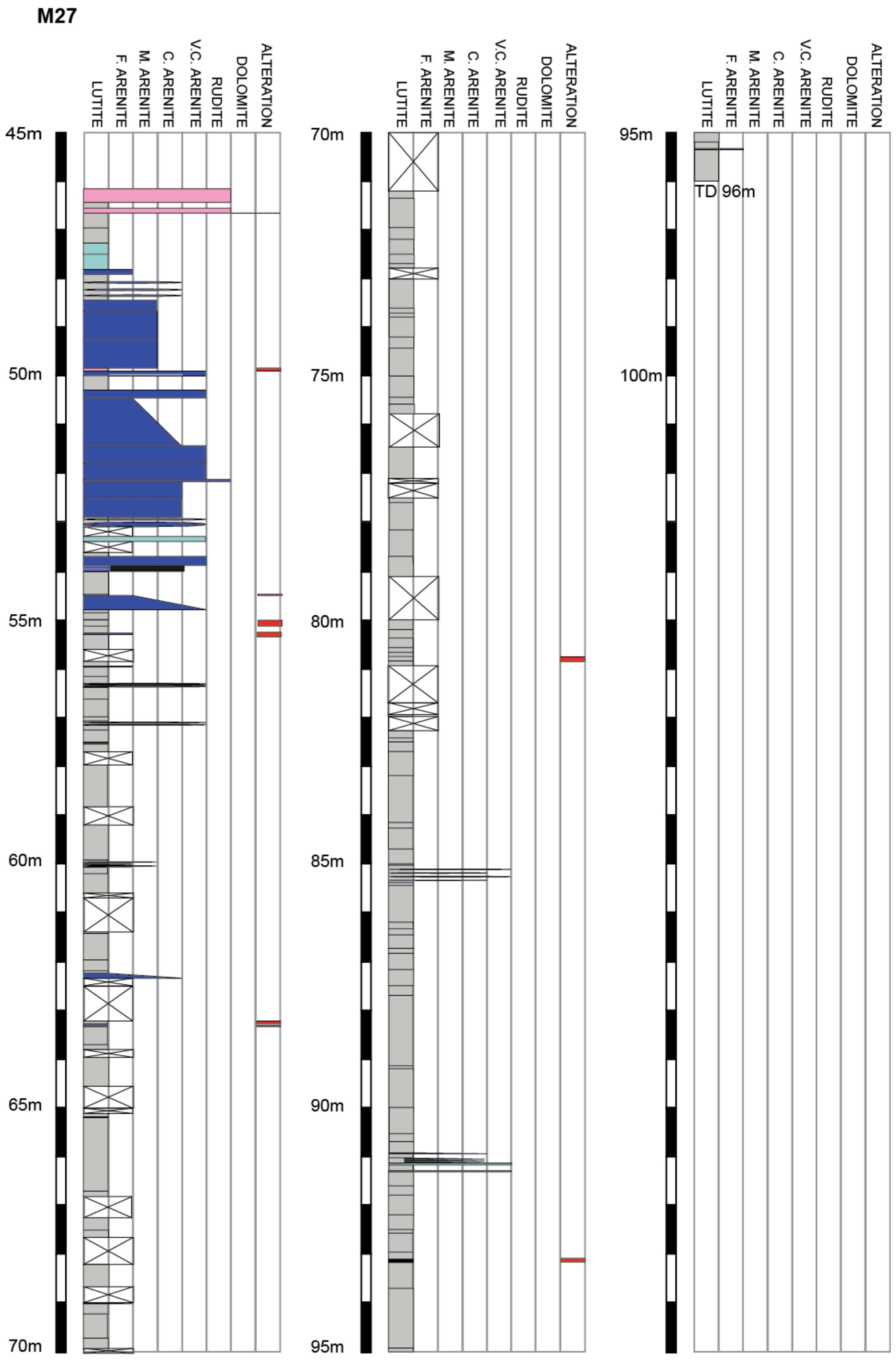

Fig 20 Summary log of M27

Borehole M27 was drilled 900m west of M14 and approximately 900m southeast of M05 (Fig 9). The summary log for borehole M27 is illustrated above in Fig 20 and the detailed log is given in Appendix 1. As previously discussed in section 2.2.9 it is not thought that there is a stratigraphic overlap between M27 and M14. Similarly it is unlikely that there is a stratigraphic overlap between M27 and M05.

2.2.10.1 Formation

Borehole M27 is assigned to the Lucan Formation (see part 1.5.4)

2.2.10.2 Rock Head

Rockhead was established at 46.65m where a calcareous mudstone with silty laminae and scattered bioclasts was encountered. Above this unit lies a clast-supported conglomerate of rounded and angular pebbles of limestone and calcareous mudstone.

2.2.10.3 Lithological succession

Borehole M27 is clearly divisible into two main sequences. The basal sequence from 96m to 55m, is made up almost entirely of bioturbated calcareous mudstone with very rare, very thin calcarenites. From 55m to rockhead the section is dominated by thick calcarenites interbedded with calcareous mudstones and argillaceous calcisiltites.

2.2.10.4 Chert

Only one chert horizon was recorded - a 220mm thick chert band at 75.50m. Zones of partial chertification were also recorded at a number of levels.

2.2.10.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

Pyrite is not abundant in borehole M27. Gypsum is more common than pyrite but still is only a minor phase.

2.2.10.6 Dolomite

No dolomite was identified in borehole M27.

2.2.10.7 Structural features: tectonic dip

Tectonic dips within borehole M27 range from 0º to 30º. The modal dip is 5º and this value is taken as the tectonic dip for borehole M27.

2.2.10.8 Structural features: veins

Thin (<1mm) calcite veins are common throughout borehole M27 with dips most frequently ranging from 70º to vertical. Bed-parallel veins are also present.

2.2.10.9 Structural features: fractures

Borehole M27 is not highly fractured. The main fractures dip steeply between 70º and vertical with several having clay films and pyrite.

2.2.10.10 Alteration

Alteration is minor and sporadic throughout borehole M27. Alteration occurs exclusively in calcareous mudstone and calcareous shale units and causes weakening of the rock and some colour alteration. Calcite veining and pyrite are commonly found in these zones of alteration.

2.2.11 Borehole M05

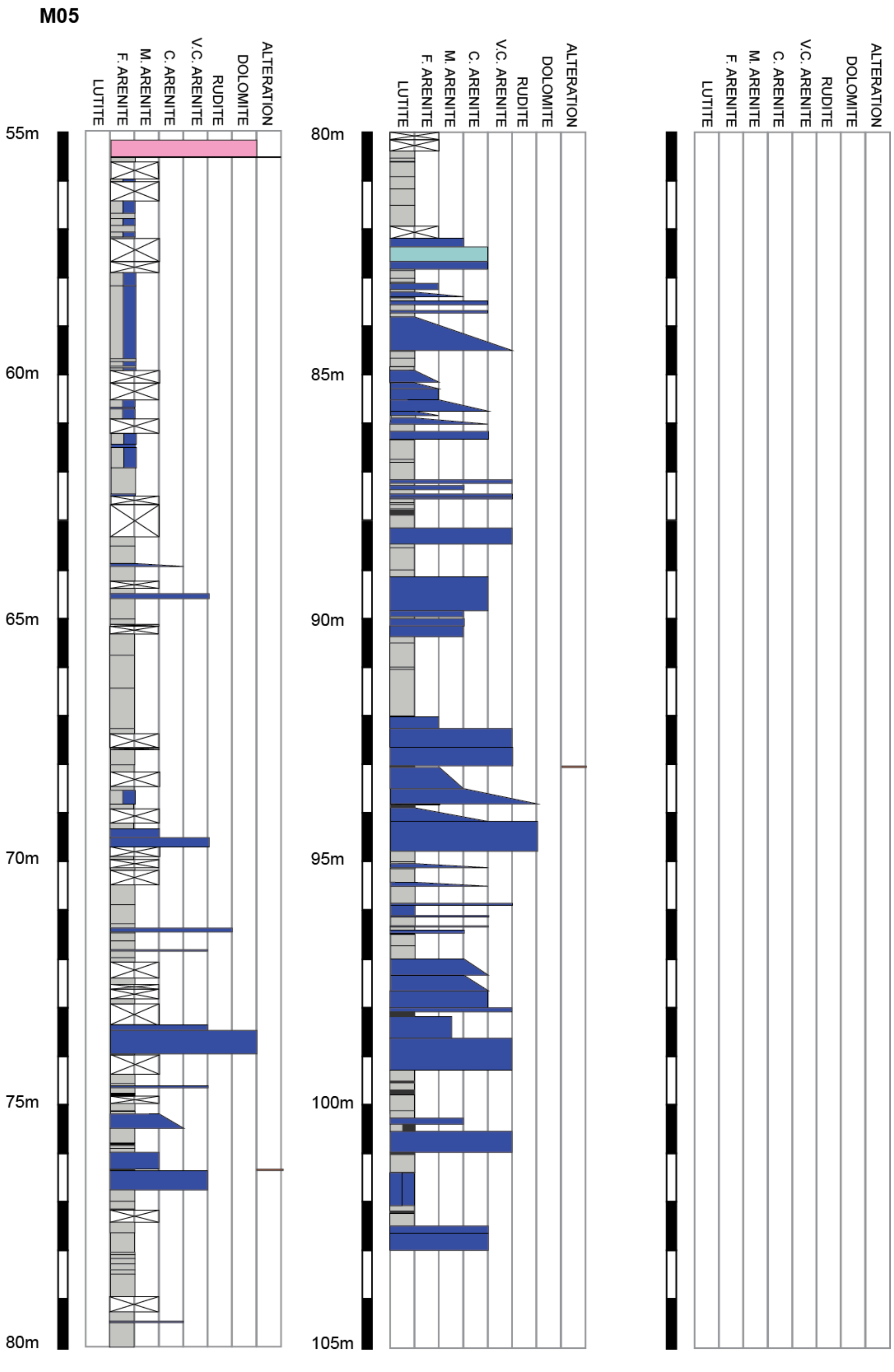

Fig 21 Summary log of M05

Borehole M05 was drilled 900m northwest of M27 and approximately 300m northeast of M29 (Fig 9). The summary log for borehole M05 is illustrated above in Fig 21 and the detailed log is given in Appendix 1. Due to the proximity of borehole M05 to borehole M29 a stratigraphic overlap is likely but due to the dolomitisation encountered within the M29 borehole direct correlation is difficult.

2.2.11.1 Formation

Borehole M05 is assigned to the Lucan Formation (see part 1.5.4)

2.2.11.2 Rock Head

Rockhead was established at 55.50m where a unit of calcareous mudstone was encountered and is overlain by gravel and dolomite and limestone cobbles.

2.2.11.3 Lithological succession

Borehole M05 may be divided into four main sequences. The basal sequence from 103m to 82.50m consists of coarse-grained calcarenites (and subordinate calcirudites) interbedded with calcareous mudstones (40%). The second sequence is from 82.50 – 77.00m and comprises almost entirely calcareous mudstones. The third sequence from 77.00 – 69.50m comprises calcareous mudstones (70%) interbedded with coarse-grained calcarenites. The uppermost sequence is from 69.50m to rockhead and consists of interbedded calcareous mudstones and calcisiltites.

2.2.11.4 Chert

In the basal 15m no chert was identified. Above this level chert is common and is found as chert bands (<50mm at 75.80m), partially chertified zones and as nodules (<7mm).

2.2.11.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

Pyrite and gypsum are common throughout borehole M05.

2.2.11.6 Dolomite

No dolomite was identified in borehole M05.

2.2.11.7 Structural features: tectonic dip

The tectonic dips within borehole M05 range from 0º to 25º with a modal value of 10º which is taken as the tectonic dip of borehole M05.

2.2.11.8 Structural features: veins

Calcite veins are present throughout borehole M05. The majority of veins have dips between 70º and vertical. Bed-parallel veins are also present. Fluorite occurs at 76.20m within calcite veins.

2.2.11.9 Structural features: fractures

Borehole M05 is not highly fractured. The fractures mainly dip between 70º and sub-vertical with many having clay films.

2.2.11.10 Alteration

There are only two occurrences of alteration in borehole M05. In both instances thin calcareous shale bands have been altered to a plastic clay.

2.2.12 Borehole M29

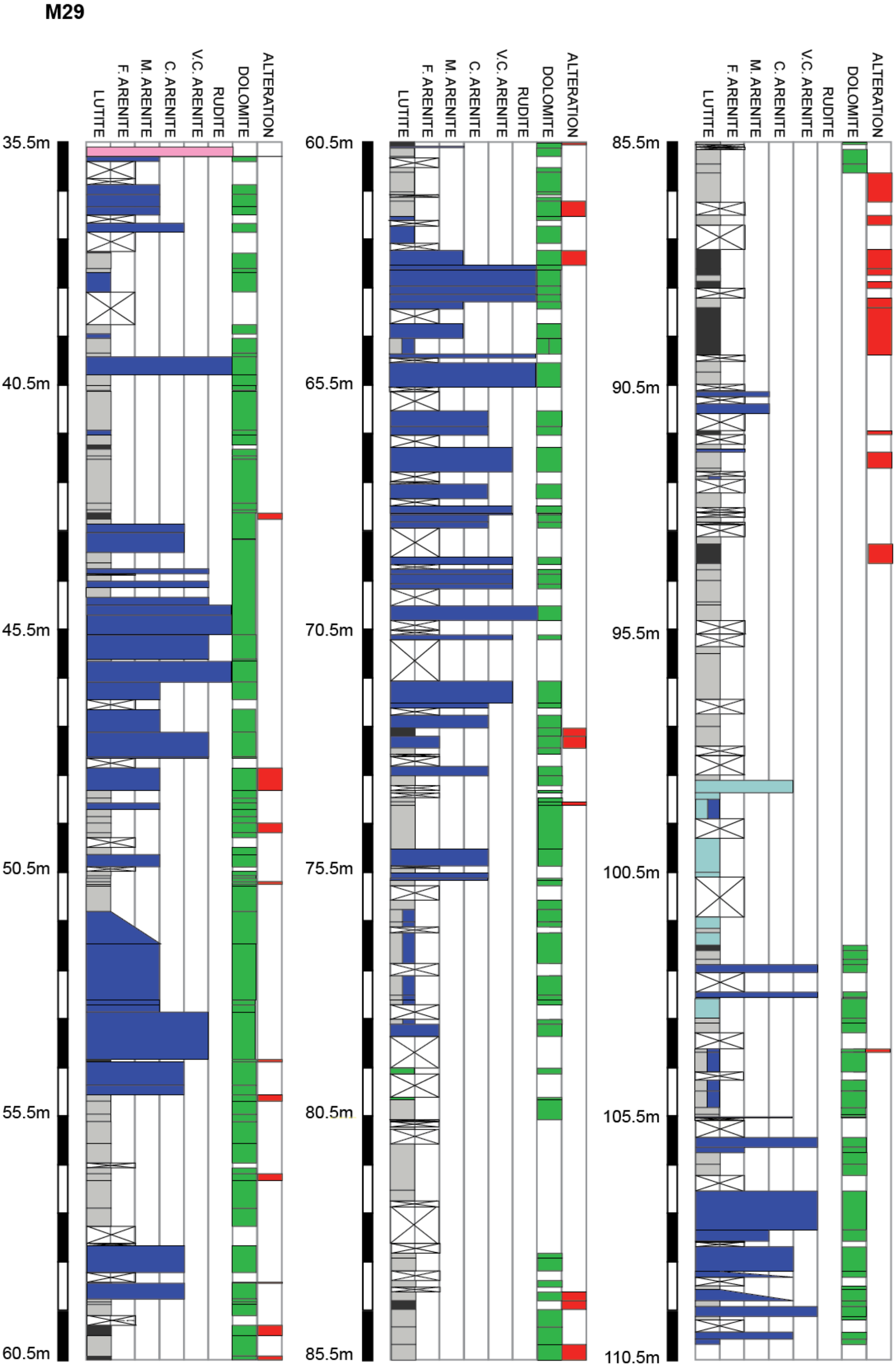

Fig 22 Summary log of M29

Borehole M29 was drilled 300m southwest of M05 and approximately 300m east of M28. The summary log for borehole M29 is illustrated above in Fig 22 and the detailed log is given in Appendix 1. As previously discussed (section 2.2.11) there is likely to be an overlap between boreholes M29 and M05 but due to the pervasive dolomitisation in the M29 borehole direct correlation is difficult. Similarly as boreholes M29 and M28 were also drilled close to one another it is likely given their respective dips that there would be a stratigraphic overlap. However the dolomitisation of both boreholes makes such correlations impossible.

2.2.12.1 Formation

Borehole M29 is likely to belong to the Lucan Formation (see part 1.5.4) but the pervasive dolomitisation has made detailed identification of the lithologies difficult.

2.2.12.2 Rock Head

Rockhead was established at 35.80m where an angular, dolomitised calcarenite rubble is overlain by rounded pebbles.

2.2.12.3 Lithological succession

Borehole M29 may be divided into several sequences. Beginning at the base, from 110.50m to 102m, the borehole is dominated by dolomitised coarse-grained calcarenites (60%) interbedded with dolomitised calcilutites which most likely represented calcareous mudstones prior to dolomitisation. From 102.00 – 86.00m the section consists of undolomitised calcilutites (predominantly calcareous mudstones) with very rare, thin calcarenite beds. Above this, from 86.00 – 75.50m, lies a similar succession of calcilutites that has undergone dolomitisation. From 75.50 – 62.50m the section consists almost entirely of dolomitised coarse to very coarse-grained calcarenites with occasional calcirudites. Above this from 62.50 – 55.00m, the borehole contains dolomitised calcilutites with two thick dolomitised coarse calcarenite beds. From 55.00 – 43.00m the succession consists largely of thick dolomitised calcarenites and calcirudites (90%) interbedded with minor dolomitised calcilutites. The uppermost sequence is from 43.00 to rockhead where the section contains dolomitised calcareous mudstones (60%) interbedded with dolomitised calcarenites.

2.2.12.4 Chert

Chert is only recorded below 49.00m. It is found as nodules, chertified mudstone and as bands (<70mm at 88.70m)

2.2.12.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

Pyrite is widespread throughout borehole M29, occurring in all lithologies but most notably within the mudstones (both calcareous and dolomitised). At 63.00m there is a unit of coarse dolomite rubble which occurs along with an unconsolidated loose sand which is very rich in very coarse-grained pyrite . Several other minerals were recorded including sphalerite, galena, possibly malachite and an as-yet-unidentified waxy, red mineral (possibly jarosite).

2.2.12.6 Dolomite

Dolomite is pervasive in borehole M29. The largest undolomitised section is from 86.00 – 102.00m. The replacement dolomite reflects the grain size of the original lithology, with coarse dolomite replacing calcarenites and fine dolomite replacing the calcilutites. Many zones of dolomite are vuggy with occasional patches of zebra dolomite recorded.

2.2.12.7 Structural features: tectonic dip

The tectonic dips of borehole M29 range from 0º - 50º. The most frequent values lie between 20º and 25º and 20º is taken as the tectonic dip of borehole M29.

2.2.12.8 Structural features: veins

Veins are common throughout borehole M29. The composition of the veins depends on the surrounding lithology i.e. in the dolomitic rocks the veins are comprised of dolomite while in the limestones the veins are made of calcite. Dips range between 70º and vertical.

2.2.12.9 Structural features: fractures

Borehole M29 is highly fractured. Fractures are steep ranging from 70º to sub-vertical.

2.2.12.10 Alteration

Alteration is most prevalent between 86.00 and 102.00m, in the undolomitised fine-grained parts of borehole M29. The calcareous mudstones are the most widely affected. Alteration has led to a loss in strength of the rock and, in some instances, its reduction to plastic clay. Alteration is also seen as staining on fracture surfaces and as dolomitic breccia in plastic clay matrices.

2.2.13 Borehole M28

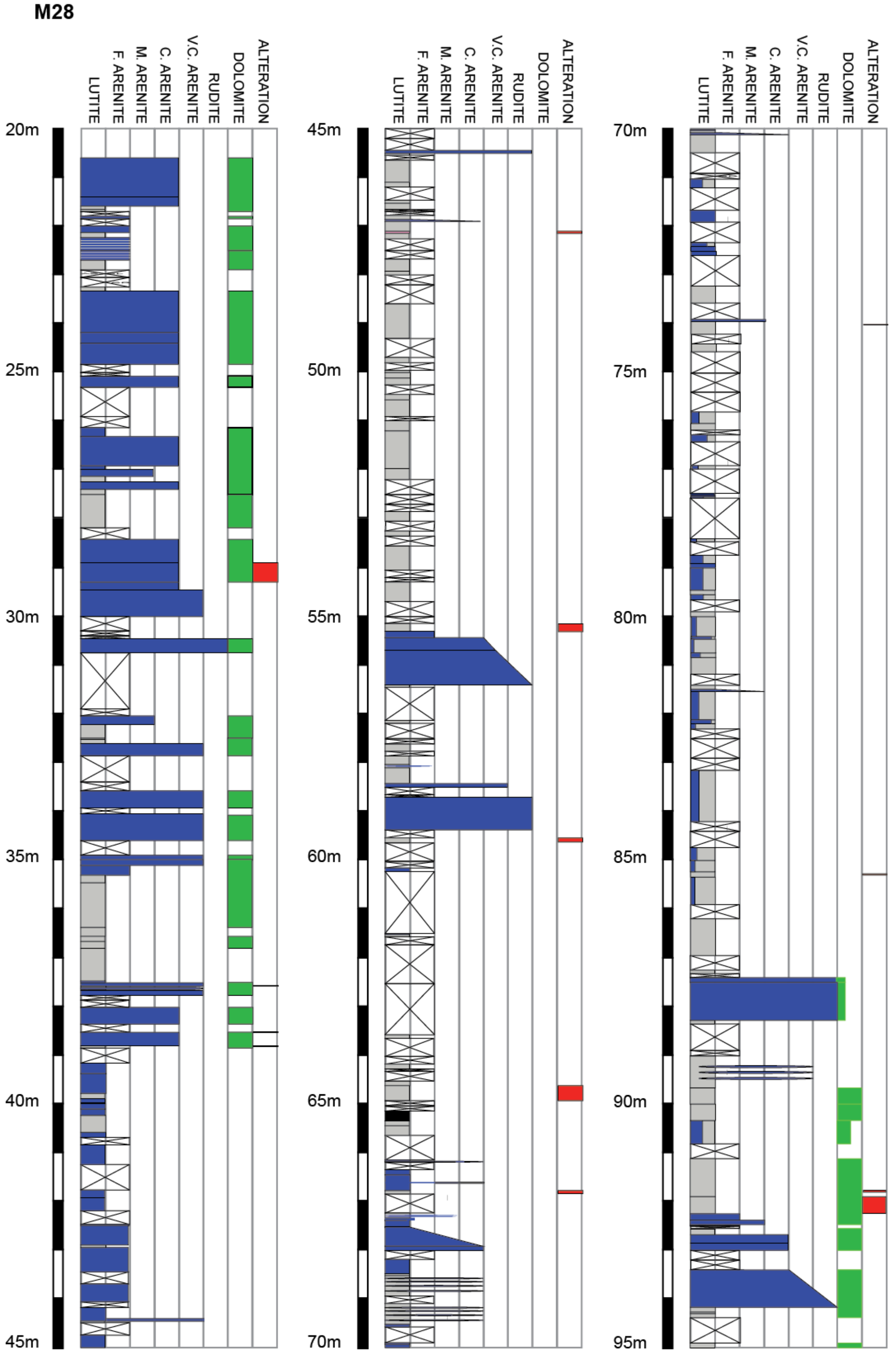

Fig 23 Summary log of M28

M28

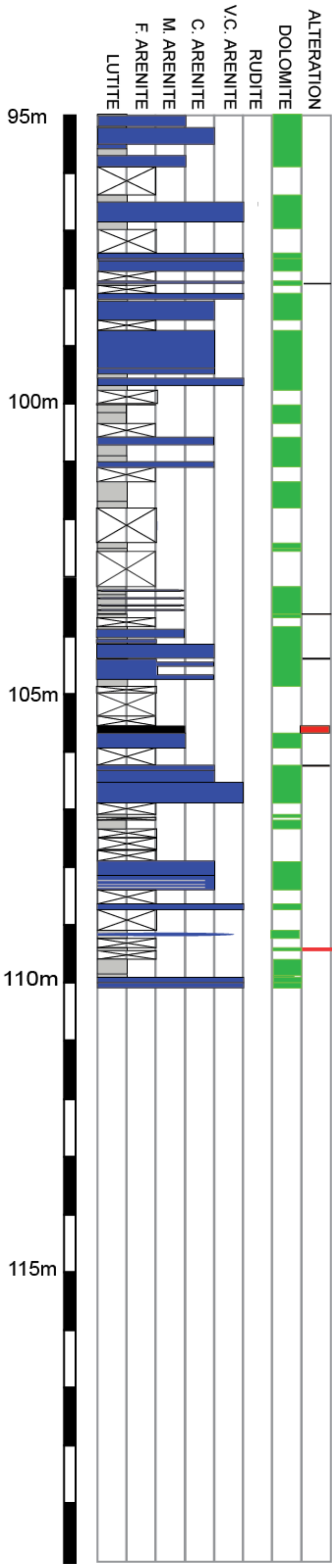

Fig 23 Summary log of M28

Borehole M28 was drilled 300m west of M29 and approximately 300m east of boreholes BHO1 and BHO2. The summary log is illustrated above in Fig 23 and the detailed log is given in Appendix 1. As discussed in section 2.2.12 it is likely that there would be a stratigraphic overlap between boreholes M28 and M29 but due to pervasive dolomitisation precise correlation is impossible. A similar situation occurs between boreholes M28, BHO1 and BHO2 where given their proximity and respective dips there should be stratigraphic overlap but the boreholes are all too heavily dolomitised for precise correlations to be attempted.

2.2.13.1 Formation

Borehole M28 most likely should be assigned to the Lucan Formation (see section 1.5.4) but the pervasive dolomitisation has made detailed identification of lithologies very difficult.

2.2.13.2 Rock Head

Rockhead was established at 20.60m at the top of a very coarse dolomite unit. No material above this level has been boxed.

2.2.13.3 Lithological succession

Borehole M28 may be divided into four sequences. The basal sequence from 87.50 – 110.00m consists largely of dolomitised coarse to very coarse-grained calcarenites (80%) interbedded with subordinate dolomitised mudstones. From 87.50 – 45.00m the section is dominated by undolomitised calcareous mudstones with several calcarenite beds. Above this from 45.00 – 38.00m is a sequence of undolomitised medium grained calcarenites which become coarser towards the top. The uppermost section from 38.00m to rockhead is predominantly comprised of dolomitised calcarenites (90%). The basal portion of this uppermost sequence is coarse grained and fines upwards into a medium grained dolomite.

2.2.13.4 Chert

Chert is found throughout borehole M28. It is recorded as bands, nodules and chertified zones typically within mudstones.

2.2.13.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

Pyrite is common throughout borehole M28 with the highest abundances of pyrite recorded within the dark mudstone units. It is also found within vuggy zones of dolomite and in calcite veins. Sphalerite was also recorded within calcite veins between 26.20 – 46.70m. Gypsum occurs as an oxidation product of pyrite. An as yet unidentified red, waxy mineral (possibly jarosite) was also recorded.

2.2.13.6 Dolomite

Borehole M28 is pervasively dolomitised between 91m and the end of the hole and between 87.00m and 91.00m the rock is partially dolomitised. From 39.00 – 87.00m the section is undolomitised and from rockhead to 39.00m the rock is pervasively dolomitised. As with previous boreholes the replacement dolomite mirrors the grain size of the original lithology, with fine dolomite replacing fine-grained limestones with and coarse-grained limestones replaced by coarse dolomite. Vuggy dolomite and zebra dolomite are also observed at several horizons.

2.2.13.7 Structural features: tectonic dip

The tectonic dips in borehole M28 range from <5º - 50º. The most common dips are 10º and 15º with 10º taken as the tectonic dip of borehole M28.

2.2.13.8 Structural features: veins

Veins are common throughout borehole M28 and as with previous boreholes they reflect the host lithology (i.e. calcite veins are found within limestones and dolomite veins are encountered in zones of dolomitic rock). The dolomite veins are largely vuggy and occasionally pink. The main vein set dips between 70º and vertical and may be seen to form *en-echelon* sets. Low-angle veins are less common but are typically thicker (<200mm) and are seen to cross-cut the steep veins. The majority of the sphalerite is found within veins.

2.2.13.9 Structural features: fractures

Borehole M28 is intensely fractured. The majority of fractures are steep dipping between 70º and sub-vertical. A number of open fractures have clay films and many fracture surfaces show discolouration. Stylolites are common and dip between bed-parallel and sub-vertical.

2.2.13.10 Alteration

Alteration is minor within borehole M28. Alteration ranges from discoloured fracture surfaces, through dolomitised breccia in clay matrices to dolomitised mudstones reduced to plastic clay.

2.2.14 Borehole BHO2

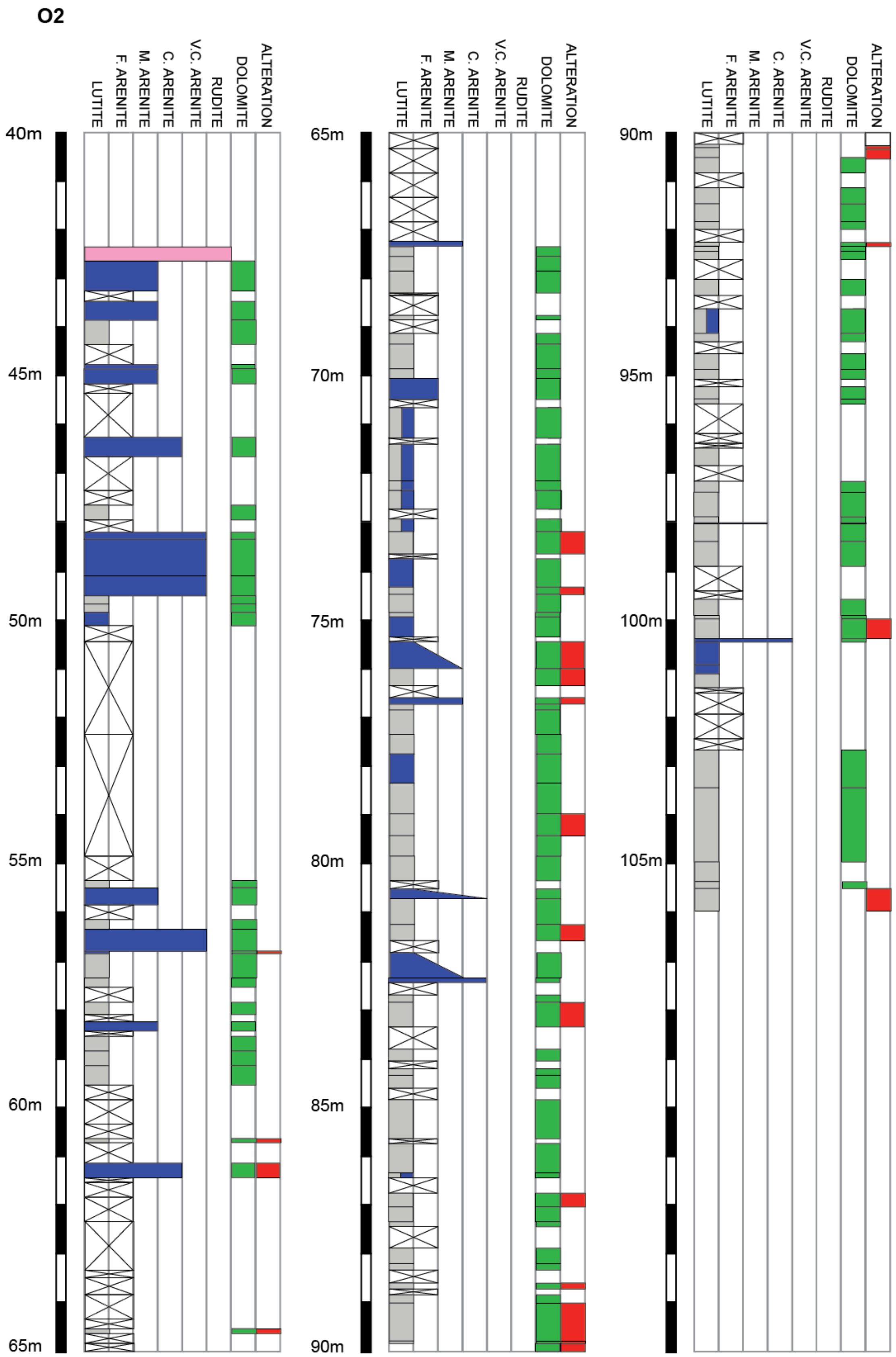

Fig 24 Summary log of BHO2

Borehole BHO2 was drilled approximately 300m west of borehole M28 and within 20m of BHO1 (Fig 9). The summary log of borehole BHO1 is illustrated above in Fig 24 and the detailed log is given in Appendix 1. As previously discussed (section 2.2.13) there may be a stratigraphic overlap between M28 and BHO2 but pervasive dolomitisation has made detailed lithological correlation impossible. As boreholes BHO2 and BHO1 are drilled within metres of one another it is almost certain that there should be a stratigraphic overlap between them. However due to the pervasive dolomitisation and intense fracturing definitive lithological correlation is impossible.

2.2.14.1 Formation

Borehole BHO2 most likely should be assigned to the Lucan Formation (see section 1.5.4) with the top calcarenite (now entirely dolomitised) section possibly belonging to the Clondalkin Formation (section 1.5.3) but the pervasive dolomitisation has made detailed identification of lithologies very difficult.

2.2.14.2 Rock Head

Rockhead was established at 42.82m at the top of the uppermost unit of highly fractured, dolomitised calcarenite. Above this lies rounded pebbles of dolomite and limestone.

2.2.14.3 Lithological succession

Borehole BHO2 can be divided into two sections. The basal section from 106.00 – 82.50m is largely comprised of pervasively dolomitised calcareous mudstone (>90%). The upper section from 82.50m to rockhead consists of pervasively dolomitised, interbedded calcareous mudstones and calcarenites. It is noted that a substantial quantity of rock was missing (zones of ‘No Recovery’ were noted by the drillers) from the upper portion of borehole BHO2 prior to this phase of logging.

2.2.14.4 Chert

Chert was not identified in borehole BHO2.

2.2.14.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

Pyrite is present but is not abundant in borehole BHO2, and was not recorded above 68.00m. The distribution of gypsum is similar. A waxy red mineral, possibly jarosite, was commonly found on fracture surfaces. Jarosite is a potassium iron sulphate hydroxide which may form from the oxidation of pyrite and its presence suggests that sulphates were/ are mobile in this lithology. Iridescent bornite (peacock ore) was also present on a small number of surfaces.

2.2.14.6 Dolomite

Dolomite is pervasive in borehole BHO2 except from 90 – 106.00m where the rock is only partially dolomitised.

2.2.14.7 Structural features: tectonic dip

The tectonic dips in borehole BHO2 range from <5º - 30º. The modal value is 10º and this value is taken as the tectonic dip of borehole BHO2.

2.2.14.8 Structural features: veins

Borehole BHO2 is highly veined with the majority of veins dipping between 70º and vertical with thicknesses of approximately 5mm. Low-angle veins are also present but less frequent. The low-angle veins are typically thicker (up to 30mm) than the steep veins. Veins above 90m are dolomitic, sometimes pink, whereas below 90m they commonly contain both dolomite and calcite.

2.2.14.9 Structural features: fractures

Borehole BHO2 is intensely fractured. Fractures are steep with dips ranging from 70º to sub-vertical. Many fractures have clay films.

2.2.14.10 Alteration

Alteration is widespread in borehole BHO2 below 57m**.** It manifests as discolouration of fracture surfaces, through friable dolomitic rubble and sand to rock reduced to plastic clay. At 66m sub-rounded, discoloured dolomite pebbles with patina are recorded and this in conjunction with large sections of 'No Recovery' of core recorded by the drillers suggests substantial carbonate dissolution.

2.2.15 Borehole BHO1

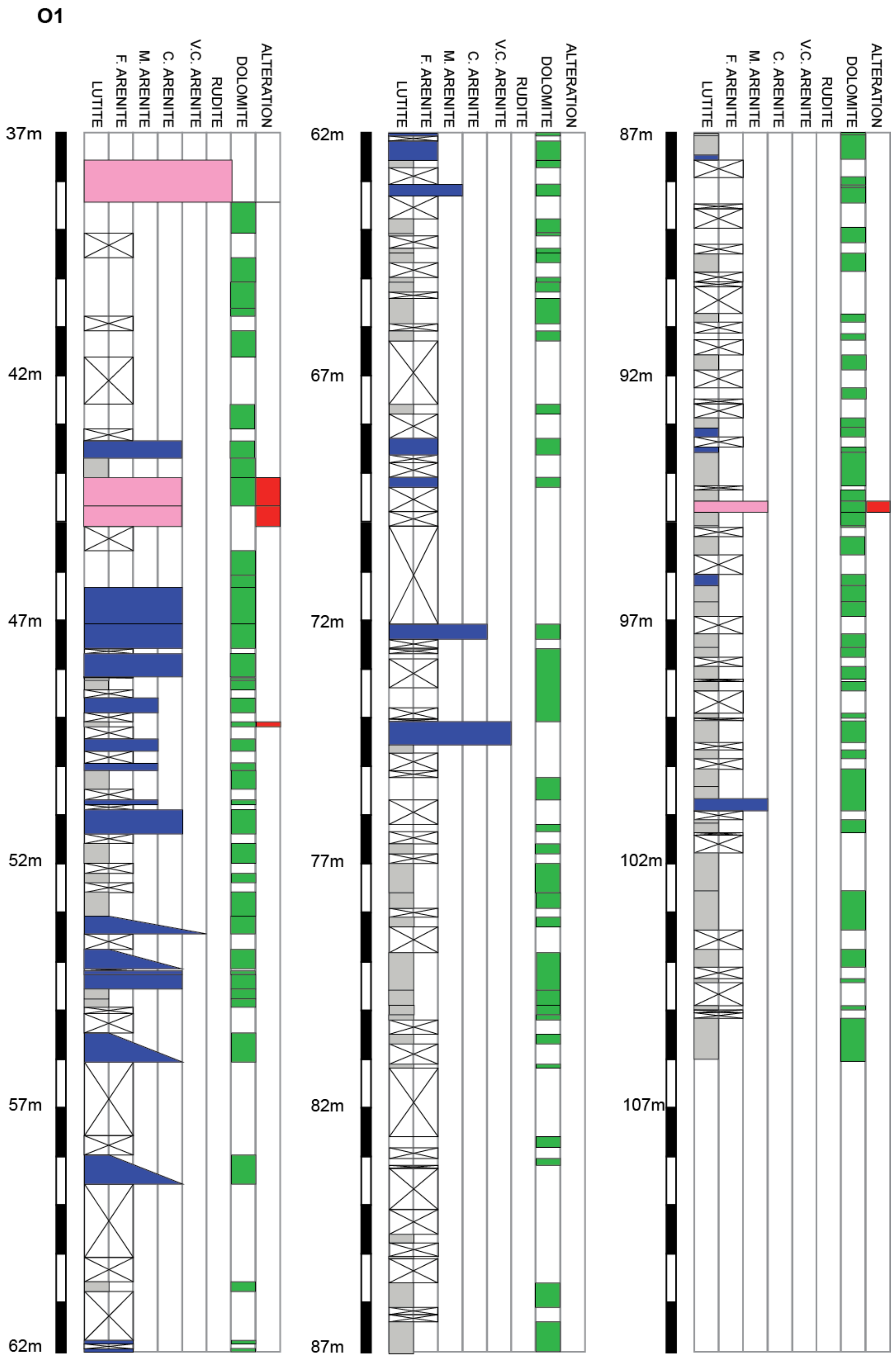

Fig 25 Summary log of BHO1

Borehole BHO1 was drilled approximately 300m west of M28 and within 20m of BHO2 (Fig 9). The summary log for borehole BHO1 is illustrated above in Fig 25 and the detailed log is given in Appendix 1. As previously discussed (section 2.2.14) a stratigraphic overlap between boreholes BHO1 and BHO2 is highly likely as they were drilled within metres of one another. However due to the pervasive dolomitisation and intense fracturing of both boreholes definitive lithological correlation is impossible.

2.2.15.1 Formation

Borehole BHO1 most likely should be assigned to the Lucan Formation (see section 1.5.4) with the top calcarenite (now entirely dolomitised) section possibly belonging to the Clondalkin Formation (section 1.5.3) but the pervasive dolomitisation has made detailed identification of lithologies very difficult.

2.2.15.2 Rock Head

Rockhead was established at 38.36m at the top of the highest dolomitised interbedded calcarenite and calcareous mudstone unit. Above this are rounded cobbles of dark limestone.

2.2.15.3 Lithological succession

Borehole BHO1 can be divided into two sections. The basal sequence from 106.00 – 74.50m is comprised of almost entirely dolomitised calcareous mudstone with very rare calcarenite beds. The second section from 74.50m to rockhead comprises dolomitised calcareous mudstones and calcarenites. Calcarenites become more numerous towards the top of the hole. It is noted that, as with BHO2, there are substantial quantities of rock missing due to sampling and ‘No Recovery’ of core (as noted by the drillers) prior to this phase of logging.

2.2.15.4 Chert

Chert was not identified in borehole BHO1

2.2.15.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

Pyrite is present but not abundant in borehole BHO1. It is also commonly seen in its oxidised state and also as gypsum most frequently on fracture surfaces. Pyrobitumen, associated with hydrothermal mineral deposits, is also recorded at two levels (82m and 86.50m).

2.2.15.6 Dolomite

Dolomite is pervasive throughout borehole BHO1. As with the other dolomitised boreholes (e.g. M28, M29) the replacement dolomite mirrors the grain size of the original lithology with coarse dolomite replacing calcarenites and fine dolomite replacing calcilutites. Some ghost structures of bioclasts are visible but the original texture of the rocks is impossible to determine. Vuggy dolomite is found in association with fractures while sugary dolomite is found in small quantities throughout the borehole.

2.2.15.7 Structural features: tectonic dip

Due to the pervasive dolomitisation and intense fracturing of borehole BHO1 few dips were measured. However, a small number of dips were recorded with values between 0º and 10º.

2.2.15.8 Structural features: veins

Borehole BHO1 is highly veined and these veins are all dolomitic. There are three vein sets within the borehole; veins dipping between 70º and sub-vertical, veins dipping between 45º and 60º and finally sub-horizontal veins.

2.2.15.9 Structural features: fractures

The majority of borehole BHO1 is described as rubble in the logs and has undergone fracturing, dolomitisation and alteration. The rock is so broken it is difficult to differentiate which processes have had what effect on the rock. It is clear however that the dominant fracture sets are steep with dips between 70º and sub-vertical but low-angle fracture sets are also recorded.

2.2.15.10 Alteration

Alteration is most likely widespread throughout borehole BHO1 but the only clear examples are noted in the logs. Alteration ranges from weakening of dolomitised mudstones to possible carbonate dissolution. A zone of potential carbonate dissolution above 45m was identified. At this level rounded rubbly clasts with patina (possibly representing cave fill) were recorded. Further indications of carbonate dissolution are the frequent zones of 'No Recovery' (as noted by the drillers).

2.3 Borehole M23 – Liassic Group

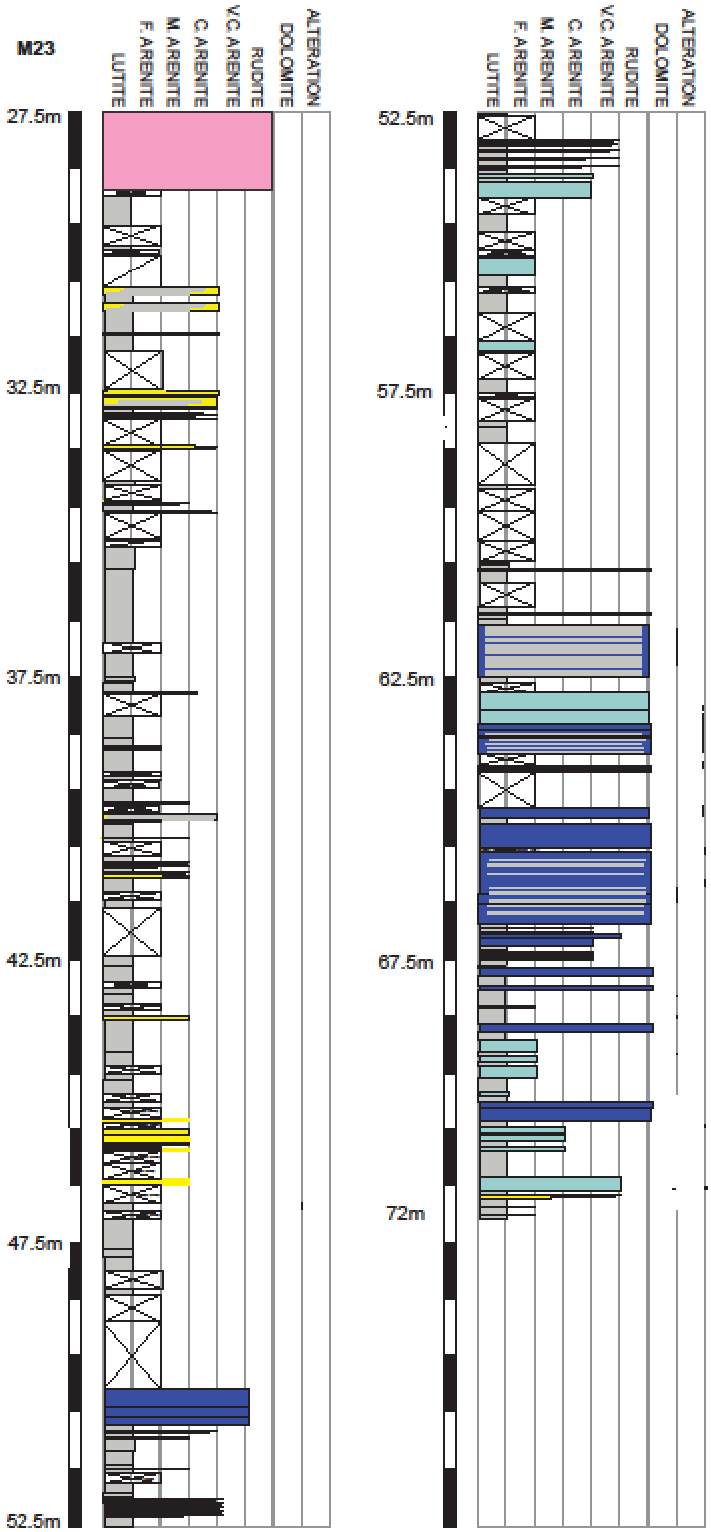

Fig 26 Summary log of M23

Borehole M23 was drilled 1500m east of borehole M22 and approximately 500m east of the Burford Bank (Fig 9). The summary log of borehole M23 is illustrated above in Fig 26 and the detailed log is given in Appendix 2. Borehole M23 is of an entirely different age to borehole M22 and thus a fault is inferred between the two boreholes, it is likely to be the Dalkey fault which bounds the Kish Bank Basin to the west.

2.2.7.1 Formation

Borehole M23 is assigned to the Liassic (see section 1.6.1)

2.2.7.2 Rock Head

Rockhead was assumed to be at 28.98m at the top of the highest interbedded calcareous sandstone and calcareous mudstone. Above this level a section of core had been removed, prior to this phase of logging, which may have included rockhead. Above this sampled section are limestone pebbles and cobbles.

2.2.7.3 Lithological succession

Borehole M23 is divided into three sequences. The basal sequence from 72.00 - 61.00 m consists of interbedded calcareous mudstones and calcirudites (as seen in photo 3 below). A number of 'shell beds' are recorded with abundant brachiopods. Siliciclastic sand is recorded within some of the calcareous mudstone units. Above this, from 61.00 - 49.00 m, the borehole comprises interbedded calcareous shale with thin calcarenites. A macroscopic example of the crinoid *pentacrinites* is recorded at 51.39m. Siliciclastic material is recorded including grains (< 1mm in size) which are believed to be derived from the Lower Palaeozoic. The final sequence from 49.00m to rockhead is composed of calcareous shale interbedded with thin calcareous sandstone units.

2.2.7.4 Chert

No chert was identified in borehole M23.

2.2.7.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

No pyrite was recorded below 52.00m. Above this level pyrite is present but is relatively minor. Gypsum was also recorded.

2.2.7.6 Dolomite

No dolomite was identified in borehole M23.

2.2.7.7 Structural features: tectonic dip

The tectonic dips within borehole M23 range from 0° - 14°. The average dip is 8° and this value is taken as the dip for borehole M23.

2.2.7.8 Structural features: veins

Only three veins are recorded in borehole M23 with dips of 50°, 70° and sub-vertical. The veins are composed of calcite.

2.2.7.9 Structural features: fractures

Borehole M23 is not highly fractured. Fractures range from 50° - vertical with the majority dipping at 80°. Only one fracture was recorded having a clay film.

2.2.7.10 Alteration

No alteration is recorded in borehole M23.

Photo 3. Core box containing a section of borehole M23.

Part III. Geology of the Boreholes of the Southern Alignment Drilling Line

3.1 Summary information from the Boreholes of the Southern Alignment

3.1.1 Location of Boreholes

The southern alignment drilling line comprises 9 boreholes all of which are offshore. The location of each borehole is marked below on Fig. 27. The boreholes shall be discussed in stratigraphic order beginning with the oldest, the Lower Palaeozoic rocks in the east of the bay.

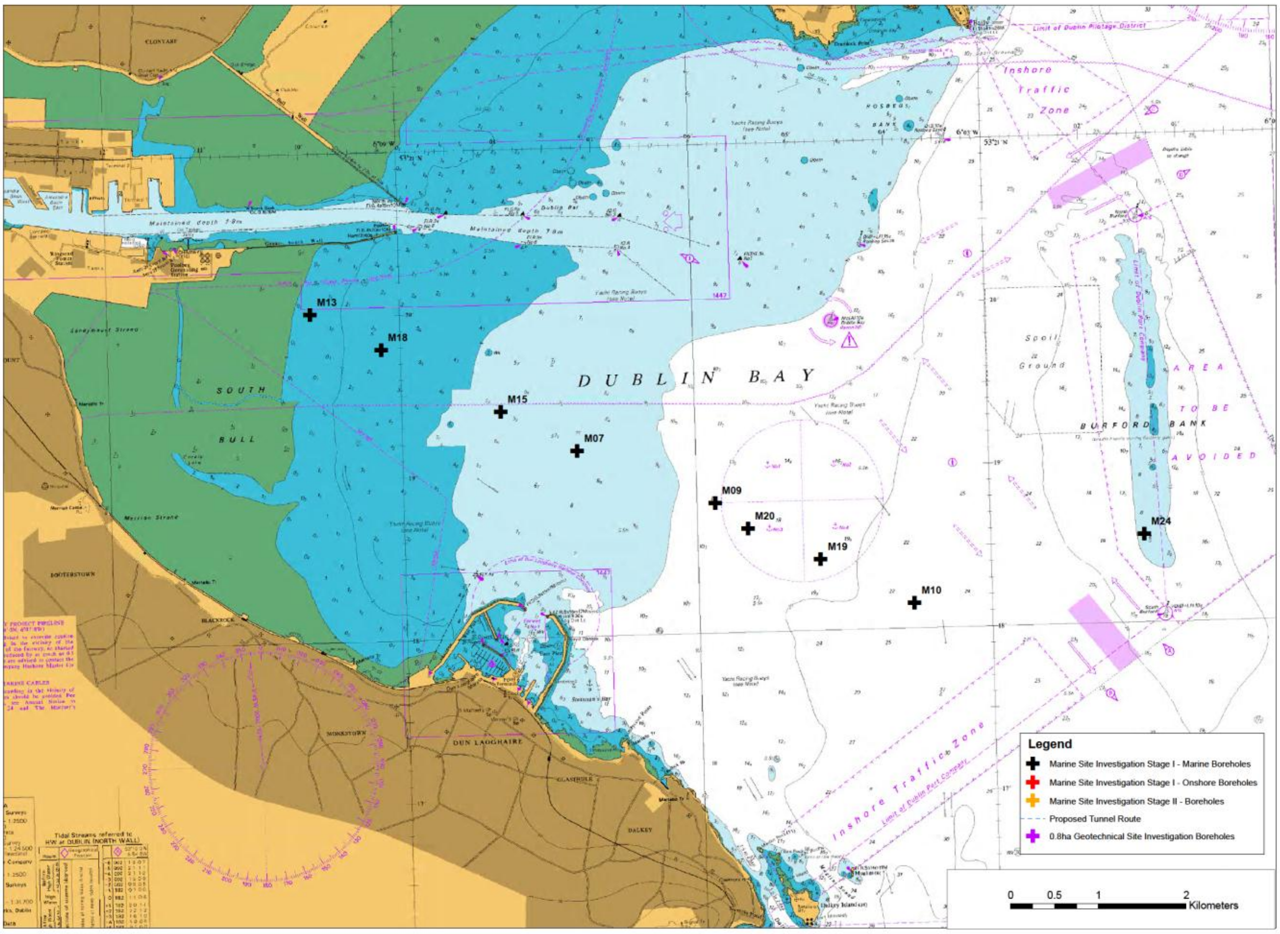

Figure 27. Location of the boreholes relevant to the Southern Alignment (modified from a map supplied by CDM Smith).

3.1.2 Key to Symbols Used in the Summary Logs

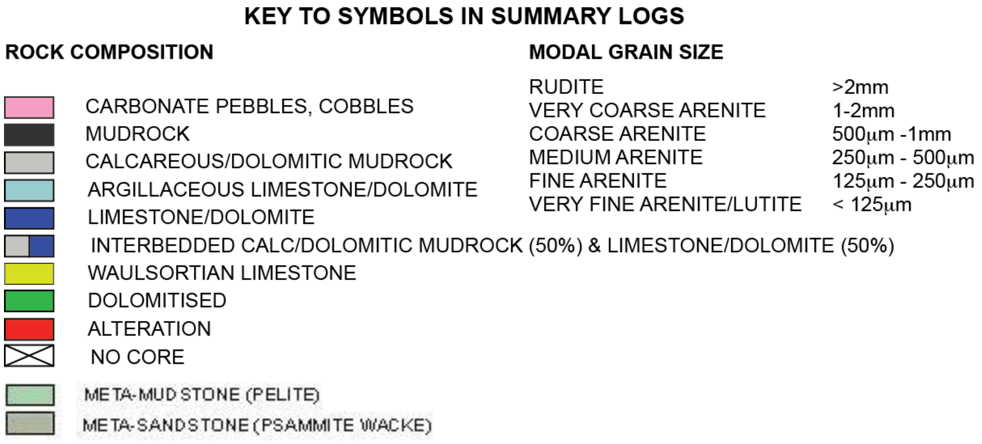

Figure 28. Key to symbols used in summary logs

3.2 Summary Logs

3.2.1 Borehole M24

Fig 29 Summary log of M24

Borehole M24 was drilled on the south-western edge of the Burford Bank approximately 1900m south-east of M22 and over 2750m from the nearest borehole, M10, on the southern alignment (Fig 27). The summary log of borehole M24 is illustrated above in Fig 29 and the detailed log given in Appendix 2.

3.2.1.1 Formation

Borehole M24 has been assigned to the Lower Palaeozoic Bray Group (see section 1.3)

3.2.1.2 Rock Head

Rockhead is assumed to be at 44.75m as no material above this level was boxed.

3.2.1.3 Lithological succession

Only 11.25m of core was drilled in borehole M24. The borehole comprises interbedded meta-sedimentary rock with almost equal proportions of fine grained pelites and coarser psammites. A large graded unit is recorded at the top of the borehole. The metasedimentary rocks of borehole M24 bare similarities to those of borehole M22 but appear to potentially be of a slightly higher metamorphic grade.

3.2.1.4 Chert

No chert was identified in borehole M24.

3.2.1.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

No pyrite was identified in borehole M24 but chlorite was seen on some fracture surfaces.

3.2.1.6 Dolomite

No dolomite was identified in borehole M24.

3.2.1.7 Structural features: tectonic dip

Only one dip measurement (35º) was taken.

3.2.1.8 Structural features: veins

Borehole M24 is intensely veined. Veins are composed of quartz and are present both as anastomosing vein sets, white vein sets and 'rusty' vein sets. The white and 'rusty' vein sets have dips ranging from 50º to vertical and thicknesses <15mm.

3.2.1.9 Structural features: fractures

Borehole M24 is intensely fractured. Fractures have dips ranging from 30º to vertical. Clay films are recorded on the 85º fractures and staining on the 80º and 45º fractures.

3.2.1.10 Alteration

Alteration in borehole M24 is minor. It is only recorded as staining on fracture surfaces and irregular colouration of some rocks.

3.2.2 Borehole M10

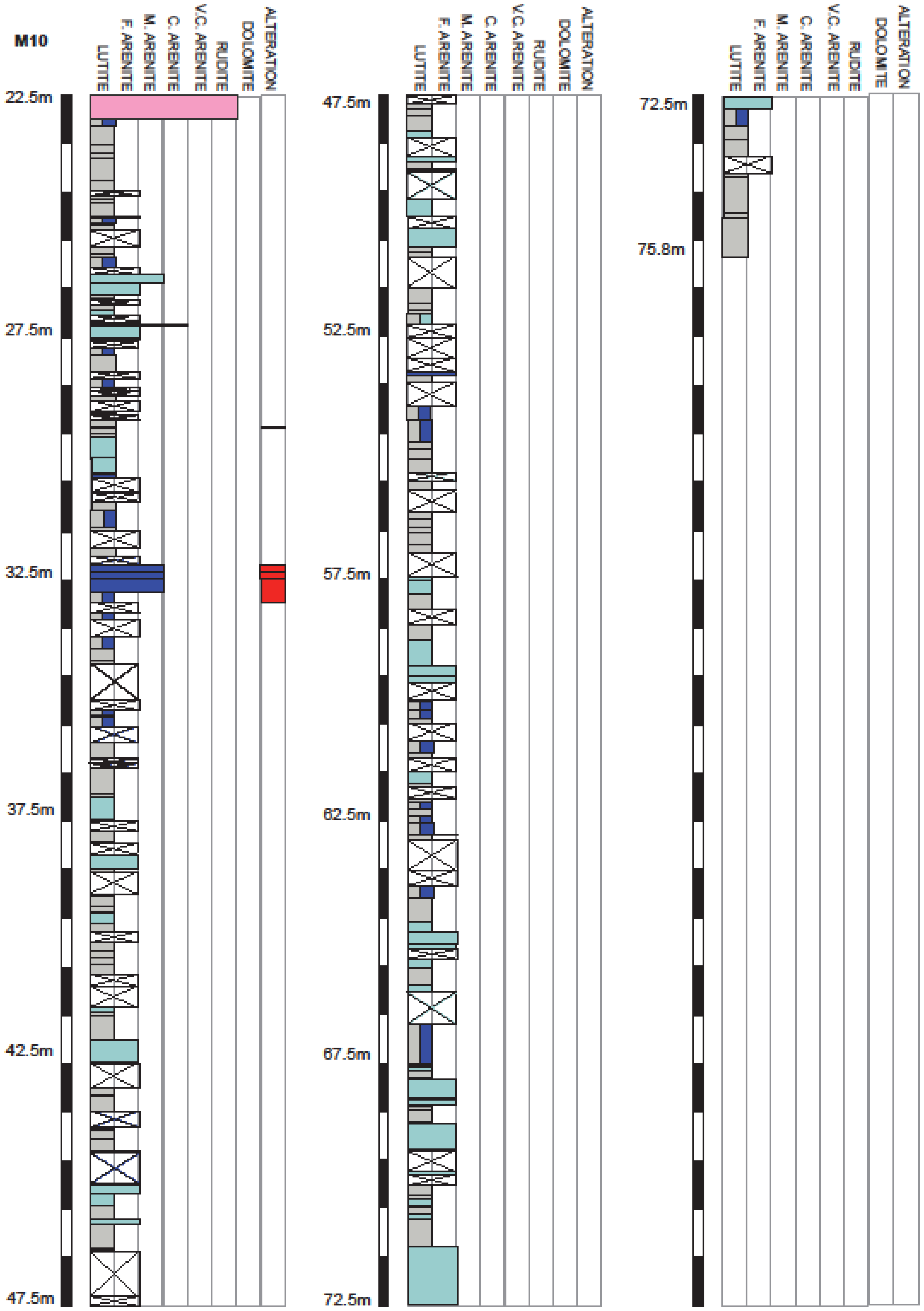

Fig 30 Summary log of M10

Borehole M10 was drilled over 2750m from borehole M24 and approximately 1250m south-east of M19 (Fig 27). The summary log of borehole M10 is illustrated above in Fig 30 and its detailed log is given in Appendix 2. Given the distance between boreholes M10 and M19 it is unlikely any stratigraphic overlap is present.

3.2.2.1 Formation

Borehole M10 is assigned to the Malahide Formation (see section 1.5.1)

3.2.2.2 Rock Head

Rockhead is assumed to be at 22.98m at the top of the uppermost unit of calcareous mudstone and calcisiltite rubble. No material is boxed above this level.

3.2.2.3 Lithological succession

The entirety of borehole M10 consists of calcareous mudstones (60%) interbedded with argillaceous fine-grained calcarenites. There is one thick unit of calcarenite at 32.50m that is medium-grained and not argillaceous.

3.2.2.4 Chert

Chert only occurs below 59.25m. It is present as bands (<60mm at 68.70m), nodules (<80x20mm at 65m) and as silicified (chert) mudstone.

3.2.2.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

Pyrite is common throughout borehole M10 in all lithologies.

2.2.2.6 Dolomite

Dolomite was not identified in borehole M10.

2.2.2.7 Structural features: tectonic dip

The tectonic dips within borehole M10 range from 10º - 45º with a modal value of 30º.

3.2.2.8 Structural features: veins

Calcite veins are present throughout borehole M10 with dips ranging from 40º to vertical. The majority are between 1 and 5mm in thickness.

3.2.2.9 Structural features: fractures

Borehole M10 is not highly fractured. Fractures range from 70º to vertical. Some fractures have <2mm of clay films on them.

3.2.2.10 Alteration

There is only one zone of alteration in borehole M10 at 33.08 – 31.62m. This alteration has caused weakening and bleaching of both the calcareous mudstones and the calcarenites.

3.2.3 Borehole M19

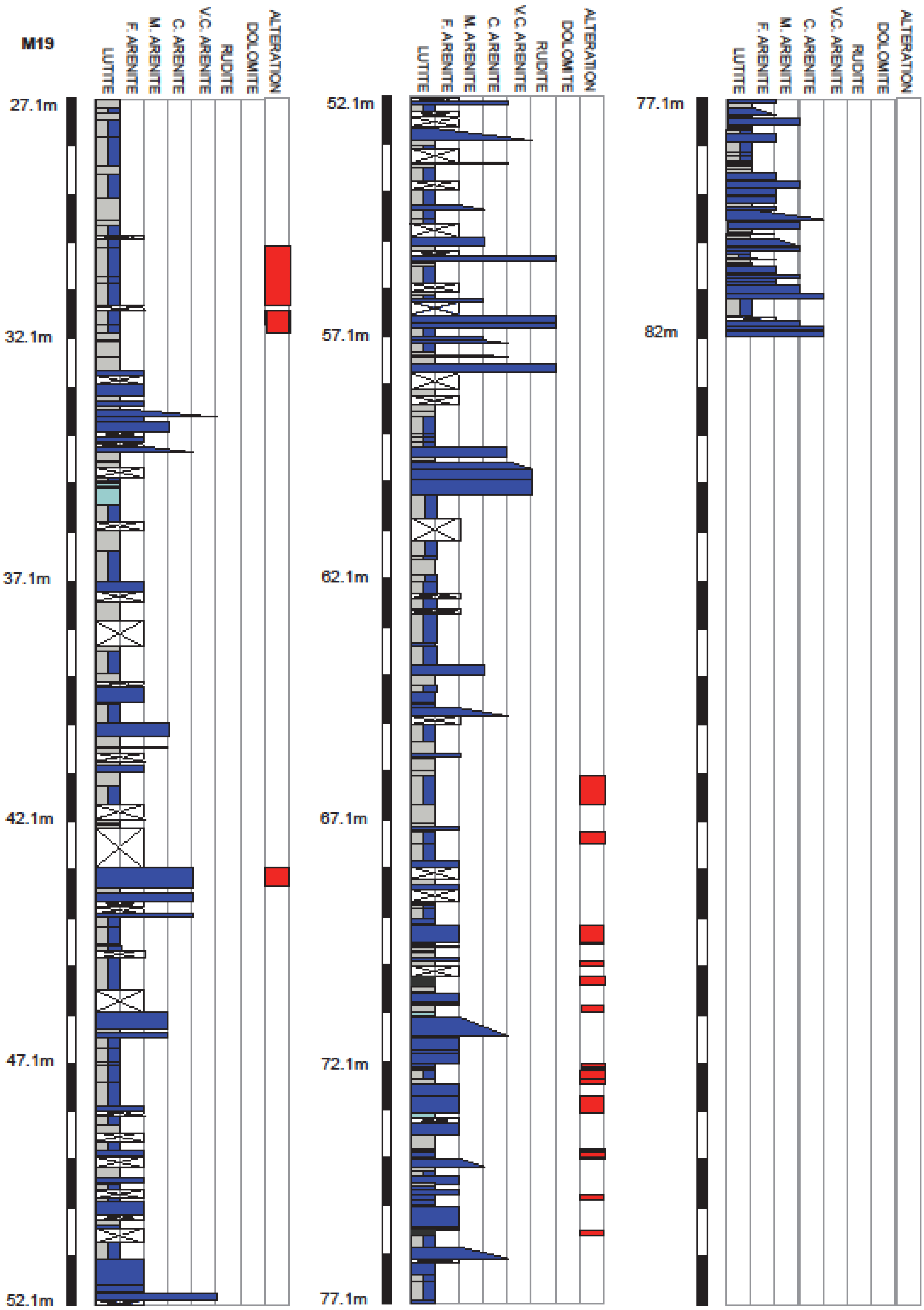

Fig 31 Summary log of M19

Borehole M19 was drilled approximately 1250m north-west of M10 and 1200m south-east of borehole M20 (Fig 27). The summary log of borehole M19 is illustrated above in Fig 31 and the detailed log is given in Appendix 2. Given the distances between borehole M19 and boreholes M10 and M20 it is unlikely that any stratigraphic overlap will be found.

3.2.3.1 Formation

Borehole M19 is assigned to the Lucan Formation (see section 1.5.4)

3.2.3.2 Rock Head

Rockhead was established at 27.10m at the top of the highest calcareous mudstone unit as no material above this level was boxed.

3.2.3.3 Lithological succession

Borehole M19 is divisible into several sections. Beginning at the base, from 82.00 – 69.50m, the borehole is dominated by calcarenite beds (90%). These calcarenite beds range in grain-size from fine to coarse with several graded beds. The calcarenite beds are interbedded with subordinate calcilutites. From 69.50 – 60.00m the section comprises interbedded calcilutites (90%) with rare calcarenite beds. Above this, from 60.00 – 33.00m, the borehole contains interbedded calcilutites (70%) with medium to coarse-grained calcarenite beds. The uppermost section, from 33.00m to rockhead comprises solely interbedded calcilutites.

There is a unit of note at 60.00m. It is a graded unit with a fine calcarenite matrix containing lithoclasts of both limestone and Lower Palaeozoic material. Also contained within this unit are chert pebbles <12mm at the base. The abundance of clasts decreases upwards. The unit is also intensely and erratically veined (calcaite).

3.2.3.4 Chert

Chert is common throughout borehole M19 and is found as both bands (<30mm) and as nodules (<30x50mm).

3.2.3.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

Pyrite is common throughout borehole M19. Gypsum is also present but less abundant.

3.2.3.6 Dolomite

Dolomite was not identified in borehole M19

3.2.3.7 Structural features: tectonic dip

The tectonic dips within borehole M19 range from 0º - 45º with a modal value of 10º. 10º shall be taken as the tectonic dip for borehole M19.

3.2.3.8 Structural features: veins

Calcite veining is common throughout borehole M19 with some units intensely veined. The dips of these veins range from 30º - vertical. The majority are <1mm with occasional veins reaching <18mm in thickness.

3.2.3.9 Structural features: fractures

Borehole M19 is not highly fractured. Fractures range in dip from 70º to vertical.

3.2.3.10 Alteration

Within borehole M19 there is one zone of alteration, from 66.50 – 76.00m, and two smaller horizons of alteration, one at 43.00m and the other at 31.70m. Alteration manifests largely as colour alteration –bleaching. However alteration in areas of calcareous shale has commonly resulted in loss of strength of the rock and in some instances the reduction of the rock to plastic clay.

3.2.4 Borehole M20

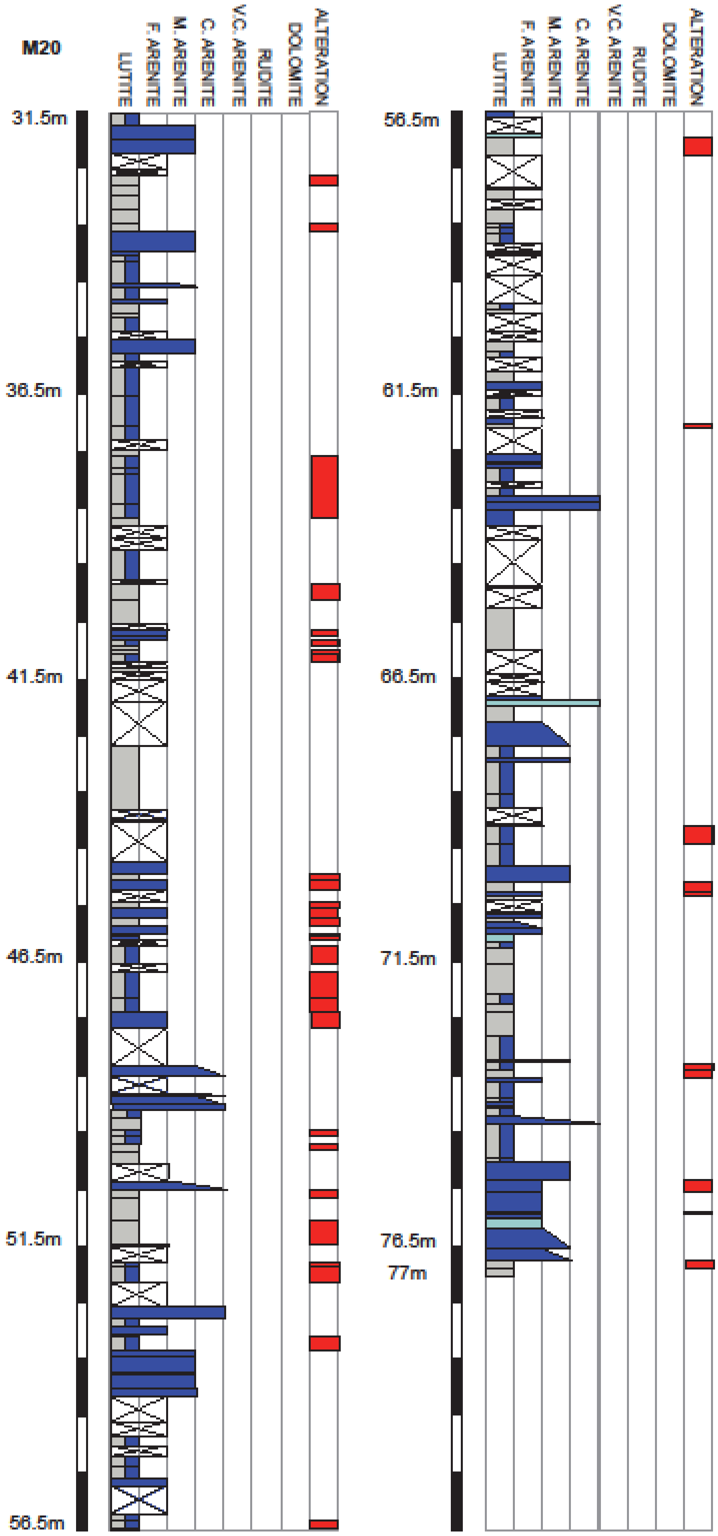

Fig 32 Summary log of M20

Borehole M20 was drilled approximately 1200m north-west of M19 and just less than 500m south-east of borehole M09 (Fig 27). The summary log for borehole M20 is illustrated above in Fig 32 and the detailed log given in Appendix 2. As previously discussed, in section 3.2.3 there is unlikely to be a stratigraphic overlap between boreholes M20 and M10. However, due to the proximity of borehole M09 to borehole M20 it is possible that there would be a stratigraphic overlap between these boreholes.

3.2.4.1 Formation

Borehole M20 has been assigned to the Lucan Formation (see section 1.5.4)

3.2.4.2 Rock Head

Rockhead was established at 31.50m at the top of the uppermost interbedded calcareous mudstone and calcarenite. No material was boxed above this level.

3.2.4.3 Lithological succession

The lithology of borehole M20 is largely uniform. The section is comprised interbedded calcilutites (70%) and calcarenites with local concentrations of calcarenites such as the basal 2.5m.

3.2.4.4 Chert

Chert was identified at four levels in borehole M20. There are three nodular occurrences, the first at 79.00m measures 10mm, the second at 63.08m measures 60mmand the third at 31.70m and measured 60x6mm. One band of chert was recorded at 37.25m and measured 25mm.

3.2.4.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

Pyrite is found throughout borehole M20 but is most prevalent in calcareous mudstones and shale. Gypsum is also recorded but with lower abundances than the pyrite.

3.2.4.6 Dolomite

No dolomite was identified in borehole M20.

3.2.4.7 Structural features: tectonic dip

The tectonic dips of borehole M20 range from 10º - 30º with a modal value of 20º. 20º shall be taken as the dip of borehole M20.

3.2.4.8 Structural features: veins

Veins are common throughout borehole M20. All veins are calcitic with possible dolomite recorded in the deepest veins. Veins are largely thin (<1mm) with maximum thicknesses of <16mm and with one bed-parallel composite vein measuring 40mm. Veins dip between 0º and vertical.

3.2.4.9 Structural features: fractures

Borehole M20 is not highly fractured. Fractures dip between 70º and vertical.

3.2.4.10 Alteration

Alteration occurs throughout borehole M20 but is largely restricted to calcareous mudstone and calcareous shale bearing units. Alteration ranges from colour alteration and bleaching through loss of strength of the rocks to reduction of the rocks to plastic mud.

3.2.5 Borehole M09

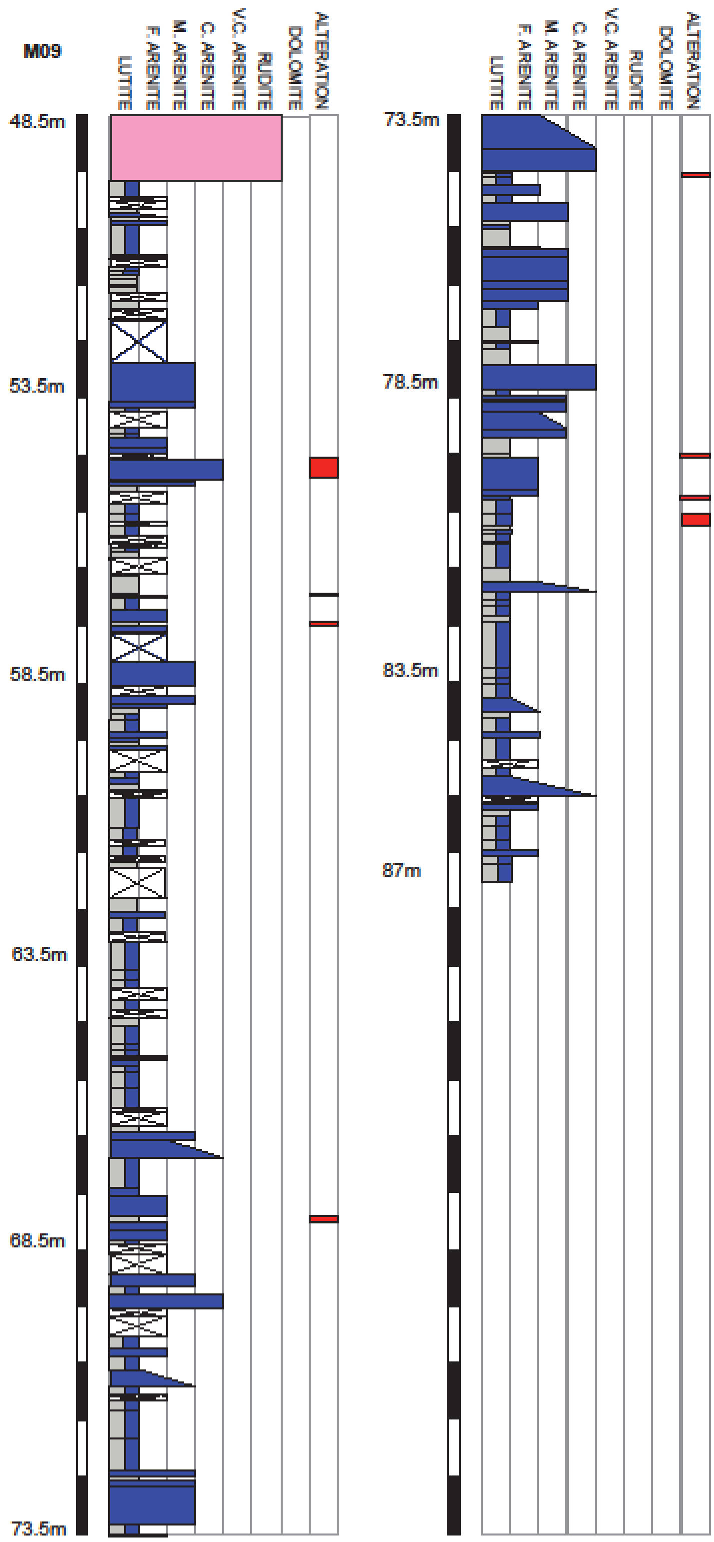

Fig 33 Summary log of M09

Borehole M09 was drill just under 500m north-west of M20 and approximately 1750m south-east of borehole M07 (Fig 27). The summary log of borehole M09 is illustrated above in Fig 33 and the detailed log given in Appendix 2. As previously discussed in section 3.2.4 there is likely to be a stratigraphic overlap between boreholes M09 and M20. Given the distance from borehole M09 to borehole M07 a stratigraphic overlap is unlikely between these two boreholes.

3.2.5.1 Formation

Borehole M09 is assigned to the Lucan Formation (see section 1.5.4)

3.2.5.2 Rock Head

Rockhead was established at 48.14m at the top of the uppermost unit of laminated calcareous mudstone and calcisiltite. Above this unit lies plastic mud with pebbles of limestone.

3.2.5.3 Lithological succession

Borehole M09 is divided into three successions. The first, from the end of the hole to 80.50m, consists of interbedded calcilutites (80%) with subordinate graded calcarenites. Above this, from 80.50 – 72.50m, is a sequence of thick calcarenite beds (80%) with interbedded calcilutites. The majority of calcarenites are medium-grained. The final succession, from 72.50m to rockhead, is similar to the first with interbedded calcilutites dominant (80%) and a minor calcarenite component.

3.2.5.4 Chert

Chert occurs at two levels in borehole M09. Both occurrences are nodular, the first at 80.20m measures 10mm and the second at 74.74m measures 35mm.

3.2.5.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

Pyrite is commonly found throughout borehole M09 both in the calcilutites, the calcarenites and within veins. Gypsum is also present but with lower abundances.

3.2.5.6 Dolomite

No dolomite was identified in borehole M09.

3.2.5.7 Structural features: tectonic dip

The tectonic dips of borehole M09 range from 0º - 30º with a modal value of 10º. 10º shall be taken as the dip of borehole M09.

3.2.5.8 Structural features: veins

Borehole M09 is not highly veined. The majority of veins are thin (<1mm) with rare thick veins (<24mm). Veins dip between 60º and vertical.

3.2.5.9 Structural features: fractures

Fractured are common throughout borehole M09. Fractures range from 70º and vertical. Orthogonal, vertical veins are also recorded. Some fractures have clay films.

3.2.5.10 Alteration

Alteration is minor in borehole M09. Calcareous shale is preferentially altered with colour alteration, weakening of the rock and reduction of the rock to plastic mud. Altered calcarenites however become friable.

3.2.6 Borehole M07

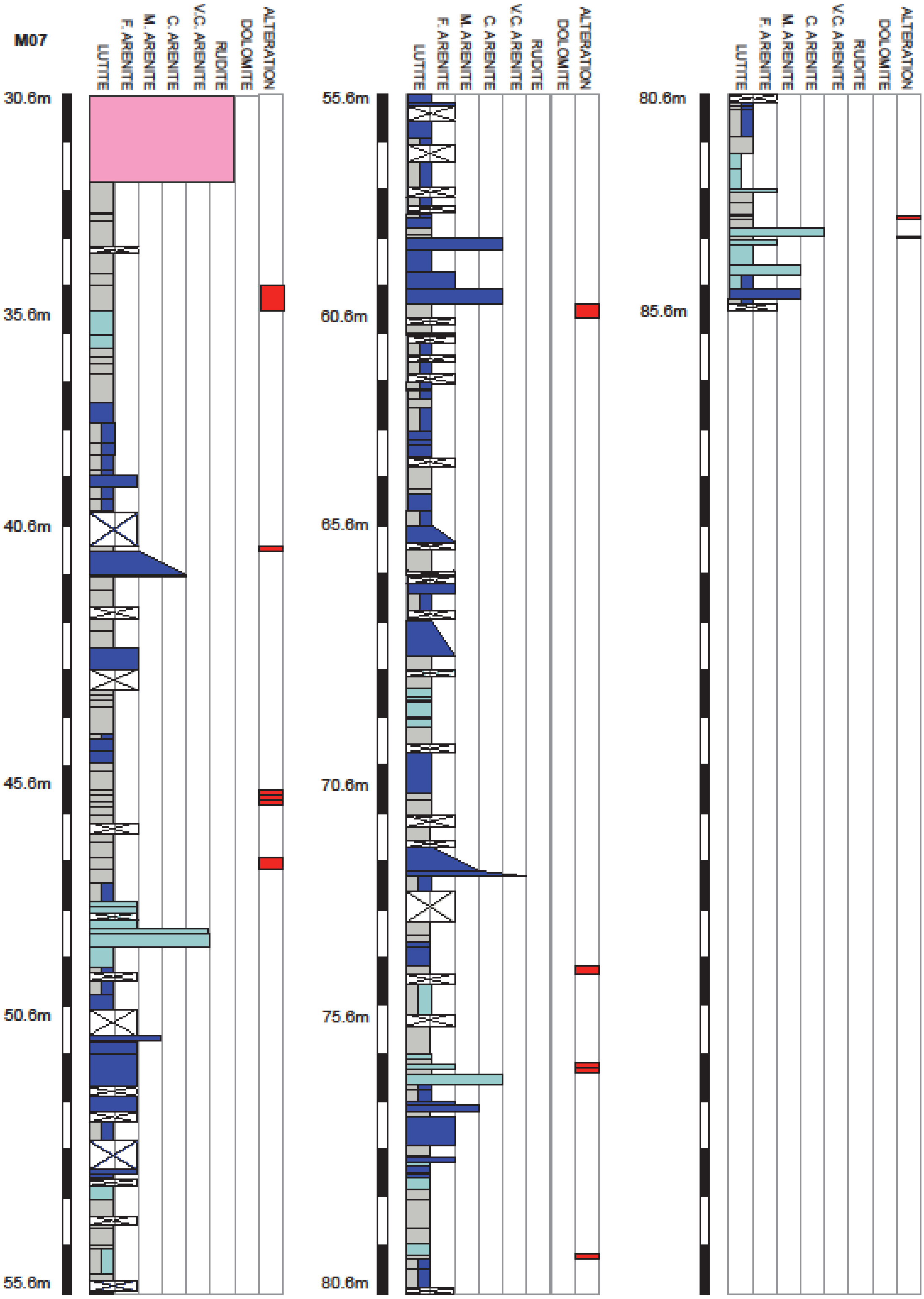

Fig 34 Summary log of M07

Borehole M07 was drilled 1750m south-west of borehole M09 and less than 1000m south-east of M15 (Fig 27). The summary log of borehole M07 is illustrated above in Fig 34 and the detailed log is given in Appendix 2. As previously discussed in section 3.2.5 there is unlikely to be a stratigraphic overlap between boreholes M07 and M09. Similarly it is unlikely there would be a stratigraphic overlap between boreholes M07 and M15.

3.2.6.1 Formation

Borehole M07 is assigned to the Lucan Formation (see section 1.5.4)

3.2.6.2 Rock Head

Rockhead was established at 32.40m at the top of the uppermost unit of calcareous mudstone. Above this level the drillers have noted that the core has slipped and also have described the occurrence of loose pebbles of limestone.

3.2.6.3 Lithological succession

The succession in borehole M07 is largely uniform throughout. The section is dominated by interbedded calcilutites (80%) with subordinate calcarenite beds, although there are several zones where calcarenites are locally dominant. Some of the calcarenite beds are argillaceous while some exhibit grading.

3.2.6.4 Chert

There is only one occurrence of chert in borehole M07, where a 20mm-thick zone of chertified calcarenite was encountered at 50.26m.

3.2.6.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

Pyrite is common below 54.00m, with numerous layers containing macroscopic pyrite, but is largely absent above this level. Gypsum is recorded throughout borehole M07.

3.2.6.6 Dolomite

Dolomite was not identified in borehole M07.

3.2.6.7 Structural features: tectonic dip

The tectonic dips of borehole M07 range from 0° - 30° with a modal value of 20°. 20° is taken as the tectonic dip for borehole M07.

3.2.6.8 Structural features: veins

Calcite veins are common throughout borehole M07. The majority of veins are <1mm with maximum thicknesses of 20mm. Veins dip between 70° - vertical.

3.2.6.9 Structural features: fractures

Fractures are widespread in borehole M07. Fractures dip between 70° and vertical. Clay films and fills are common with fills >8mm thick.

3.2.6.10 Alteration

The alteration in borehole M07 is relatively minor and is evenly distributed throughout the borehole. Alteration is largely restricted to calcareous mudstone and calcareous shale. Some calcareous mudstone and shale are bleached while others have been reduced to a plastic clay. Alteration in calcarenites is largely manifested as weakening of the rock.

3.2.7 Borehole M15

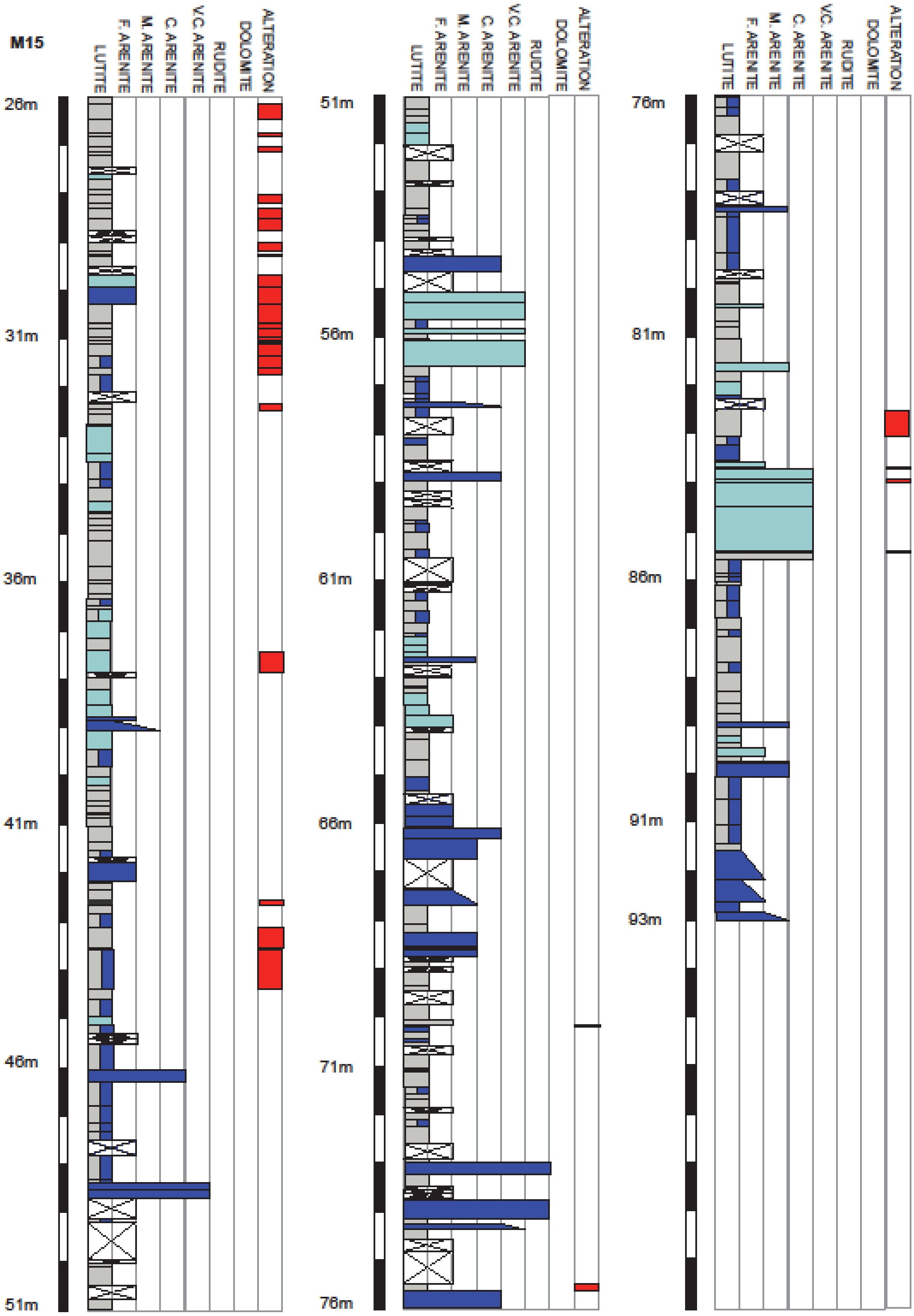

Fig 35 Summary log of M15

Borehole M15 was drilled less than 1000m north-west of borehole M07 and approximately 1600m south-east of borehole M18 (Fig 27). The summary log of borehole M15 is illustrated above in Fig 35 and the detailed log is given in Appendix 2. As previously discussed in section 3.2.6 there is unlikely to be a stratigraphic overlap between boreholes M15 and M07. Similarly the significant distance between boreholes M15 and M18 means it is unlikely that there would be a stratigraphic overlap between them.

3.2.7.1 Formation

Borehole M15 is assigned to the Lucan Formation (see section 1.5.4).

3.2.7.2 Rock Head

Rockhead was assumed to be at 26.10m at the top of the highest calcareous mudstone unit. There was no material boxed above this level.

3.2.7.3 Lithological succession

Borehole M15 can be divided into two sequences. The basal succession from 93.00 - 40.00m comprises interbedded calcilutites (70%) and calcarenites. The calcarenite beds are predominantly coarse to very coarse-grained with the very coarse-grained units being argillaceous. Above this, from 40.00m to rockhead the section comprised of almost entirely of interbedded calcilutites (90%+) with approximately 30% of beds being argillaceous.

3.2.7.4 Chert

Chert was not identified in borehole M15 below 70.10m. Above this level several occurrences of chert are recorded. At four levels chert nodules have been noted up to a maximum size of 70 x 100mm. Two zones of chertification were recorded, one at 46.25m and the other at 41.75m.

3.2.7.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

Pyrite is present but is not abundant in borehole M15.

3.2.7.6 Dolomite

No dolomite was identified in borehole M15.

3.2.7.7 Structural features: tectonic dip

The tectonic dips in borehole M15 range from 0° to 45° with a modal value of 10°. 10° is taken as the tectonic dip of borehole M15.

3.2.7.8 Structural features: veins

Calcite veins are common throughout borehole M15 with the majority <1mm and with a maximum thickness of 12mm. Veins dip between 30° to vertical.

3.2.7.9 Structural features: fractures

Borehole M15 is highly fractured with many fractures having clay films. Fractures dip between 20° and sub-vertical.

3.2.7.10 Alteration

The alteration in borehole M15 is concentrated above 44.00m. The alteration is restricted to calcareous mudstone units. Many of these units are weakened with many reduced to plastic clay.

3.2.8 Borehole M18

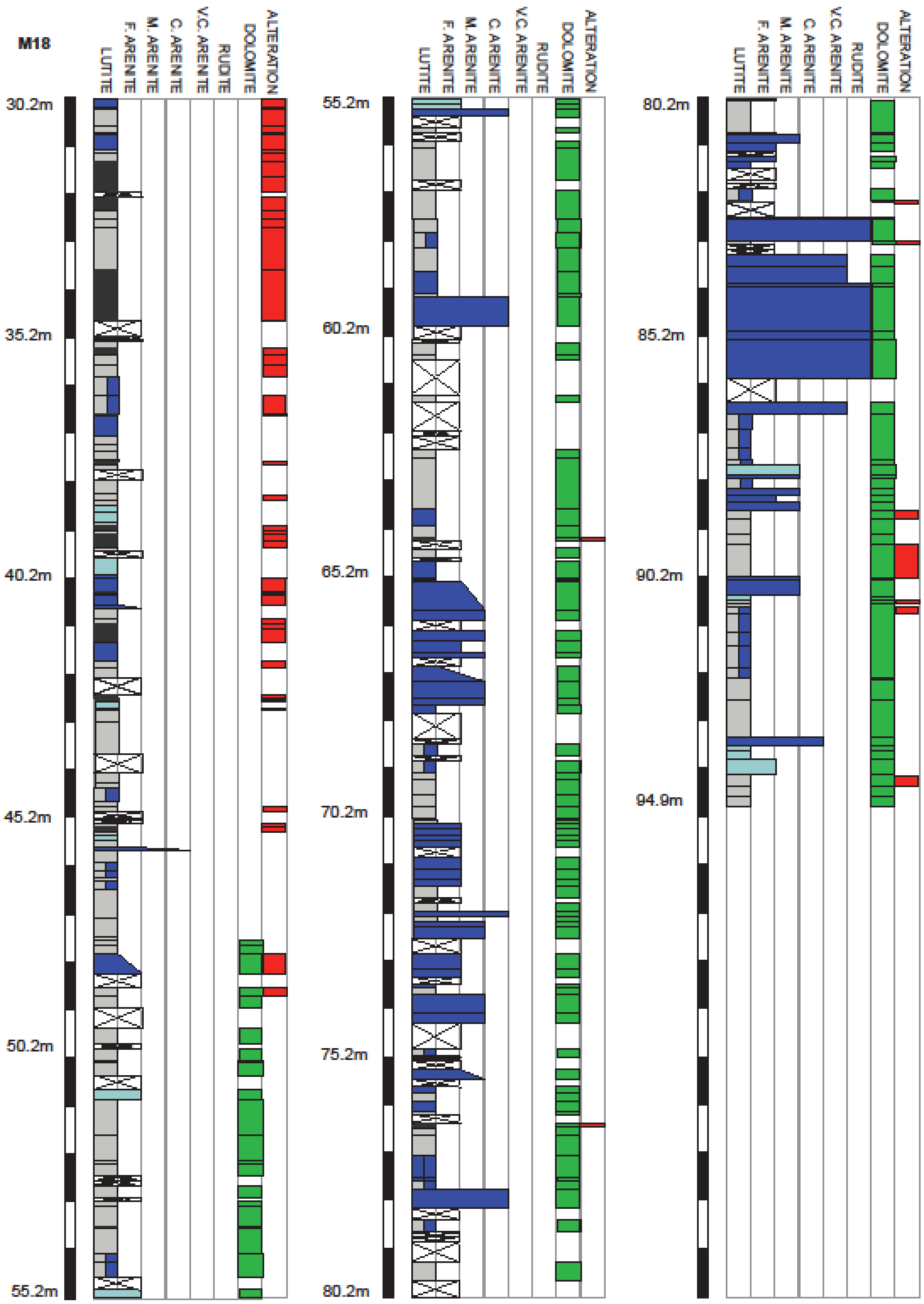

Fig 36 Summary log of M18

Borehole M18 was drilled approximately 1600m north-west of borehole M15 and approximately 1000m south-east of borehole M13 (Fig 27). The summary log for borehole M18 is illustrated above in Fig 36 and the detailed log given in Appendix 2. As previously discussed, in section 3.2.7 it is unlikely that there is a stratigraphic overlap between boreholes M18 and M15. Similarly the large distance between boreholes M18 and M13 means it is unlikely that there would be a stratigraphic overlap between them.

3.2.8.1 Formation

Borehole M18 is assigned to the Lucan Formation (see section 1.5.4).

3.2.8.2 Rock Head

Rockhead is assumed to be at 30.20m at the top of the uppermost calcisiltite unit. There is no material boxed above this level.

3.2.8.3 Lithological succession

The dolomitisation in borehole M18 below 48.00m is discussed below in section 3.2.8.6. Borehole M18 may be divided into four successions. The basal sequence from 94.90 - 86.00m is dominated by dolomitised calcilutites (70%) interbedded with dolomitised calcarenite beds. There is one intensely veined crackle breccia bed recorded at 83.48m. Above this, from 86.00 - 81.00m, the section is almost entirely comprised of thick interbedded dolomitised calcirudite and calcarenite beds (90%+) with rare dolomitised calcilutites. From 81.00 - 60.00m is a sequence of dolomitised medium-grained calcarenite beds (70%) interbedded with dolomitised calcilutites. The uppermost succession from 60.00m to rockhead consists of interbedded calcareous mudstones (80%) and calcisiltites. This section is dolomitised in the basal 60.00 – 48.00m.

3.2.8.4 Chert

No chert was identified in borehole M18.

3.2.8.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

No pyrite was identified above 44.80m. Below this level however, pyrite is common throughout the borehole with zones of conspicuous pyrite (e.g. from 72.25 - 62.51m). Bornite was recorded at several horizons with a prominent occurrence at 87.45m. Other minerals identified include jarosite (e.g. at 67.35m) and galena (e.g. at 71.45m) which are both found in association with veining.

3.2.8.6 Dolomite

Borehole M18 is pervasively dolomitised from 94.90m - 48.00. Replacement dolomite reflects the original texture of the rock with coarse dolomite replacing coarse-grained calcarenites and fine dolomite replacing calcilutites.

3.2.8.7 Structural features: tectonic dip

The tectonic dips of borehole M18 range from 10° - 60° with a modal value of 40°. 40° is taken as the tectonic dip of borehole M18.

3.2.8.8 Structural features: veins

Borehole M18 is highly veined with the majority of veins >1mm with maximum thicknesses of 50mm. Above 48.00m the veins are comprised of calcite and below this level they are dolomite. Galena and jarosite are found in several veins. The veins dip between 20° - 70°.

3.2.8.9 Structural features: fractures

Borehole M18 is highly fractured with the core reduced to rubble at numerous levels. The fractures dip from 50° to vertical and several fractures have clay films.

3.2.8.10 Alteration

Alteration is restricted to two zones. From 94.90m - 89.00 alteration is manifested as weakening of the rock and in some instances the reduction of the rock to a plastic mud. A second zone of alteration is recorded from 48.00m to rockhead which is similar in style but more pervasive with bleaching also recorded.

3.2.9 Borehole M13

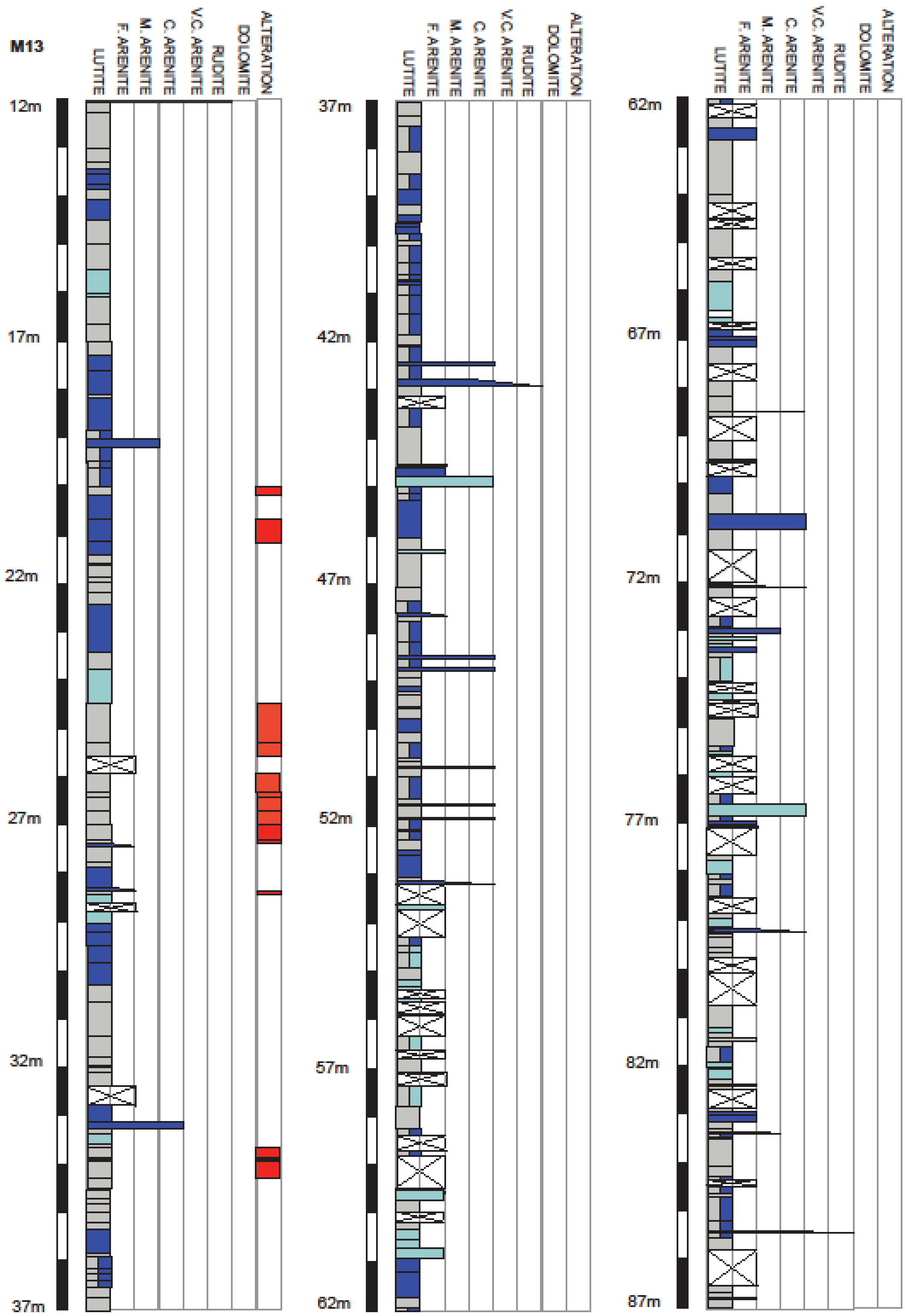

Fig 37 Summary log of M13

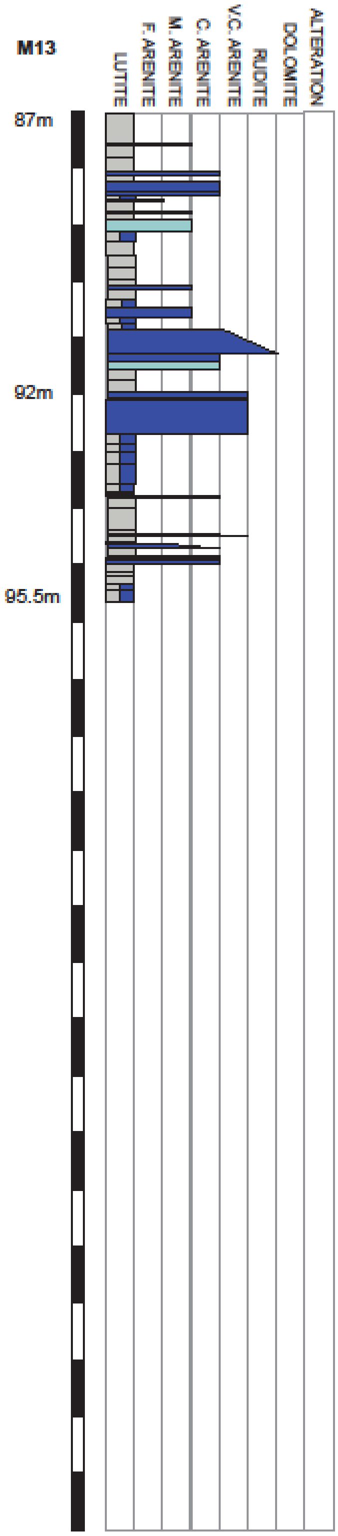

Fig 37 Summary log of M13

Borehole M13 was drilled approximately 1000m north-west of borehole M18 and approximately 1300m south-east of boreholes BHO1 and BHO2 (Fig 27). The summary log of borehole M13 is illustrated above in Fig 37 and the detailed log is given in Appendix 2.

3.2.9.1 Formation

Borehole M13 is assigned to the Lucan Formation (see section 1.5.4)

3.2.9.2 Rock Head

Rockhead was established at 11.98m at the top of the uppermost calcareous mudstone unit. This unit is overlain by pebbles.

3.2.9.3 Lithological succession

Borehole M13 is divided into four sections. The basal section from 95.55 - 87.00m comprises calcilutites (60%) interbedded with calcarenite units. The calcarenite units range in grain-size from medium to very coarse. From 87.00 - 53.00m the section is largely dominated by calcareous mudstone (80%) interbedded with thin calcarenite beds. The sequence from 53.00 - 42.50m borehole comprises interbedded calcilutites (80%) with rare, thin, coarse-grained calcarenite beds. The final succession extends from 42.50 to rockhead and contains interbedded calcareous mudstone and calcisiltites with only three thin calcarenite beds recorded.

3.2.9.4 Chert

Chert is identified at three levels in borehole M13. At 88.37m and at 43.10m chert nodules are recorded with the lower occurrence having dimensions of (50 x 80mm). At 48.63m a chertified calcarenite is also recorded.

3.2.9.5 Pyrite, other sulphides, gypsum and miscellaneous secondary minerals

Pyrite is found throughout borehole M13 but in small quantities.

3.2.9.6 Dolomite

Dolomite was not identified in borehole M13.

3.2.9.7 Structural features: tectonic dip

The tectonic dips within borehole M13 range from 0° - 45° with a modal value of 10°. This value shall be taken as the dip for borehole M13.

3.2.9.8 Structural features: veins

Calcite veins are common throughout borehole M13 with the majority <1mm. At 66.40m fluorite is recorded in a calcite vein. There are two vein sets present in borehole M13; a bed-parallel set and a set ranging from 70° - vertical.

3.2.9.9 Structural features: fractures

Borehole M13 is not highly fractured. The fractures dip between 50° and vertical, with the majority dipping at 70°. There are several tight, vertical stylolites.

3.2.9.10 Alteration

Alteration of borehole M13 is confined to between 35.00 - 19.50m. The majority of alteration occurs in the calcareous mudstone units. There is bleaching along fractures and weakening of the rock and in some instances the rock has been reduced to plastic clay.

Part IV: Palaeoenvironmental Interpretation of the Dublin Bay Region derived from the borehole logging

4.1 Palaeoenvironmental Interpretation

4.1.1 Lower Palaeozoic

During Cambrian times the Iapetus Ocean separated north-west Ireland, which formed part of the Laurentian continent, from south-east Ireland which formed part of the Avalonian microcontinent. The Iapetus Suture is believed to run from the Shannon Estuary to County Louth, and hence the Dublin Basin is thought to be underlain by Avalonian crust. The Iapetus Ocean began to close during the Late Cambrian and had closed completely by the Late Silurian (Chew and Stillman, 2009).

The Cambrian Bray Group forms the rocky promontories of the Hill of Howth and Bray Head which are situated to the north and south of Dublin Bay respectively. In the literature the depositional environment of the Bray Group has been interpreted based on its litho- and ichnofacies. The most widespread trace fossil, found at both Bray and Howth Head, is *Oldhamia*. The presence of *Oldhamia* is believed to indicate a relatively deep water depositional environment (Holland, 2009). Sedimentary rocks from the Bray Group commonly exhibit Bouma sequences typical of turbidite flows, including laminations and grading which also attest to these rocks being relatively deep water deposits. Locally, on Howth Head, other trace fossils are found (such as *Arenicolites* and *Skolithos*) that are representative of shallower marine depositional environments.

Boreholes M22 and M24 are believed to be Lower Palaeozoic in age, and probably represent Bray Group rocks. Both boreholes are predominantly pale green-grey in colour with occasional zones of pale purple colour alteration which is probably related to fluid migration. Borehole M22 comprises interbedded pelites and psammites. Many sedimentary structures typical of submarine fan systems are observed in the basal 25.00m of borehole M22 including graded units, cross-bedding and lamination. Several units with poorly sorted, steeply imbricated (70º) mudstone and limestone clasts may represent debris flows. Borehole M24 is lithologically similar to borehole M24 but potentially shows a slightly higher degree of metamorphic re-crystallization throughout. Due to this re-crystallization event, original sedimentary structures are not as readily identifiable. A sample from borehole M22 was taken at 55.90m for U-Pb detrital zircon analysis. The detrital zircon data confirm that the meta-sedimentary rocks in borehole M22 were sourced from Avalonian crustal rocks and are post-Early Cambrian in age (section 4.2.4).

Brück and Reeves (1976) suggest that the majority of folding of the Bray Group in the Dublin region is syn-sedimentary in origin. However Max et al. (1990) believe that sinistral transcurrent faulting and north-westerly directed thrusting during the Late Silurian – Early Devonian was responsible for deforming the Cambro-Ordovician rocks. This tectonic activity may explain the low-grade metamorphism seen in both borehole M22 and M24.

4.1.2 Carboniferous

During the early Carboniferous Ireland was situated at equatorial latitudes on the southern margin of the continent of Laurussia (Sevastopulo, 2009). Laurussia and Gondwana began to move towards one another, closing the Rheic Ocean and opening the Palaeotethys Ocean. During closure of the Rheic Ocean, Ireland is thought to have been situated in a back-arc setting. During this time Ireland was experiencing a major marine transgression thought to be caused by both tectonic subsidence and a eustatic rise in sea level. Much of the Irish landmass at this time was a shallow marine shelf. Within this shallow water shelf existed a number of deeper basins, such as the Dublin Basin which extended across Ireland and the Irish Sea to join with the Craven Basin on the present day English mainland (Sevastopulo, 2009).

The Dublin Basin was bounded by the Balbriggan Shelf to the north which is thought to represent a block of positive relief which is possibly underlain by Caledonian granites (Nolan, 1989). To the south the Dublin Basin was bounded by another shelf overlying both the Leinster Granite and Lower Palaeozoic rocks. The basin margin to the south was defined by the contact between Carboniferous rocks and the Leinster Granite and it was believed to be tectonically active in the Arundian and Asbian (Sevastapulo and Wyse-Jackson, 2009).

The boreholes which penetrated Carboniferous rocks and their respective palaeoenvironmental interpretations are discussed below in stratigraphic order, beginning with the oldest unit, the Malahide Formation.

4.1.2.1 Malahide Formation (Late Tournaisian)

The thickness of the Malahide Formation increases substantially with distance from the eastern coast to a maximum of 1200m in the 'East Midlands Depocentre'. From the depocentre to the type coastal section in the northern Dublin region there is a transition in depositional environment from deep basinal through slope to deep ramp conditions. Shallowing-up sequences may also be seen on the coastal section, with oolites at the top, interbedded with more argillaceous units (Philcox et al., 1995).

Boreholes M11 and M10 are both assigned to the Malahide Formation. Borehole M11, on the northern alignment, comprises medium to very coarse-grained calcarenites with conspicuous pyrite. The constituent bioclasts include crinoid ossicles, brachiopods and coral (including *syringopora*). Bioturbation is a common feature throughout the borehole. The argillaceous content of the calcarenites is markedly higher in the top half of borehole M11. Borehole M10, on the southern alignment, is composed of interbedded calcareous mudstones and medium-grained calcarenites with conspicuous pyrite. The calcarenites contains similar bioclasts to those in borehole M11 and comparable levels of bioturbation, but the lithology is more argillaceous throughout in borehole M10. Such fossil assemblages, including dasyclad algae which are restricted to the photic zone and bioturbation suggest that the sediment was laid down in a shallow marine environment, possibly a tidal flat or close to wave base (Tucker and Wright, 1990).

4.1.2.2 Waulsortian Formation (Late Tournaisian)

The Waulsortian Limestone Formation is discussed earlier in section 1.5.2. In the Dublin region it is believed to have been deposited under shallow marine conditions, most likely within the photic zone (Philcox et al., 1995). It is characterized by massive or weakly stratified heterogeneous limestone with sparry stromatactis cavities and fossil assemblages including bryozoan and coral.

Borehole M21, on the northern alignment, is entirely composed of the characteristically massive calcilutites with frequent stromatactis cavities and bioclasts including crinoids, an orthocone nautiloid and bryozoans. The core surface was also very rough making detailed lithological analysis challenging. Determining a specific depositional environment from the borehole alone is difficult but it may be assumed that the succession in borehole M21 was deposited under similar conditions to those of the other Waulsortian mounds within the Dublin region, i.e. in shallow marine conditions.

4.1.2.3 Lucan Formation (Arundian – Asbian)

The Lucan Formation (as discussed in section 1.5.4), which reaches thicknesses of over 1100m, was deposited as distal turbidite flows in moderate to deep marine conditions (at least below storm wave base). It is characterised by interbedded dark, argillaceous limestone, shales and calcareous mudstones. Skeletal units are also recorded but are relatively minor. Both chert and pyrite are common in the Lucan formation. The western margin of the Balbriggan Shelf is thought to have been the source for the shallow water clastics in the formation. Four mega-cycles are contained within the Lucan formation. The first two occurred in the Arundian, the third in the Holkerian and the final began in the Holkerian and finished in the Asbian. All cycles begin with coarse detrital material and terminate with the deposition of thick basinal limestones and shales.

4.1.2.3.1 Arundian

Borehole M30 is the most easterly borehole on the northern line (Fig 9) of Arundian age. The borehole consists of calcarenites interbedded with calcirudites, calcareous mudstones and calcisiltites. A significant number of the calcarenites are graded. Borehole M30 is thoroughly dolomitised and thus detailed lithological examination is difficult

Borehole M06 is sited west of borehole M30 on the northern line and is also Arundian in age. The borehole is comprised of interbedded calcilutites with occasional calcarenites, the majority of which are graded, with rare bioclasts throughout. Several slumped units are also recorded. In terms of lithofacies, borehole M06 bares closer resemblance to borehole M08 than to borehole M30.

On the southern line borehole M19 is the most easterly borehole of Arundian age. This borehole is composed of calcilutites interbedded with calcarenites with sporadic concentrations of bioclasts and mud clasts. At 60.00m there is one unit of fine-grained limestone with abundant, very coarse (<12mm) clasts including lower Palaeozoic clasts and chert pebbles. The abundance of these clasts decreases up section.

Borehole M09, again on the southern line, is separated from the other Arundian borehole (M19) by borehole M20 (Holkerian in age), and this stratigraphic relationship is discussed in more detail in the following section. Borehole M09, similar to the other Arundian boreholes, consists of calcarenites interbedded with calcilutites and these units are typcially laminated. Bioclasts are less abundant than in the other Arundian boreholes.

All four Arundian boreholes (M30, M06, M19 and M09) show components that are characteristic of distal turbidite flows in a deep marine depositional environment. These components include laminations and the presence of frequent graded units.

4.1.2.3.2 Holkerian

Borehole M20 is the most easterly Holkerian borehole on the southern line. This borehole is dominated by well bedded calcilutites with subordinate calcarenites. Bioclasts, mud rip-up clasts and limestone clasts become more abundant towards the top of borehole M20.

Borehole M07 is sited west of borehole M20 on the southern line. As with borehole M20, borehole M07 is comprised largely of bedded calcilutites with lesser calcarenites. Bioclasts are present but rare and occur predominantly in the coarser limestone units.

Borehole M15 is sited west of borehole M07 on the southern line. It is composed largely of bedded calcilutites with calcarenites. Unlike the other Holkerian boreholes, borehole M15 does not contain graded calcarenites. Bioclasts show variable abundances throughout borehole M15 while the units are well laminated at numerous levels.

Borehole M08 (A&B) is the most easterly borehole of Holkerian age on the northern line. The borehole is composed of interbedded calcilutites and calcarenites. Laminated beds are common and the majority of calcarenite beds are graded. Bioclasts are common and include crinoid ossicles and brachiopods.

Borehole M17 is sited east of borehole M08 (A&B) on the northern line. Borehole M17 is dominated by calcilutites interbedded with subordinate calcarenites. As with borehole M08 (A&B), the majority of the calcarenites are graded and the borehole contains relatively abundant bioclasts including crinoid ossicles and brachiopods.

Borehole M16 is sited west of borehole M17 on the northern line. Based on the lithology of borehole M16 it has been assigned to the Lucan Formation but no biostratigraphic dates have been obtained. However, given its location between two boreholes of Holkerian age and its position due north of another borehole (M15) dated as Holkerian, it is assumed that borehole M16 is also Holkerian in age. The basal 32m of borehole M16 is dominated by bedded calcilutites with the top 31m comprising almost entirely of thick calcarenite units, several of which are graded. Crinoid ossicles and brachiopod shells along with limestone clasts are common throughout borehole M16.

Borehole M14 is sited west of borehole M16 on the northern line. The borehole is largely comprised of bedded calcilutites with calcarenite units which are locally abundant at several horizons. As with borehole M15 the calcarenite units are not graded. Bioclasts are rare within borehole M14.

The boreholes of Holkerian age (M20, M07, M15, M08 A&B, M17 and M14) contain sedimentary structures including laminated and graded units that are characteristic of moderate to deep-marine distal turbidites.

4.1.2.3.3 Asbian

Borehole M27 is the most easterly borehole of Asbian age on the northern line. The borehole consists of two main sequences. The basal 41m is composed almost entirely of bedded calcareous mudstone whilst the uppermost 8m is dominated by thick graded calcarenites. Borehole M27 is bioturbated throughout.

Borehole M05 is sited to the west of borehole M27 is and is also Asbian in age. Borehole M05 is divided into two main sequences. The basal 21m contains interbedded calcareous mudstones and calcarenites, several of which are graded. The top 26m is dominated by bedded calcareous mudstones with occasional, thin calcarenite units. Bioclasts are rare in borehole M05.

Borehole M18 on the southern line has been assigned to the Lucan Formation but no conclusive biostratigraphic age has been determined. It lies north-northwest of borehole M15 on the southern line which is of Holkerian in age. However it is situated closer to borehole M13 on the southern line and borehole M27 on the northern line, both of which have been dated as Asbian in age and thus borehole M18 is thus assumed to be Asbian in age. The frequency of calcarenite beds within borehole M18 decreases up section. At approximately 85m there are a number of thick ‘crackle breccia’ beds with intense veining and possible jarosite present. Throughout borehole M18 laminated units are common. Bioclasts are also present but minor. Below 48m borehole M18 is pervasively dolomitised.

Borehole M13 is situated north-northwest of borehole M18, on the southern line, and south of boreholes M27 and M05. Boreholes M18, M27 and M05 are all assigned to the Asbian and thus borehole M13 shall be assumed to be Asbian also. Borehole M13 is dominated by bedded calcilutites interbedded with thin calcarenites. Several calcarenite units are graded and numerous laminated and slumped units are recorded. Bioclasts are locally abundant and bioturbation is common throughout borehole M13.

In all four Asbian boreholes (M27, M05, M18 and M13) sedimentary structures typical of moderate to deep-marine distal turbidites are found. These include laminations and grading with high proportions of calcareous mudstones.

4.1.2.3.4 Highly dolomitised boreholes assigned to the Lucan Formation (not conclusively dated)

Borehole M29 is the most easterly of the undifferentiated, highly dolomitised boreholes assigned to the Lucan Formation. It is comprised of several lithological sequences but is chiefly comprised of interbedded dolomitised mudstones and calcarenites. The dolomitised calcarenite units are thick (~1m) but are largely ungraded.

Borehole M28 lies west of borehole M29 and is divided into three main sequences. The basal 15m comprises bedded dolomitised calcarenites with dolomitised mudstones. Above this, from 95.00 – 45.00m, the borehole is composed largely of dolomitised mudstones with occasional calcarenites, a number of which are graded. In the top 24m the borehole is dominated by thick dolomitised calcarenites, largely ungraded, which are interbedded with subordinate dolomitised mudstones.

Borehole BHO2 is located onshore east of borehole M28. It is dominated by dolomitised mudstone with a number of dolomitised calcarenite units towards the top.

Borehole BHO1 was also sited onshore within 20m of BHO2. The basal 31m comprises bedded dolomitised mudstones. Above this there is 36m of interbedded dolomitised calcarenites, some of which are graded, and mudstones.

Boreholes M29, M28, BHO2 and BHO1 have all been assigned to the Lucan formation based on lithological analysis but due to their pervasive dolomitisation it is extremely difficult to constrain the age of these rocks further.

4.1.3 Jurassic

During the Rhaetian transgression of the Late Triassic and into the Early Jurassic, marine conditions existed over large, low relief areas of southern England and Ireland (BGS, 1995). The Jurassic rocks in the Dublin region are thought to have been deposited under such conditions. The Jurassic rocks are characterised by interbedded calcareous mudstone, calcisiltites and calcarenites with sporadic influxes of carbonate shelf material. Bioclasts may be common and include bivalves and ammonites.

Borehole M23 is located at the easternmost end of the northern drilling line. The basal half of the borehole comprises interbedded calcareous mudstone and calcareous sandstone units with the upper half consisting of interbedded calcareous shale and calcareous sandstones. Siliciclastic material is common throughout, as are bioclasts. Bioclasts include crinoid ossicles, abundant shells, belemnites and occasional gastropods.

Borheole M23 comprises two main depositional facies. The Lowest units are predominantly interbedded bioclastic limestones and calcareous mudstones. These lithologies are suggestive of an inner shelf position. The upper units of borehole M23 however, show an influx of sandier sediment and bioclastic material. Given the abundance of bioclasts and the presence of this coarse-grained siliciclastic material it is likely that these rocks were deposited in relatively higher energy, shallower marine environment than the older rocks.

4.2 Sediment Provenance

4.2.1 Lower Palaeozoic

A sample was taken for U-Pb detrital zircon dating from the Lower Palaeozoic rocks of borehole M22 on the eastern end of the northern drilling line. A full description of the techniques used and a detailed discussion of potential sediment sources are discussed in section 4.2.4. The section concludes that the Avalonian crustal rocks proximal to the Dublin Basin are the most probably source for the detrital material in borehole M22. Given the similarity in lithologies of boreholes M22 and M24 it may be assumed that the meta-sedimentary rocks in borehole M24 were also sourced from nearby Avalonian crustal rocks.

The photomicrograph in Fig 38 is from a typical very fine-grained sandstone (mean grain size of 75 microns from borehole M22. Darker bands visible in the thin section comprise 15-20% by volume clay-rich matrix. The grains are sub-angular to angular and display a uniform orientation throughout the thin section. Biotite and muscovite grains are common throughout (15% and 5% by area respectively) with both micas aligned along the bedding planes. This suggests that they may be detrital and that the ‘buckling’ that is visible in the thin section was potentially caused by post-depositional compaction.

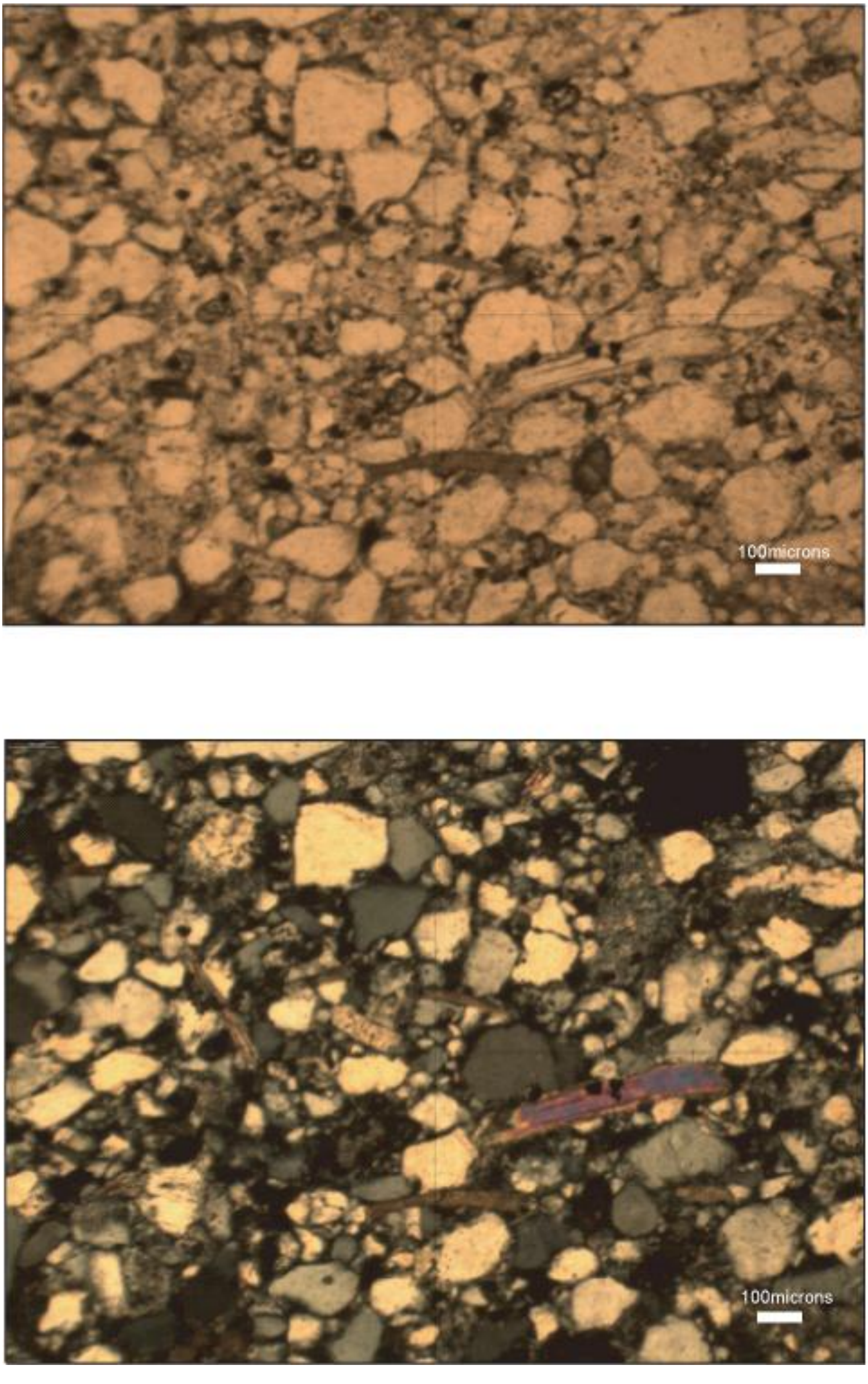

Fig 38 Micrograph of borehole M22 at 71.50m; above in PPL (a) and below in XP (b)

4.2.2 Carboniferous

The Carboniferous boreholes studied in this thesis are comprised primarily of calcareous sedimentary rocks, some of which have been subsequently dolomitized. Mudstone clasts which are found within a number of boreholes are most likely intraclasts introduced by local slumping and debris flows. However the majority of fine-grained carbonate and bioclastic material was most likely derived from a carbonate shelf that would have surrounded the Dublin Basin during Carboniferous times. Two boreholes on the northern line (boreholes M17 and M05) and three boreholes at the eastern end of the southern line (boreholes M19, M20 and M09) contain Lower Palaeozoic clasts. The most probable source of such material is from a postulated submarine fault scarp facing north that contained Lower Palaeozoic material (Nolan, 1989).

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4.2.3 Jurassic

Two samples were taken from borehole M23, the first at 34.25m and another at 49.95m, and thin sections produced. Both samples are representative of siliciclastic sand-bearing units in borehole M23. The thin section in Fig 39a shows rounded – sub-angular grains of quartz and plagioclase feldspar. The sandstone is of medium-grained (400 microns) and has a micritic matrix. Some discrete zones of silicification are also visible. Opaque grains (in plane-polarised light) have been identified as pyrite and bitumen. Bioclastic fragments are also common including crinoid and bivalve material.

The second thin section (39b) similarly contains rounded – sub-angular quartz and plagioclase feldspar grains but is poorly sorted. No pyrite was identified but bitumen is again present. Bioclastic material includes crinoid plates, algae, echinoid spines, bivalves and ostracodes.

Based on the prevalence of quartz and plagioclase feldspar it is likely that the siliciclastic sediment within borehole M23 was sourced from the Leinster Granite to the south. A palaeoflow direction for the carbonate material in the M23 borehole is harder to constrain as it is likely that the Dublin Basin was surrounded by a carbonate shelf during the Jurassic.

Fig 39a

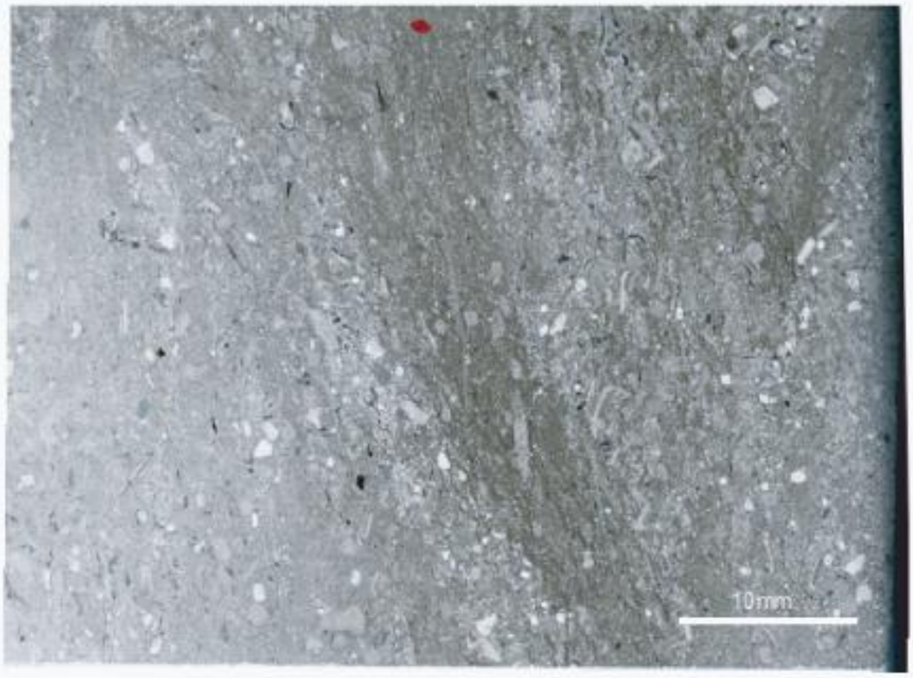

Fig 39b

Fig 39 Scanned images of thin sections from borehole M23; (a) at 34.25m and (b) at 49.95m

In fig 40, below a photomicrograph of borehole M23 clearly shows the prevalence of feldspar (plagioclase and potassium) in borehole M23. This photomicrograph also shows an isocrinid crinoid ossicle with a local syntaxial cement (pink in XP).

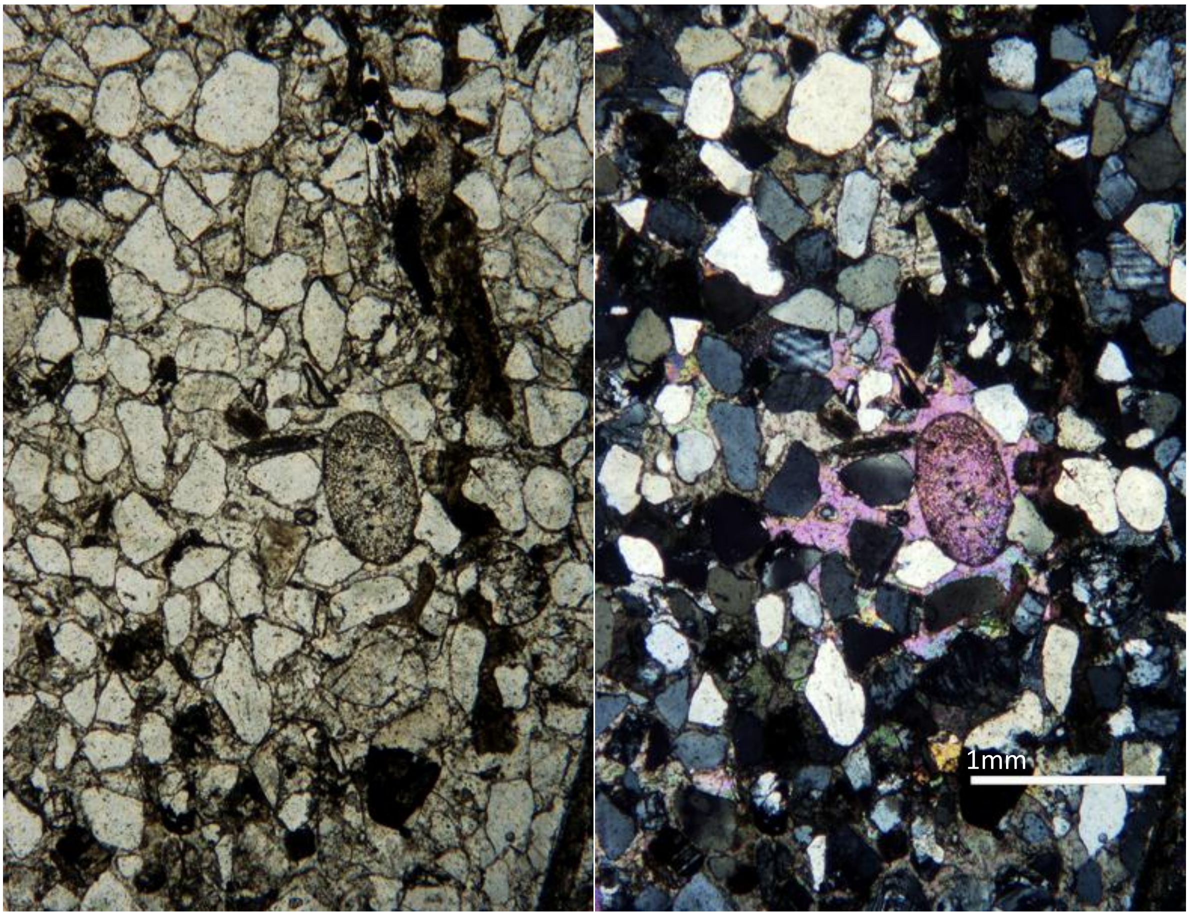

Fig 40 Photomicrograph of borehole M23; left in PPL and right in XP

4.2.4 Zircon Dating

4.2.4.1 Sample Preparation

Zircons were separated from several kilograms of a psammitic wacke sample from the M22 borehole by conventional means. The sub-300 μm fraction was processed using a Wilfey table, and then the Wilfey heavies were passed through a Frantz magnetic separator at 1 A. The non-paramagnetic portion was then placed in a filter funnel with di-iodomethane with a specific gravity of 3.3. The resulting heavy fraction was then passed again through the Frantz magnetic separator at full current. All zircons were hand-picked in ethanol using a binocular microscope (Fig. 41).

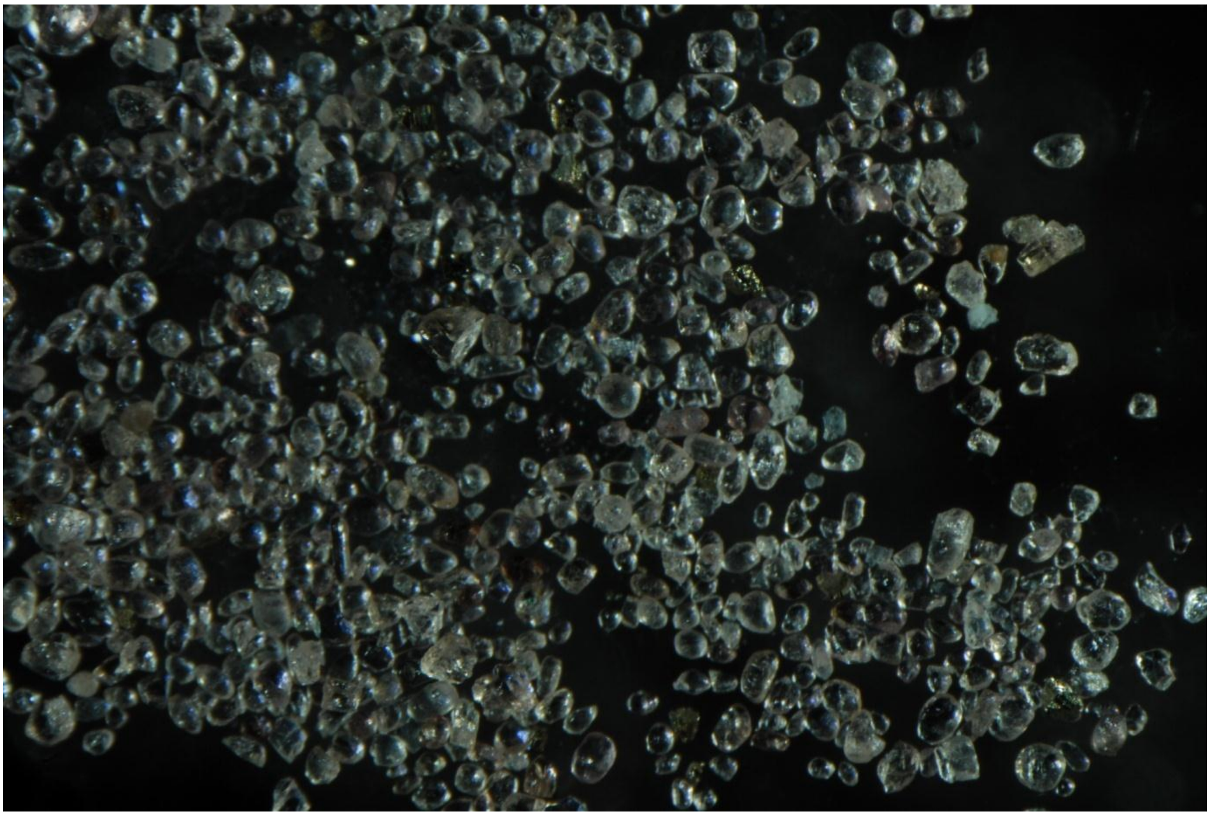

Figure 41. Zircon separate from the M22 borehole under a binocular microscope using reflected light. Field of view is 2.9 mm.

Zircons were then mounted in a resin disk (Fig. 42) and ground and polished using progressively finer diamond polishing fluids to reveal the grain interiors. The zircons were then placed in the sample holder of the laser ablation system and a series of tiled reflected light images of the zircon mount was generated using the software package which controls the laser (Chromium by Photon Machines).

4.2.1.2 ICP-MS Analytical Technique

Zircon U-Pb data was acquired using a Photon Machines Analyte Exite 193 nm ArF Excimer laser-ablation system coupled to a Thermo Scientific iCAP Qs at the Department of Geology. A 30 µm laser spot, a 4 Hz laser repetition rate and a fluence of 3.8 J/cm2 were used. Each zircon was analysed for nine isotopes: ^{88}Sr, ^{91}Zr , ^{200}Hg, ^{204,206,207,208}Pb, ^{232}Th and ^{238}U.

Each analytical session comprised cycles of four standard analyses followed by 20 analyses of zircon unknowns. The four standard analyses consisted of two primary and two secondary zircon analyses. The primary was c. 1065 Ma 91500 zircon (Wiedenbeck et al., 1995). There then followed one analysis of Plešovice zircon (337.13±0.37 Ma, Slama et al., 2008) and one analysis of Temora 2 zircon (Temora 1: 416.75 ± 0.24 Ma, Black et al., 2003). These analyses were then followed by analysis of 20 unknown zircons and the entire cycle was repeated five times (yielding 100 analyses of zircons from the M22 sample).

Figure 42. Zircon separate mounted in epoxy resin on a glass slide prior to grinding and polishing. The yellow mould is 2.5 cm in diameter.

Data reduction was undertaken using the 'Vizual Age' data reduction scheme (Petrus and Kamber, 2012) of the freeware IOLITE package of Paton et al. (2011). IOLITE processes a whole analytical session of data. In order to calculate session-wide baseline-corrected values for each isotope, user-defined time intervals are established for the baseline correction procedure. 91500 was used as the primary standard and *Plešovice* and *Temora 2* zircons were used as secondary standards (i.e. age monitors) using a sample – standard bracketing approach. *Temora* and *Plešovice* yielded Corcordia dates of 419.0 ± 2.3 Ma (Fig. 44) and 339.4 ±1.3 Ma (Fig. 45) respectively which corresponds well with the U-Pb TIMS ages for Temora (416.75 ± 0.24 Ma) and Plešovice (337.13±0.37 Ma). The Temora age was within error, while the Plešovice is just outside of the 2 sigma analytical uncertainty. The data were then plotted using Isoplot v.3.1.

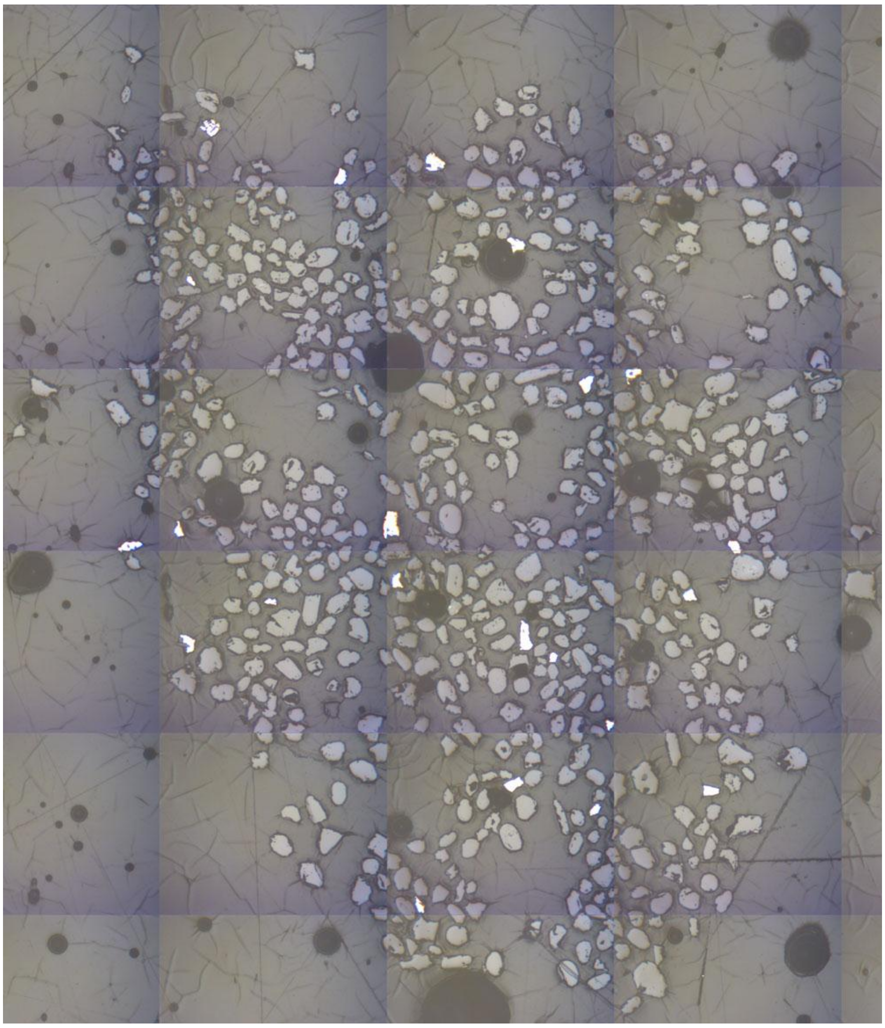

Figure 43. Tiled image of the M22 zircon separate under reflected light produced by the laser ablation system software (Chromium).

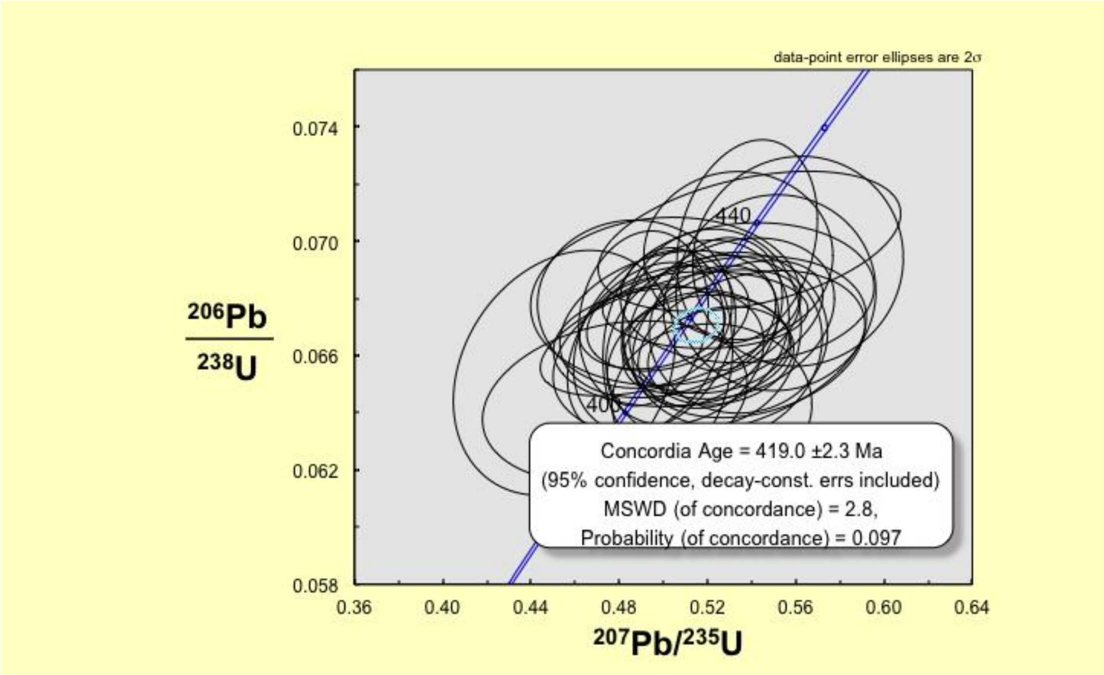

Figure 44. Concordia age for Temora

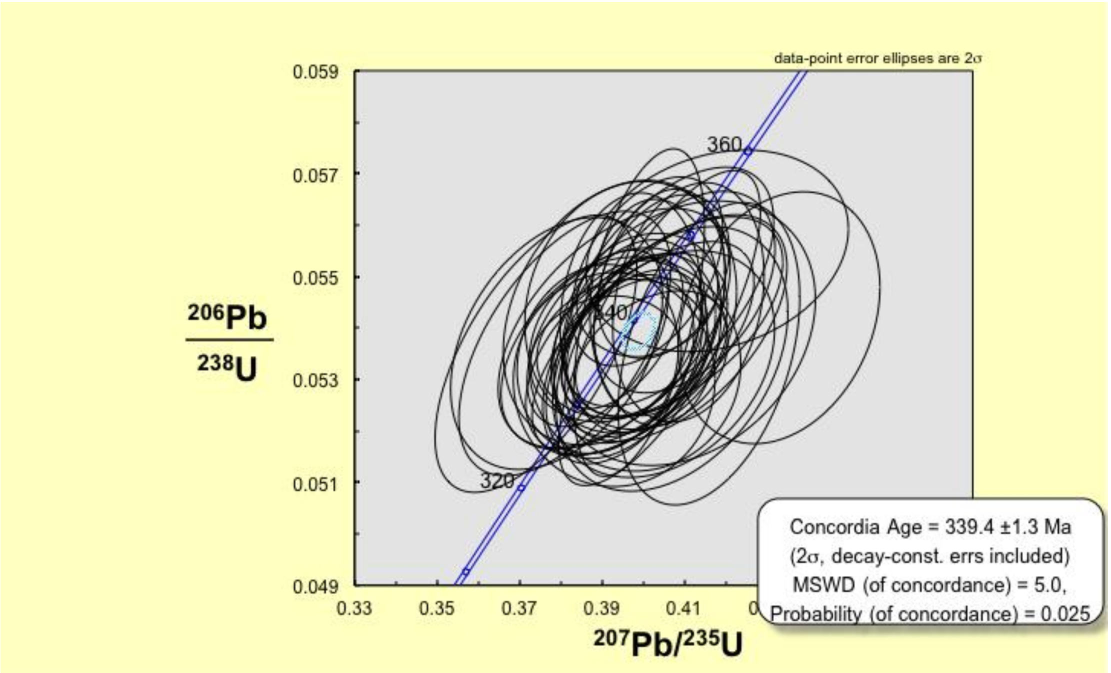

Figure 45. Concordia age for Plešovice

4.2.1.3 Results

The detrital zircon record of clastic sediments is an important provenance tool, which can link sedimentary basins to potential source regions. When examining these data on a conventional (Weatherhill) Concordia, it can be seen that some data are markedly discordant (Fig. 46). Data >5% discordant were then removed, and a probability density plot of ^{206}Pb-^{238}U zircon ages was then constructed. Detrital zircons separated from the M22 borehole yield U-Pb detrital zircon spectra with prominent peaks at 550 - 630 Ma and minor peaks at 1200 Ma, 1500 - 2200 Ma and 2500 - 2900 Ma (Fig. 47).

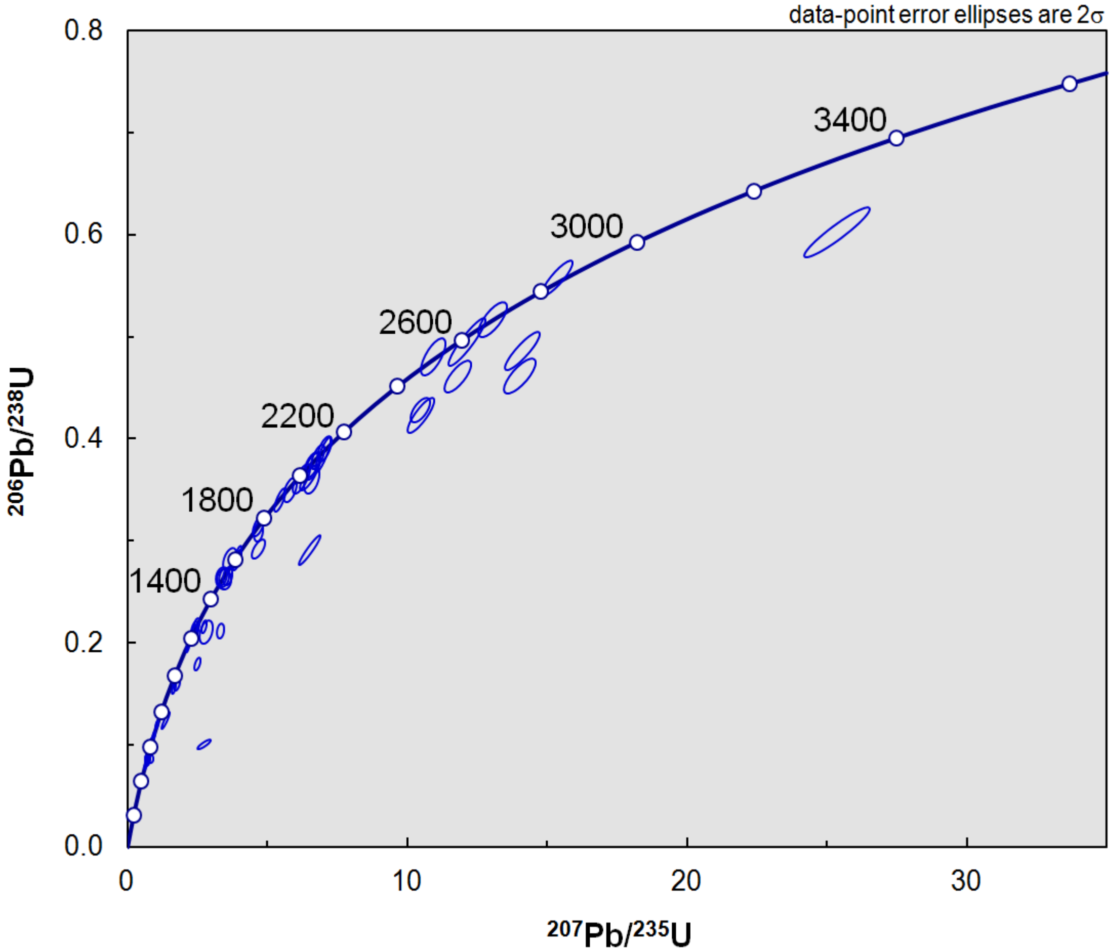

Figure 46. Conventional Concordia plot of all detrital zircon data.

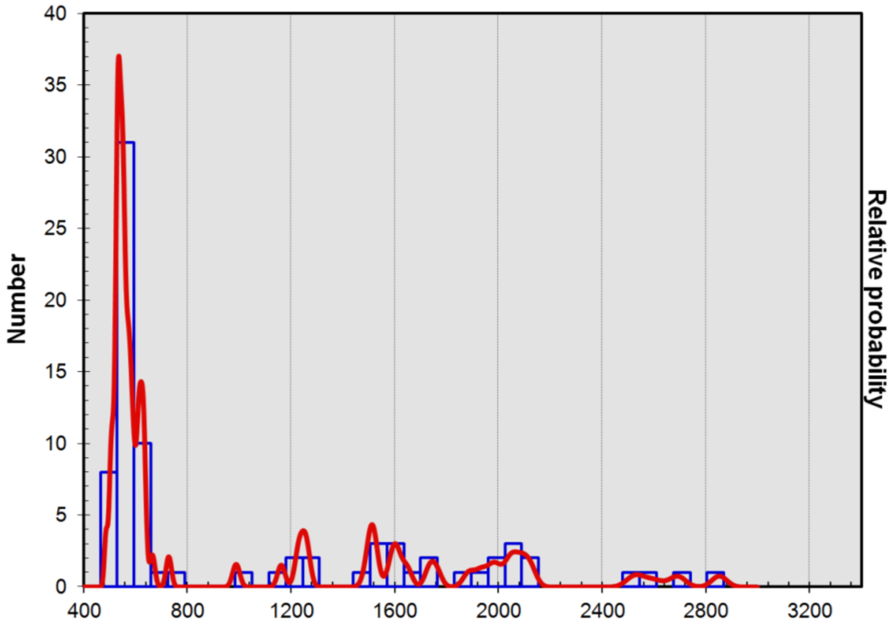

Figure 47 Probability density plot of ^{206}Pb-^{238}U zircon ages from sample M22 (only data <5% discordant illustrated).

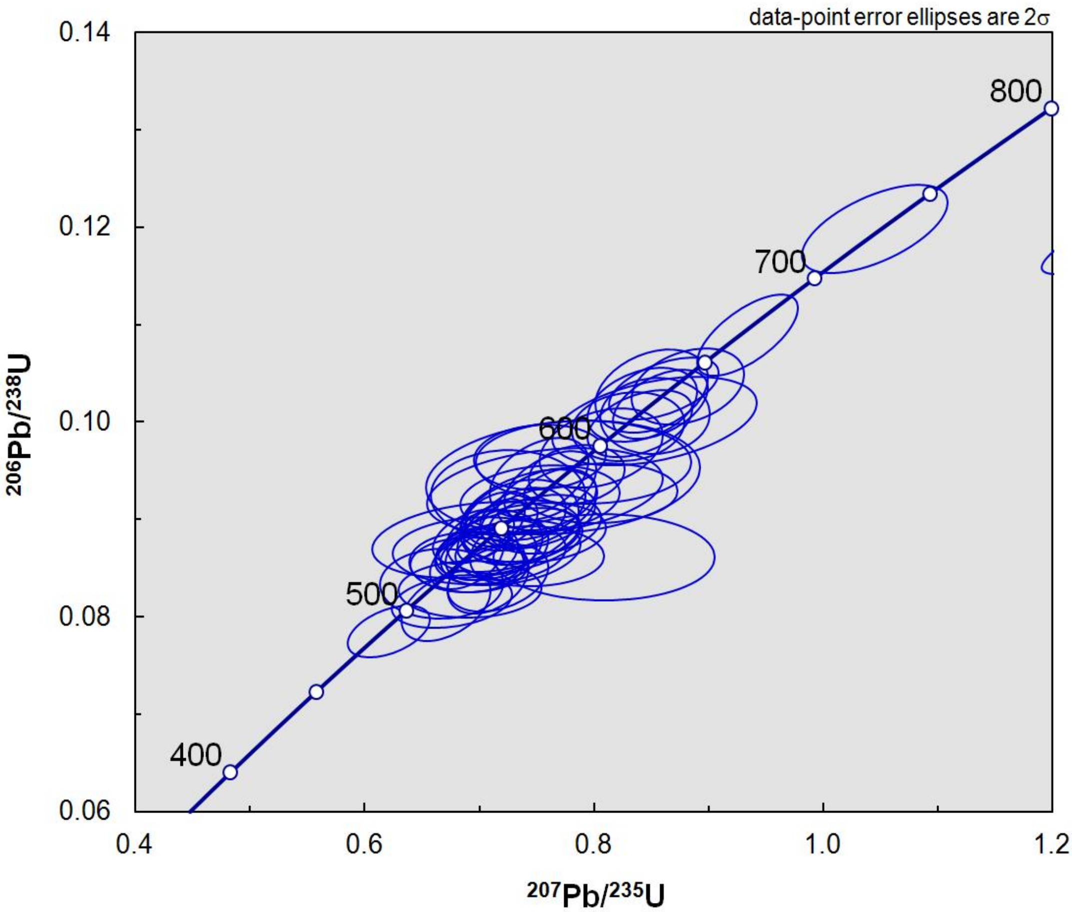

Figure 48. Conventional Concordia plot of concordant detrital zircon data younger than 800 Ma.

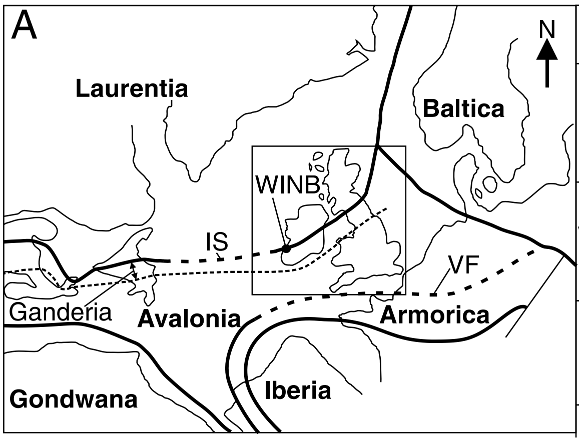

Figure 49. Tectonic terranes in the North Atlantic region (from Pointon et al., 2012)

4.2.1.4 Interpretation

The Dublin Bay region lies to the south of the Iapetus Suture. As the Iapetus Ocean did not close until the Late Silurian (Chew and Stillman, 2009), it is therefore unlikely the Lower Palaezoic rocks could have been sourced from Laurentia. Hence potential source terranes for the Lower Palaeozoic detritus include the peri-Gondwanan terranes of Avalonia, Armorica and Iberia (Figure 49). The lack of c. 1 Ga Grenvillian detritus on Fig. 47 would appear to rule out an Iberian source. Avalonian sources contain minor zircon detritus in the 1 – 1.8 Ga age range (Fig. 47) while Armorican sources typically do not. Given that zircon of this age is present in the sample from the M22 borehole, and the Dublin Basin region is sited closest to Avalonian crust, and Avalonian source is viewed as most likely. The youngest concordant zircon in a sedimentary rock can provide valuable constraints on the depositional age of a sample. Several concordant zircons cluster at c. 525 Ma, while the youngest detrital zircon is a solitary concordant analysis at 490 Ma (Fig. 48). The danger of interpreting a solitary zircon analysis as a maximum age is that it could represent sample contamination or mild Pb loss, and hence the post-525 Ma constraint is viewed as more robust. The age of the rocks in the M22 borehole is therefore Early Cambrian or younger.

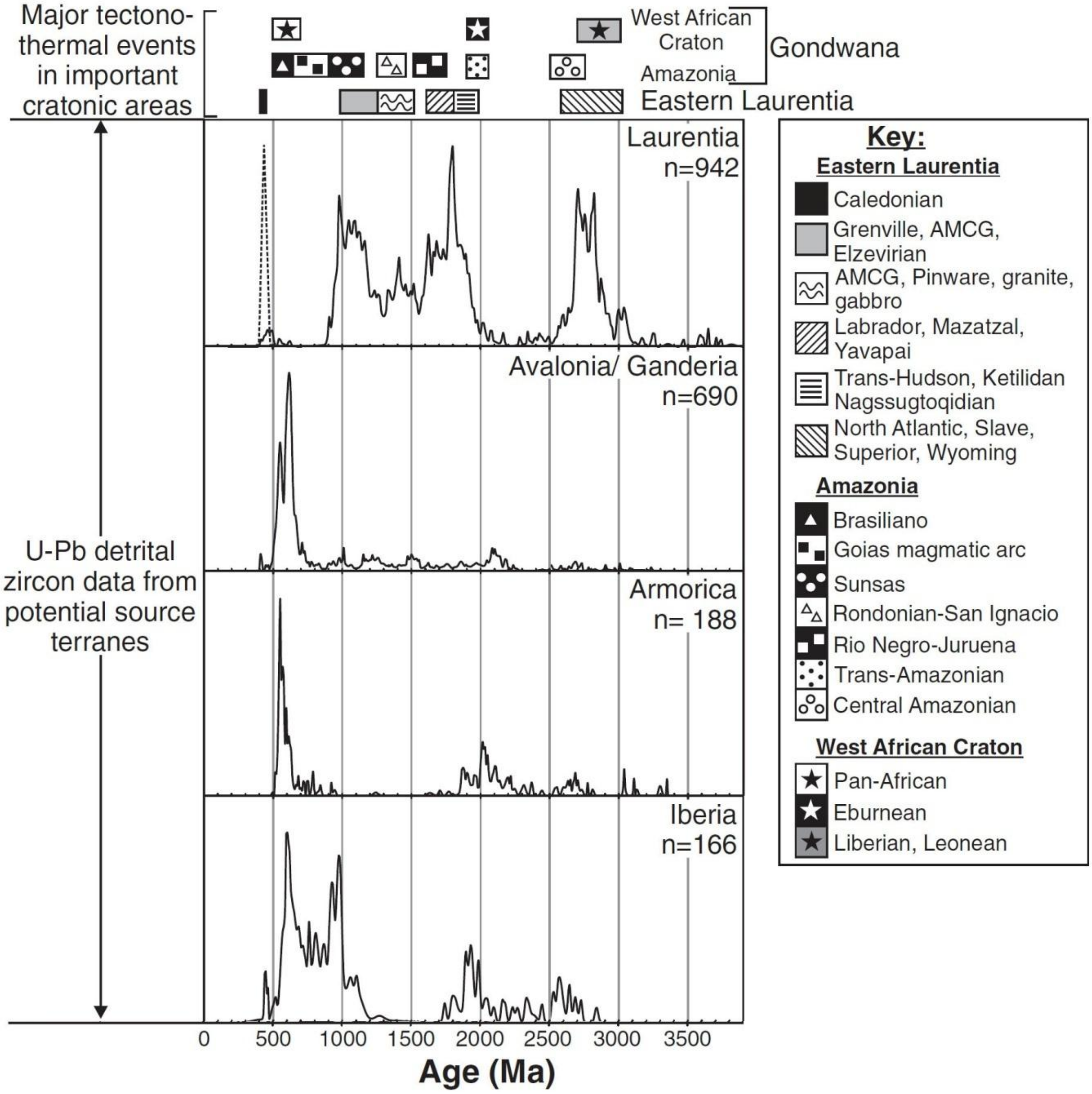

Figure 50. Detrital zircon spectra from potential source terranes in the North Atlantic region (from Pointon et al., 2012).

4.3 Biostratigraphy

This section will briefly discuss the micro-fossil assemblages of each borehole in stratigraphic order beginning with the Lower Palaeozoic boreholes M22 and M24.

4.3.1 Lower Palaeozoic

No bioclasts were found in either borehole M22 or M24. Potential burrows were recorded but not conclusively identified.

4.3.2 Carboniferous

4.3.2.1 Late Tournaisian

Based on the identification of the forams (plate 1) eoparastaffella ovalis (first appearing at MFZ 8 and extending through the lower Viséan), pseudolituotubella (appearing first in MFZ7 and extending through the lower Viséan), brunsia spirillinoides (top of the Tournasian) and cf. eblania sp. (extinct in Viséan, not extending into MFZ9) in thin section borehole M11 has been dated as Late Tournaisian.

M21 has been also been dated as Late Tournaisian. The Waulsortian Formation, including borehole M21, of the Dublin region has been assigned throughout the literature to the Tournaisian but it is the presence of Sphaerinvia piai (plate 1) at 74.75m that conclusively dates borehole M21 to the Late Tournaisian.

At 33.52m borehole M10 is identified as an argillaceous, poorly sorted, skeletal (brachiopod, crinoid) packstone/very coarse calcarenite. No microbiota were identified.

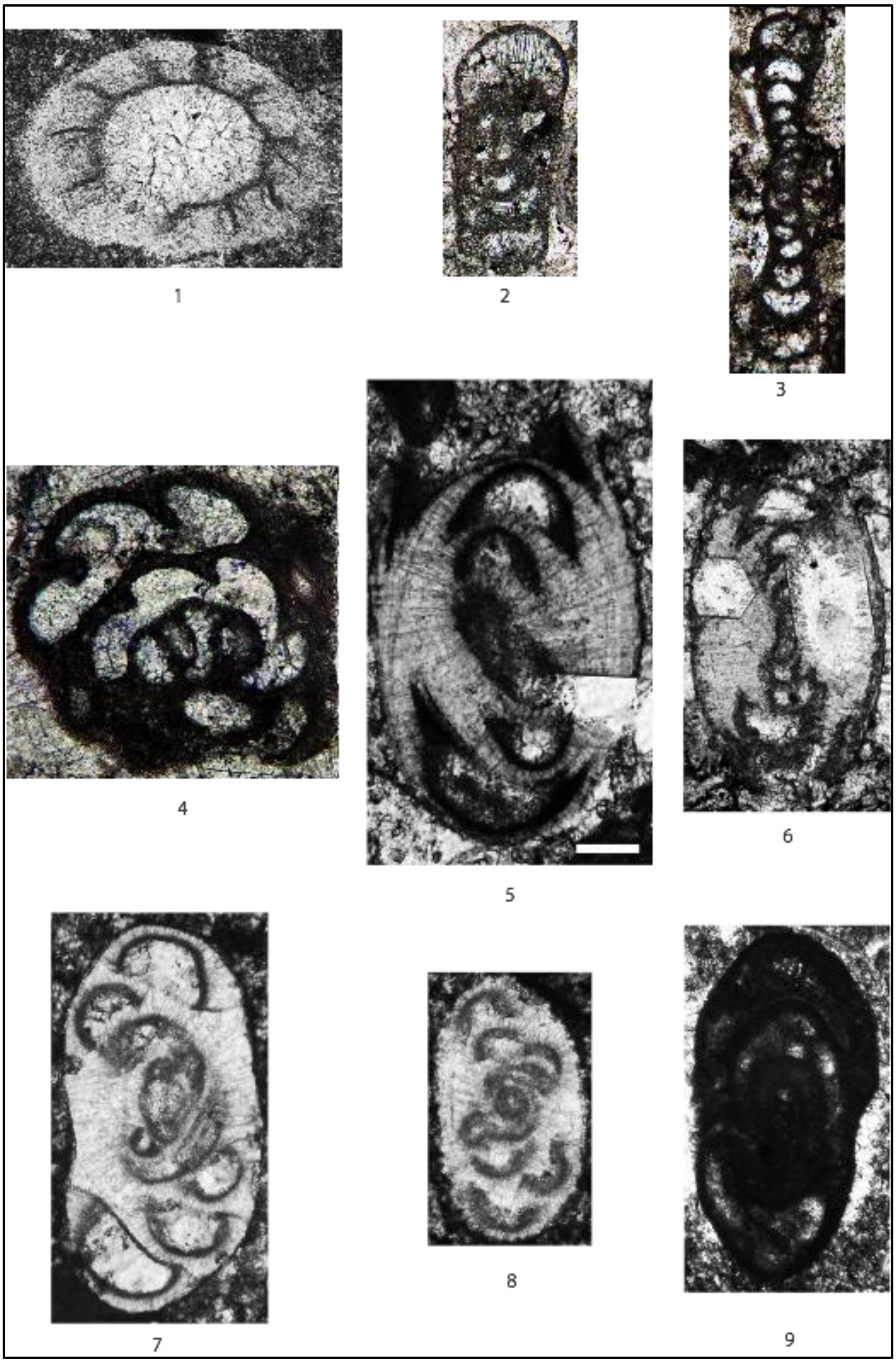

Plate 1. (created by Sevastopulo, G.)

Scale = 100 microns, figures are all at the same magnification.

1. Sphaerinvia piai, borehole M21 74.75m, 2. Eoparastaffellaovalis Morphotype 1, borehole M11 50.09m, 3.Brunsiaspirillinoides, borehole M11 50.09m, 4.Cf. Eblanaia sp., borehole M11 50.09m, 5. Glomodiscus sp., borehole M06 52.5m, 6.Uralodiscus sp., borehole M06 52.5m, 7.Archaediscus sp. at angulatus stage, borehole M05 64.5m, 8.Nodosarchaediscus sp., borehole M05 64.5m, 9.Eostaffella cf. mosquensis, borehole M05 93.9m

4.3.2.2 Arundian

At 40.68m borehole M19 is seen to be a cherty, skeletal grainstone. It is seen to grade from coarse to medium calcarenite with scattered detrital quartz/quartzite grains up to medium sand grade. The quartz is commonly strained. The microbiota found are moderately abundant and moderately well preserved, including abundant *Uralodiscus rotundus*, *Valvulinella* sp., *Koninckopora* sp. The presence of such an assemblage indicates that borehole M19 is Arundian in age.

At 54.13m borehole M09 is seen to be a quartz-rich peloidal (rounded micritised grains), skeletal grainstone and is a graded very coarse to coarse calcarenite with abundant coarse to very coarse detrital quartz/quartzite grains. Many of the quartz grains are strained.The microbiota are rare but does include *Uralodiscus rotundus* which dates this rock as Arundian.

Borehole M06, due to the identification of uralodiscus sp. (which is confined to the Arundian) has been dated as Arundian in age.

4.3.2.3 Holkerian

At 67.85m the lithology of borehole M20 is cherty, and is dominantly a spicular packstone/fine calcarenite with laminae containing more diverse skeletal grains including rare forams. Angular, detrital quartz/quartzite grains up to fine sand grade are common. The quartz is commonly strained. The microbiota are in poor condition and are silicified but includes *Archaediscus* spp. at involutus, concavus stages. The presence of this microbiota date this lithology as Holkerian.

At 59.65m borehole M07 is a neomorphosed skeletal (crinoid) packstone/medium calcarenite. Its microbiota is moderately abundant but very poorly preserved. It includes *Archaediscus* spp. @involutus, concavus stage, *Tetrataxis* sp., common *Koninckopora* sp. This assemblage dates this lithology as Holkerian.

At 66.45m borehole M15 is identified as an oolitic, skeletal (crinoid, foram, gastropod), intraclastic (rounded micrite granules with sparry calcite patches) grainstone. Microbiota are abundant and well preserved. They include *Archaediscus* spp. at involutus, concavus stage, abundant *Eostaffella*, palaeotextulariids, *Tetrataxis* sp., aoujgaliids. and abundant *Koninckopora* sp. This assemblage establishes borehole M15 as Holkerian in age.

At 40.20m borehole M08 (A&B) is seen to be a skeletal (crinoid, mollusk, foram), ooid grainstone/coarse calcarenite. Several ooids have detrital quartz nuclei (with quartz overgrowths).

The microbiota are moderately abundant and include *Archaediscus* spp. at involutus, concavus stage, cf. *Uralodiscus* sp., *Eostaffella* sp., *Tetrataxis* sp. *Pseudolituotubella* sp., *Draffania* sp. and abundant *Koninckopora* sp. Borehole M08 (A&B) is assigned to the Holkerian But the occurrence of cf. *Uralodiscus* sp. in conjunction with *Archaediscus* spp. at concavus stage is unusual. In Belgium, the range of *Uralodiscus* does not overlap with that of *Archaediscus* spp. at concavus stage. However, there is a major non-sequence marked by a palaeosol at the base of the Livian regional substage, equivalent to the Holkerian of Britain and Ireland (where *Archaediscus* spp. at concavus stage first occur). Possibly this sample falls within this hiatus, in which case the age is Arundian. Alternatively the cf. *Uralodiscus* sp. is reworked. The latter explanation is preferred.

Two further thin sections from borehole M08 (A&B) were studied. Both of these thin sections date borehole M08 (A&B) as Holkerian.

At 37.90, borehole M17 was seen to be a skeletal (crinoid, mollusc), intraclastic (micrite and ooid grainstone grains) grainstone/very coarse calcarenite. Its microbiota are moderately abundant and moderately well preserved. Microbiota include *Archaediscus* spp. @involutus, concavus stages, *Lapparentidiscus* sp., *Palaeotextularia* sp., *Koninckopora* sp., aoujgaliids dating this level as Holkerian.

At 49.50m borehole M17 is a bimodal oolitic, skeletal grainstone/medium calcarenite with scattered very coarse crinoid ossicles and quartz. The ooids in some cases have detrital quartz cores. Larger quartz grains are subangular to subrounded and are dominantly of polycrystalline strained quartz Microbioat are_moderately abundant and moderately well preserved, they include *Archaediscus* spp. @involutus, concavus stage, *Eostaffella* sp., *Koninckopora* sp. Based on this fossil assemblage this level has also been dated as Holkerian.

Borehole M16 was not conclusively identified using biostratigraphy. It has been assigned to the Holkerian due to its position between boreholes M17 and M14 and its position north of boreholes M07 and M15 which have all been conclusively dated as Holkerian in age.

At 40.55m boreholes M14 is identified as a very well sorted skeletal, lithoclastic grainstone/very coarse calcarenite. The lithoclasts are mostly micrite with silica replacement but also include oosparite.The microbiota are moderately abundant and well preserved and include *Archaediscus* spp. at involutus, concavus stage, *Eostaffella* sp., *Palaeotextularia* sp. and abundant *Koninckopora* sp., aoujgaliids which date this lithology as Holkerian.

Four further thin sections were studied and all contained fossil assemblages that concur with a Hokerian age for borehole M14.

4.3.2.4 Asbian

At 53.05m borehole M27 has been identified as a skeletal (crinoid, bryozoan), lithoclastic (rounded micrite grains with diagenetic quartz) grainstone and packstone/very coarse calcarenite. Its microbiota are moderately abundant and moderately well preserved and include *Archaediscus* spp. at involutus, concavus stages and ?angulatus stage, *Palaeotextularia* sp. with an incipient bilayered wall, abundant aoujgaliids, abundant *Koninckopora* spp. including *Koninckopora mortelmansi* and *K. minuta*. This fossil assemblage assigns borehole M27 to the Asbian.

A further thin section was analysed for borehole M27 and also proved to be of Asbian age.

M05 is Asbian in age, dated by the presence of the foram archaediscus sp., nodosarchaediscus sp. and eostafella cf. mosquensis (plate 1)

At 84.16m borehole M13 is seen to be a well sorted intraclastic (generally rounded micritised skeletal), skeletal (brachiopod, crinoid, *Koninckopora*, gastropod), ooid grainstone/coarse to very coarse calcarenite. Its microbiota are moderately abundant and moderately well preserved. The microbiota include *Archaediscus* spp. at involutus, concavus stage, *Eostaffella* cf. *mosquensis*, abundant aoujgaliids, abundant *Koninckopora* sp. This fossil assemblage is indicative of a Holkerian or Early Asbian age.

4.3.2.5 Highly dolomitised boreholes assigned to the Lucan Formation

Boreholes M30, M29, M28, BHO2 and BHO1 yielded no identifiable micro-fossils due to the pervasive dolomitisation in each. Their respective ages have been assigned based on lithology and their relative position to conclusively dated boreholes.

4.4 Jurassic

Borehole M23 has been dated as Early Jurassic based on the identification of the crinoid *pentacrinites*.

Part V: Geological map and cross section of the Dublin Bay Region

5.1 Introduction

This chapter integrates existing knowledge on the structural geology of the Dublin region with stratigraphic and structural data gathered from each of the boreholes studied on both the northern and southern drilling lines (Fig 51). Boreholes within this section shall be discussed from west to east beginning with the Jurassic rocks at the easternmost end of the northern drilling line. Combined these data are employed to produce a new geological map and cross section for the Dublin Bay Region.

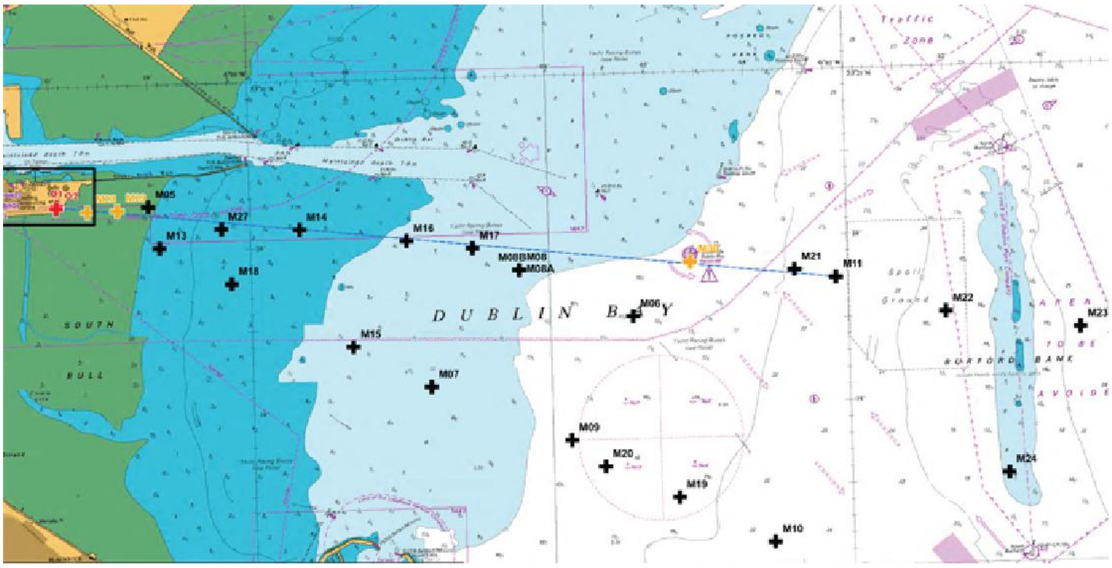

Fig 51 Location of all the boreholes on both the Northern and Southern Alignment drilling lines (Map supplied by CDM Smith).

5.1.1 Caledonian Orogeny

During the Caledonian Orogeny (475 – 400 Ma) the Bray Group rocks experienced sinistral transcurrent faulting and north-westerly directed thrusting (Max et al., 1990) with subsequent folding (Nolan, 1989). Contemporaneously (at 405 ± 2Ma), the Leinster Granite was emplaced. The northern limit of the Leinster Granite is a faulted contact with the Carboniferous rocks of south Co. Dublin. This fault, the Rathcoole Fault, most likely delineated the southern margin of the Dublin Basin and was reactivated during the later Variscan Orogeny. At Portrane and Howth the main tectonic structures associated with the Caledonian Orogeny are east-west trending upright synclines.

5.1.2 Variscan Orogeny

The intensity of deformation associated with the Variscan Orogeny (late Carboniferous – early Permian) varies throughout Ireland. In the south of Ireland, Variscan folds are tight but become more open towards the north where they are commonly associated with local fault re-activation (Graham, 2009). Within the Bray Group, Variscan compression was accommodated by movement on pre-existing faults. Folds in the overlying Carboniferous strata (such as those seen on the coastal sections at Loughshinny, north Co. Dublin) often exhibit similar trends (east-northeast to northeast) with axial planes that typically are steeply dipping to the south to near-vertical. This indicates that shortening was directed towards the north-northwest during the Variscan Orogeny.

5.2 Major Variscan structural features in the region of County Dublin

5.2.1 Faults

There are two main fault sets of Variscan age in the Dublin region (Fig 52). The first set is orientated parallel to the regional Caledonian (NE-SW) strike. The second set comprises minor faults with a north-northwest orientation. The most important faults, with regard to this thesis, are the Rathcoole Fault and the Howth Fault. The Rathcoole Fault, in south Co. Dublin, forms the contact between the Leinster Granite and Carboniferous rocks and was most likely the bounding fault of the Dublin Basin. It is thought to have been active during the Variscan Orogeny. Its trace is arcuate with a variable throw of 100m (at Newcastle) to possibly over 2000m (at Belgard) (Rothery, 1985). Assuming that its offshore continuation eastwards into Dublin Bay has a simlar trend to the fault onshore then it may be assumed that the Rathcoole Fault dies out before intersecting the southern line.

The second major fault relevant to this thesis is the Howth fault which crops out on Howth Head. The Howth Fault is orientated northeast-southwest with a throw of over 300m. The continuation of the Howth Fault towards the southwest is not known but it is likely to be the fault encountered in the onshore boreholes which are pervasively dolomitised.

5.2.2 Folds

Fig 52 Illustrates the distribution and nature of the main Variscan folds within the Dublin region. The majority of fold axes are orientated east-northeast and northeast (Graham, 2009). A syncline is inferred in the vicinity of the onshore drilling sites (Fig 52). It may be assumed that the fold distribution and style seen onshore is continued offshore into the Dublin Bay region.

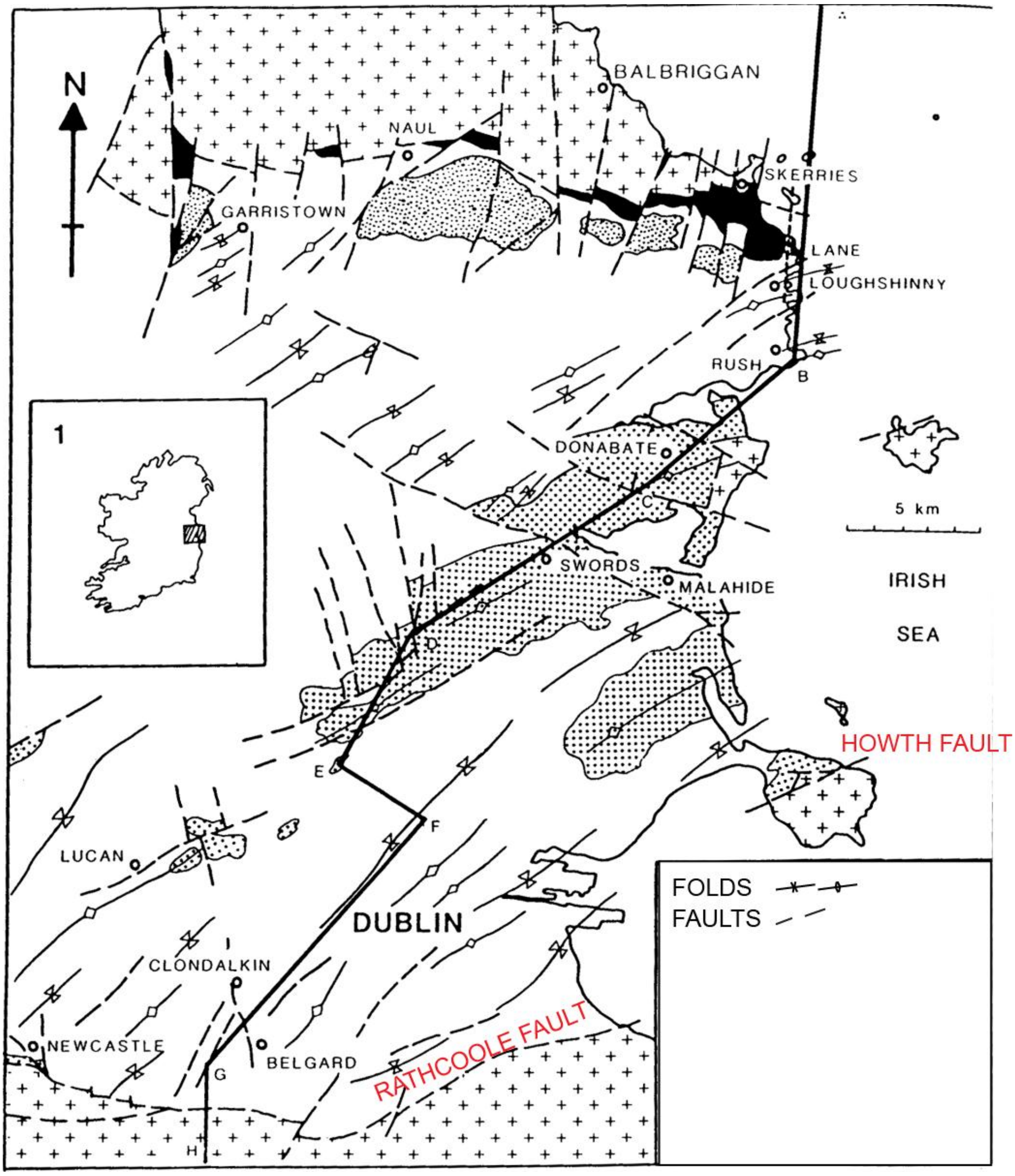

Figure 52. Outline structural map of the Dublin region (adapted from Nolan 1989 by Sevastapulo 2013)).

5.2.3 Joints

The majority of the information on jointing in the Dublin region comes from Rothery (1985). In his work he describes the main joint sets as horizontal and orientated north-northwest and west-northwest. These joints were primarily caused by post-Dinantian (Variscan) deformation. These measurements are consistent with other joint sets in the Dublin region. Rothery also explains that there are many local variations in joint orientation due to local factors (such as the local lithologies).

5.3 Stratigraphic and structural relationships derived from the borehole study

5.3.1 Jurassic

Using biostratigraphy borehole M23 was assigned to the Early Jurassic. Borehole M23 was drilled approximately 1500m west of borehole M22 which was dated as Early Cambrian. The dips of boreholes M23 and M22 are 8º and 40º respectively. Given the distance and dips involved it is not feasible for there to be a continuous stratigraphic succession from the Early Cambrian to Late Jurassic between the two boreholes as the Cambro-Ordovician in the Dublin region alone reaches thicknesses of up to 4500m. The most probable cause for the Early Cambrian rocks occurring close to the Early Jurassic rocks is the presence of a fault between boreholes M23 and M22 (Fig 53). This fault may potentially be the Dalkey Fault, the bounding fault of the Kish Bank Basin, or a fault splay from the Dalkey Fault (Fig 53). No jointing is recorded in borehole M23 with only occasional steep fracturing present.

The seismic section (Figure 53) below illustrates the position of borehole M23 relative to the Dalkey Fault. It is evident from this section that there is a substantial thickness of Jurassic rock against the fault. The figure shows the unconsolidated overburden (in pink) and suggests the positions of the boundaries of the lower Kish Bank Basin fill including the Sherwood Sandstone (in orange) and the Westphalian beneath it. Borehole M22 lies to the left of the Dalkey Fault in the figure below. The dip of the Dalkey Fault cannot be directly inferred from this figure as no seismic velocity information was obtained to convert the two-way-travel times to depths. Hugh Anderson in UCD is gratefully acknowledged for this figure.

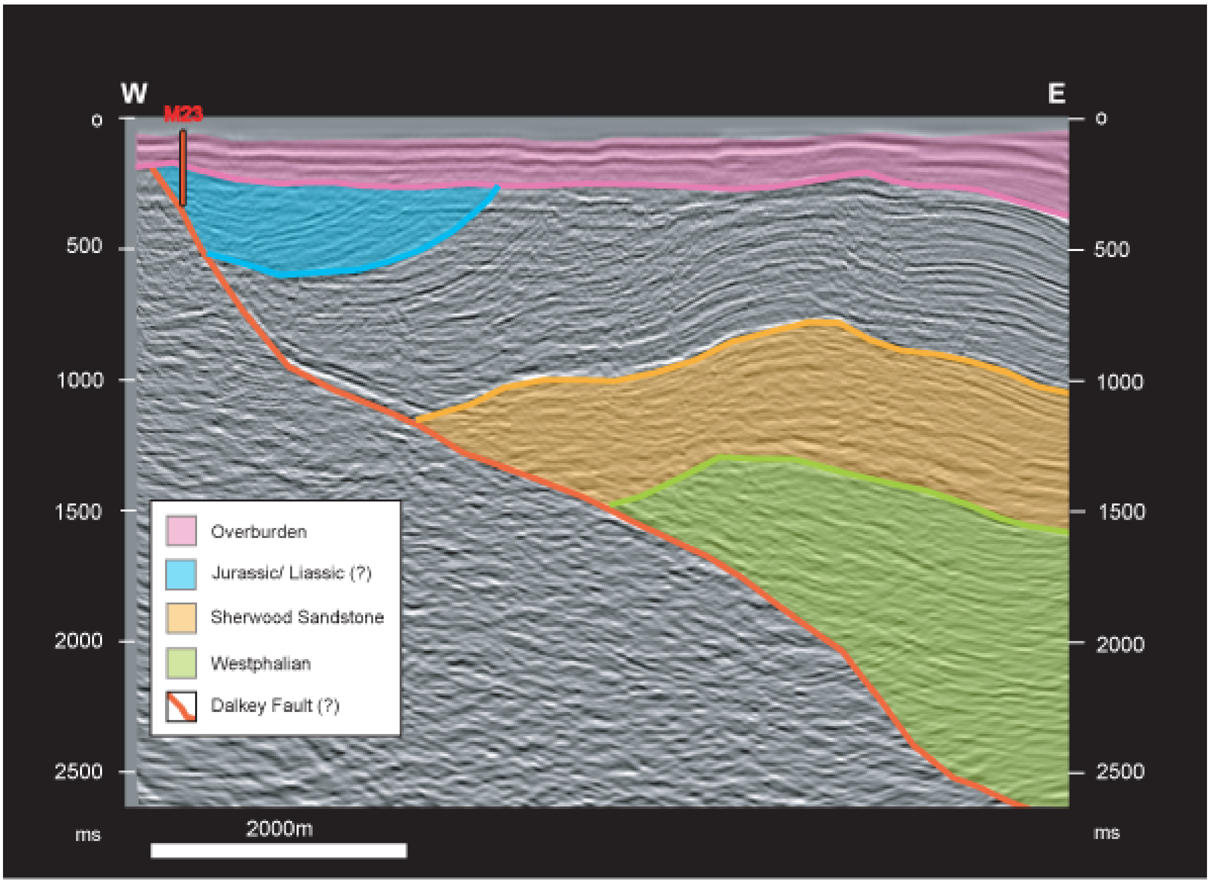

Fig 53. Interpretation of seismic data shot along the Dalkey Fault (?) (Anderson- UCD, 2013)

5.3.2 Lower Palaeozoic

An age of Early Cambrian or younger (post 525Ma) was determined for borehole M22 on the northern line from the LA-ICPMS detrital zircon dating study (see section 4.2.4). Borehole M22 was drilled approximately 1500m south-southeast of borehole M11 which was dated as very Late Tournaisian. The dips for boreholes M22 and M11 are 40º and <5º respectively. Similar to section 5.3.1 there is an insufficient distance to accommodate a stratigraphic sequence from the Early Cambrian to Late Tournaisian and hence a fault is inferred between boreholes M22 and M11. A steeply dipping (60º) spaced fracture cleavage is recorded within pelitic layers in borehole M22. The borehole is also highly fractured. Within borehole M11 fracturing is widespread and two main sets are present; a closely spaced bed-parallel set and a second steeply inclined set. Stylolites are common throughout borehole M11 with the majority having a horizontal orientation which indicates vertical shortening.

Borehole M24 on the southern line is thought to be of a similar age to borehole M22 based on lithological analysis. Borehole M24 was drilled 1900m southeast of borehole M22 and over 2750m from the nearest borehole on the southern line (M10- Late Tournaisian). The dips in boreholes M24 and M10 are moderately steep with values of 35º and 30º respectively. Simial to the above, a stratigraphic relationship between these two boreholes is not thought possible and hence it is thought that the fault between boreholes M22 and M11 continues southwards in between boreholes M24 and M10.

5.3.3 Carboniferous Boreholes

5.4.3.1 Malahide Formation Boreholes

Borehole M11 is assigned to the Malahide Formation. It was drilled 1500m west-northwest of borehole M22 and 500m south-southwest of borehole M21. The stratigraphic relationship between boreholes M11 and M22 is discussed above in section 5.3.2. Boreholes M11 and M21 are both dated as Upper Tournaisian in age and have dips of <5º and 0º respectively. There are two possibilities for their juxtaposition. The first possibility is that there is a lateral-facies change from the bedded calcarenites of borehole M11 to the massive, un-stratified rocks of the Waulsortian Formation in borehole M21. In this instance no fault is necessary to explain their juxtaposition but this scenario is thought unlikely as within such a relatively small geographical area it unlikely that the facies would have been sufficiently varied to produce both an interbedded calcarenite sequence and a mud-mound formation closeby (see section 1.5). The second possibility assumes that the sequence in borehole M11 immediately underlies borehole M21 stratigraphically. In this scenario, a minor fault with minimal throw is required to juxtapose the Malahide Formation rocks of borehole M11 with the Waulsortian Formation rocks of borehole M21. The contact between borehole M10, which is also assigned to the Malahide Formation and borehole M21 is poorly constrained due to the large distance between them (approximately 3000m).

5.3.3.2 Waulsortian Formation Boreholes

Borehole M21 is assigned to the Waulsortian Formation of Late Tournaisian age. It was drilled 500m east-northeast of borehole M11 and approximately 1100m east of borehole M30. The relationship between borehole M21 and M11 is discussed above in section 5.4.3.1. The extent of the Waulsortian Formation mud-mound in Dublin Bay is not known precisely. It is possible that borehole M21 forms a unique and independent mound or it may be part of a larger sequence of mounds. However, no Waulsortian boreholes were recorded on the southern line.

The contact between boreholes M21 and M30 is thought to be stratigraphic as borehole M21 is Late Tournaisian in age and borehole M30 is Early Viséan. Given the large distance between them this is the option chosen.

5.3.3.3 Lucan Formation Boreholes

Borehole M30 is assigned to the Lucan Formation and is Arundian in age. It was drilled 1100m west of borehole M21 and approximately 1800m east of M08 (A&B) and just less than 1000m northeast of M06. The contact between boreholes M30 and M21 is discussed above in section 5.3.3.2. Borehole M30 has been significantly dolomitised. Within the Dublin region (such as on Howth Head) dolomitisation is frequently seen in association with faulting and thus it is suggested that borehole M30 is proximal to a fault structure.

The relationship between boreholes M30 and M06 is thought to be stratigraphic as both boreholes M30 and M06 are Arundian in age.

The relationships between the lowermost Lucan Formation boreholes on the southern line are somewhat more complex than those of the northern line. These Lower Lucan Formation boreholes lie on the eastern end of the southern line. Boreholes M19 and M09 are dated biostratigraphically as Arundian in age. However, borehole M20, which lies between boreholes M19 and M09, is dated as Holkerian. There are two possibilities for this relationship. The first requires two minor fault offsets but fracturing is relatively minor in both boreholes M19 and M20. The second possibility is the presence of a north-south trending syncline, which is restricted to the southern line and passes close by borehole M20. This is somewhat in conflict with the dip information from boreholes M19, M20 and M09 (which have dips of 10º, 20º and 10º respectively) as the dips from borheole M20 would be expected to be close to horizontal if it is in the vicinty of the fold axis.

The remaining Holkerian boreholes assigned to the Lucan Formation include boreholes M08 (A&B), M17, M16, M14, M07 and M15. They occur on both the northern and southern lines and the contacts between them are assumed to be stratigraphic. On the northern line (boreholes M08 A&B, M17, M16 and M14) the tectonic dip ranges from <5º to 12.5º and veining and fracturing are minor across all boreholes. On the southern alignment boreholes M07 and M15 have dips of 20º and 10º respectively. Unlike the northern alignment the Holkerian boreholes on the southern alignment record abundant veining (with steeply inclined vein sets) and fracturing (dips of 20º to vertical).

There are four boreholes dated as Asbian. Boreholes M27 and M05 (on the northern line) and borehole M13 (on the southern line) have dips of 5º, 10º and 10º respectively. Within these boreholes veining is common (with steeply inclined vein sets) but fractures, which are typically steep, are minor. Borehole M18 is also dated as Asbian in age. It has a relatively steep dip of 40º and is highly fractured and cut by abundant dolomitic veins. This along with pervasive dolomitisation suggests the presence of a fault near to borehole M18. The relationship between the Asbian boreholes is assumed to be stratigraphic.

In the intertidal zone and onshore there are four boreholes (M29, M28, BHO2 and BHO1) that are assigned to the Lucan Formation. Dolomitization is pervasive in each borehole, preventing conclusive biostratigraphic dating, with the intensity of fracturing increasing towards the west in the onshore boreholes BHO2 and BHO1. This suggests the presence of a substantial fault in the area, possibly the continuation of the Howth Fault to the southwest.

5.4 Geological map and Cross Section of Dublin Bay

Below, in Figure 54, is a geological map created as part of this thesis using existing knowledge from the literature and the data gathered from logging each of the twenty-five boreholes drilled. The differing shades of blue represent different Carboniferous formations. These are from east to west (the direction of younging) the Malahide and Waulsortian Formations (Late Tournaisian) and the Lucan Formation (spanning the Arundian – Asbian). The Lower Palaeozoic rocks are highlighted in purple and the Jurassic rocks are shown in pink on the east of the map.The Leinster Granite is highlighted in red on the south of the map.

Several faults are also depicted. The accepted position of the Rathcoole Fault (to the south) and the Howth Fault (to the north) as well as the positions of the faults proposed by this thesis (such as between boreholes M11 and M22). The revised position of the Dalkey Fault is depicted, to the east of the map.

In Fig. 55, a geological cross section along the northern drilling line was created. The vertical scale in Fig. 55a is exaggerated 2.5 times. The proposed faults, including the revised position of the Dalkey Fault may be seen to the east whilst the fault zone encompassing the onshore boreholes (BHO1&2) and the intertidal boreholes (M28 and M29) is visible to the west. The Waulsortian is shown with variable thickness as its lateral extent is unknown. The Tober Colleen Formation is also illustrated as it is assumed to lie beneath the Lucan Formation.

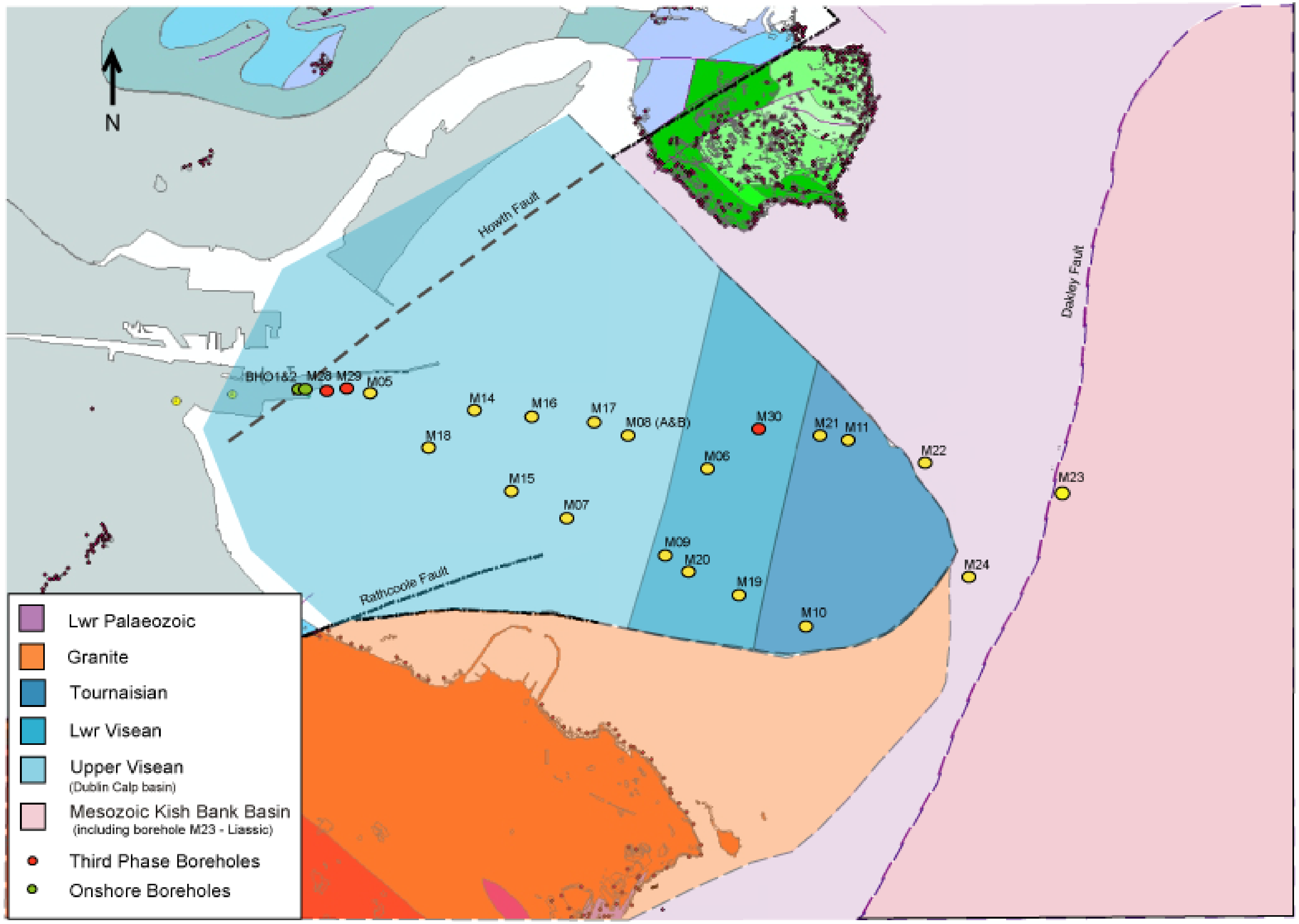

Fig. 54 Geological map of Dublin Bay

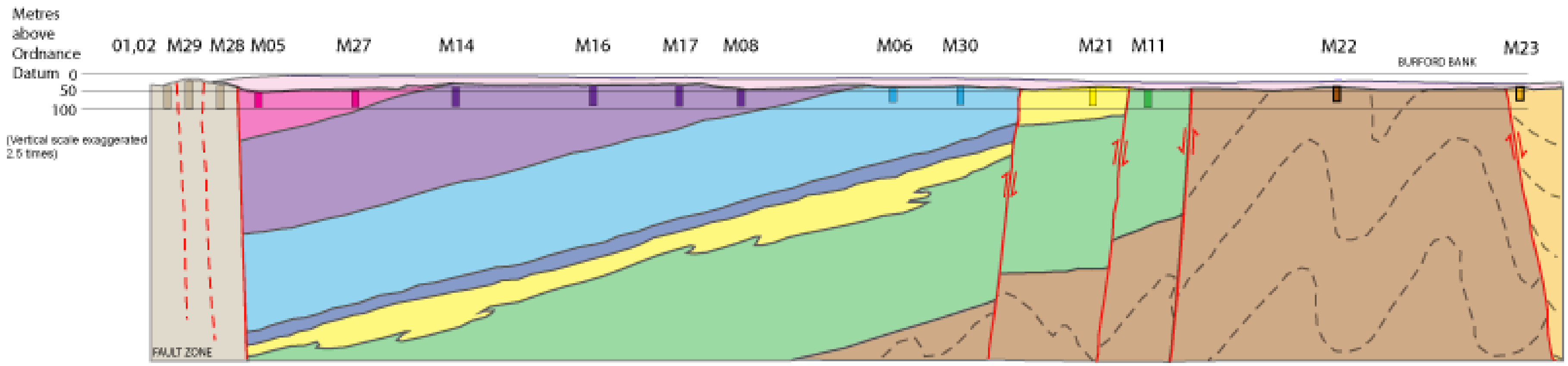

Fig. 55a

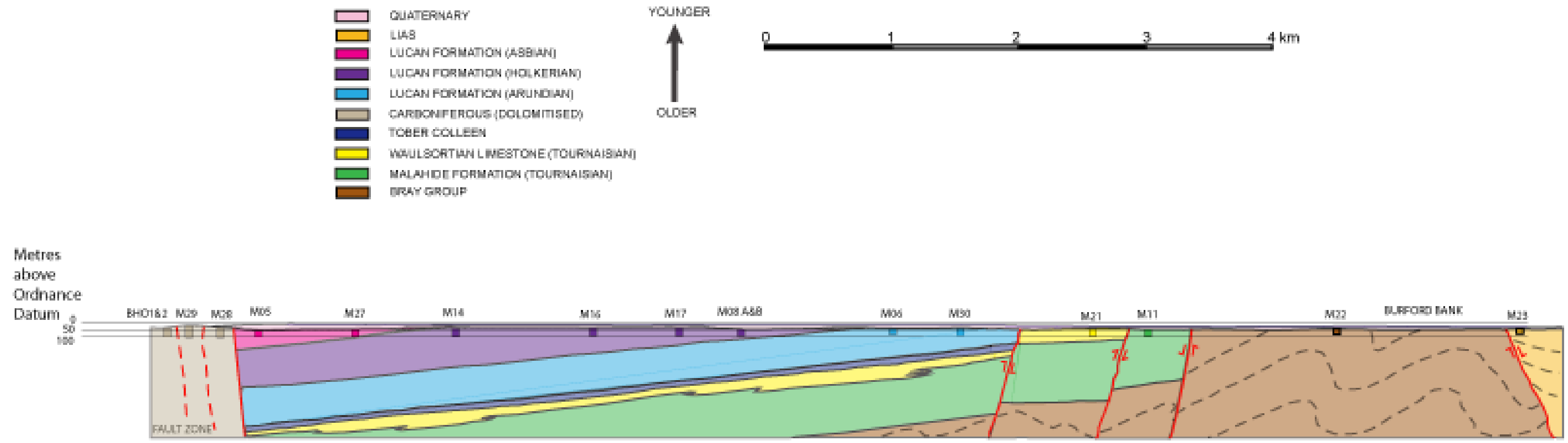

Fig. 55. Geological cross section along the northern drilling line. Above (a) the vertical scale is exaggerated 2.5 times

6.1 Conclusions

Twenty-five boreholes along both the northern and southern alignment drilling lines have been logged in this thesis. The field logs for each borehole were digitised using Adobe Illustrator and summary logs have been produced. Data gained from logging the boreholes was integrated with existing knowledge of the local geology to produce a geological map for Dublin Bay. In addition to this a cross section has also been created.

This thesis has constrained the ages of boreholes M22 and M24, on the eastern edge of the study area, as post-Early Cambrian (c. 525Ma) and thus, along with lithological analysis, they have been assigned to the Lower Palaeozoic Bray Group. The lithologies of boreholes M22 and M24 are characteristic of deposition in a submarine fan system sourced from Avalonian basement.

This thesis has also shown the prevalence of Carboniferous limestones across the majority of the Dublin Bay. Using biostratigraphy and lithological analysis three Carboniferous formations have been identified ranging in age from Late Tournaisian to Asbian. These formations include the Malahide Formation (seen in the Late Tournaisian boreholes M11 and M10) which is characterised by interbedded calcarenites and calcareous mudstones with conspicuous pyrite, common bioclasts and bioturbation throughout. It has been concluded that these lithologies represent a shallow marine environment, possibly a tidal flat or close to wave base.

Borehole M21 has been assigned to the Waulsortian Limestone Formation (Late Tournaisian) and comprises massive, un-stratified limestones deposited in a shallow marine depositional environment.

The majority of boreholes have been assigned to the Lucan Formation which ranges in age from the Arundian to Asbian. The Arundian boreholes (M30, M06, M19 and M09) are characterised by interbedded calcilutites and calcarenites, and the calcarenite units are very commonly graded. These lithologies are typical of distal turbidite flows in a deep-marine depositional environment.

The Holkerian boreholes (M08 A&B, M17, M20, M07, M16, M15 and M14) largely comprise bedded calcilutites with subordinate calcarenites. Sedimentary structures identify these boreholes as moderate to deep-marine distal turbidites.

The Asbian boreholes (M27, M05, M18 and M13) are dominated by bedded calcareous mudstones with locally abundant calcarenites. Graded and laminated units in conjunction with the prevalence of calcareous mudstone suggest these boreholes represent moderate to deep-marine distal turbidites.

There are four boreholes (M29, M28, BHO2 and BHO1) for which interpretation is limited due to pervasive dolomitisation.

This thesis has identified and described the first *in situ* rock sample conclusively dated as Early Jurassic in the Dublin region. Borehole M23 is characterised by interbedded calcareous mudstones and calcareous sandstones which become more shale dominant towards rockhead. The lithology is typical of a relatively shallow marine depositional environment.

This thesis has proposed a number of new faults and revised the location and extent of other previously known faults in Dublin Bay. A continuation of the Howth Fault from Howth Head towards the southwest close to the onshore boreholes (BHO1 and BHO2) has been proposed due to the intensity of fracturing and the pervasiveness of dolomitisation within these boreholes. Boreholes M28 and M29 in the intertidal zone have also shown high levels of fracturing and dolomitisation suggesting these are also possible fault splays from the Howth Fault. Offshore, the position of the Dalkey Fault which bounds the Kish Bank basin has been revised with the recognition that borehole M23 contains Early Jurassic rocks. The Rathcoole Fault is now known to die out before reaching the southern drilling line. The new faults proposed by this thesis are located between borehole M22 and M11, between boreholes M11 and M21 and between boreholes M21 and M30.

The presence of a potential syncline is also suggested by this thesis proximal to boreholes M19, M20 and M09.

More boreholes would have to be drilled in order to understand better the stratigraphic relationships of the lithologies at the eastern end of both lines. In particular establishing the boundary of the Kish Bank Basin and its extremely thick succesion of Jurassic sediments would require further boreholes to be drilled proximal to the Burford Bank close to the trace of the Dalkey Fault.

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