Preliminary Geological Investigation Of

The Skerd Rocks Foreshore License Area For

Fuinneamh Sceirde Teoranta (FST) ©

By

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EXECUTIVE SUMMARY

The geology of the Foreshore License Area (FLA) has been studied. The constituent geological units are: (1) Ordovician Skerd Formation (SI); (2) Carboniferous limestones (Carb); (3) Ordovician Metagabbros (Mg); (4) Devonian Errisbeg Townland Granite (GaEb); and (5) Devonian Cuilleen-Type Granite (GaCu). The latter two are sub-units of the Galway Granite. Two regionally important faults occur within the FLA: (1) the EW trending Skerd Rocks Fault (SRF); and (2) the WNW trending Carboniferous Bounding Fault (CBF).

The SI occupies a small triangular shaped area in the southwest corner of the FLA (approx. 9% of FLA), and outcrops at the Skerd Rocks. The SI is a heterogeneous package of metavolcanics and metasediments. The SI is not favoured for siting turbines, as it is steeply dipping and heavily faulted, as well as occurring in an area of treacherous currents, high maximum wave heights and extreme bathymetry. The Carb occupies a small, narrow WNW trending tract (approx. 10% of FLA) parallelling the southern boundary of the FLA, but occurs in deep water unsuited for siting turbines. The Mg occupies a larger tract (approx. 17% of FLA) in the northwestern part of the FLA, and outcrops at Mile Rocks, Doonpatrick, Doonmanebeg, and possibly Doonmane. The Mg tends to be massive and weakly foliated, but is largely composed of hydrous sheet silicates. Thus, the Mg is largely mechanically isotropic, but likely exhibits relatively low mechanical strength. Because much of the Mg lies in waters deeper than 30 m, and occurs remotely in the northwestern corner of the FLA, the Mg is generally not favoured for siting of turbines.

Subunits of the Galway Granite occupy approximately 64% of the FLA (approx. 26.5 km^2). Except for the very southern FLA, granite occupies all of the area east of a NNW trending sinuous line running just east of Mile Rock to Doonguddle. The GaEb occupies an extensive NNW trending tract (approx. 49% of FLA) in the central FLA, and outcrops at Doolick, Doolickbeg, and possibly Doonmane. The GaCu occupies a smaller tract (approx. 15% of FLA) in the eastern FLA. Both granite types exhibit primary mineral assemblages and granular textures indicating that they are extremely indurate, with comparable susceptibilities to weathering. Differences in the mechanical properties of the granites are probably more dependant on foliation, faulting and jointing. The GaCu is weakly foliated and is probably mechanically isotropic. The GaEb is strongly foliated with extensive sub-vertical magmatic layering, and is probably mechanically anisotropic. The principal faults in the granites occur as a set of curved, closely-spaced faults with a NE trend, and a later set of near vertical, NW trending faults. A third set of SW trending faults also occurs. Low angle sheet jointing is common throughout the granites. Conjugate joints coincide with the major fault trends. The distribution of faults and joints in the FLA is largely unknown, but where mapped faulting is intensive.

Inferred bedrock exposure in the FLA is 75% or greater. Accumulation of unconsolidated seafloor sediment is minimal above 20 m water depth. Sediment accumulating in 20-30 m water depths is likely in a shallow trough running along the northeastern boundary of the FLA.

The 5-20 m water depth interval identifies a large, irregular and discontinuous area covering much of the central FLA extending from The Big Breaker to Doolick - the Kelly Rock Plateau. Significant areas at Mile Rocks and Fools Shoal are also identified. The 5-30 m water depth interval identifies a large, continuous area including the Kelly Rock Plateau, Fools Shoal and Mile Rocks areas and extending to the northeastern and northern boundaries of the FLA. A significant area around the Wild Shoals is also identified. Data critical to siting turbines used in this study are: (1) favourable bedrock geology, (2) optimum water depth interval; (3) proximity to mainland, with inverse length of cabling; and (4) wave height distribution. These data indicate that an extensive area of the eastern side of the FLA including the Kelly Rock Plateau and extending towards the northeastern and northern boundaries of the FLA is the most favourable for siting turbines, where the optimum water depth interval for turbine installation is 5-30 m. That area shrinks to the Kelly Rock Plateau, Fools Shoal and possibly northeastern Mile Rocks areas, where the optimum water depth interval for turbine installation is 5-20 m, or sediment accumulation in the shallow trough east of Kelly Rock Plateau is excessive.

INTRODUCTION

The current geological investigation of the Skerd Rocks foreshore license area (FLA) was conducted as a preliminary study in advance of the planning/feasibility phase of a project dedicated to the installation of a wind farm. The principal objective of the study is to document and evaluate the available geological data pertaining to the Skerd Rocks locality so as to inform and complement future geotechnical investigations. The latter are directed at defining the foundations of the turbine piers, which constitute a substantial component of the capital costs of offshore wind parks (*Ottesen Hansen* 2002a and b). The latter author notes that in order to define the type of foundation structure the following parameters are absolutely essential:

(1) Water depth
(2) Long term changes in water depth due to sea bed movement and erosion
(3) Type of sea bottom sediment (if any)
(4) Strata of the underground
(5) Strength and mechanical properties of the soils in the underground

This preliminary geological investigation addresses points 3 and 4, and to a lesser degree points 1 and 2. The collection of representative rock samples of constituent geological units in the FLA for geotechnical testing will assist in addressing point 5. The study consists of three components.

A. **Literature Review:** Documentation and evaluation of the available geological information in the form of geological reports published by the Geological Survey of Ireland (GSI), and published papers and monographs in the scientific literature, as well as any theses available at university libraries. A copy of the marine map with bathymetric data of the area was also acquired.

B. **Sampling:** Collection of hand specimen-sized samples of the constituent geological units occurring within the FLA from nearby mainland, and in one case island, onshore outcrops for later geotechnical testing. Samples of seabed sediments were not collected, as this would require the use of a vessel and significant follow-on laboratory analyses, which is outside the scope of this study.

C. **GIS Model:** Generation of a Geographic Information Systems (GIS) computer model in order to integrate the various data sets collected during the course of the study. The model allows comparative analysis of the data and the production of multimedia displays of generated maps. Quantitative data on seafloor sediment types and thicknesses are currently unavailable and could not be integrated into the GIS model.

The Skerd Rocks foreshore license area held by Fuinneamh Sceirde Teoranta (FST)[1] constitutes an expansive polygonal area (approx. 40 km^2) within the northern approaches of Galway Bay. The bounding coordinates of the FLA as received from FST, are as follows: (1) 10.02800 W 53.30250 N; (2) 10.05000 W 53.29166 N; (3) 10.02500 W 53.25000 N; (4) 9.95000 W 53.23333 N; (5) 9.92500W 53.26666 N; and (6) 9.98333 W 53.30250 N in decimal degrees

[1] Fuinneamh Sceirde Teoranta (FST) is the new name of the company hitherto called Gaoithe Sceirde Teoranta (GST).

longitude and latitude. However, the area studied and the official FLA are not exactly coincident[2]. The area studied is nonetheless here termed the FLA, and includes the Fools shoal and Wild shoals within the easternmost and southeast boundaries, respectively, the Skerd Rocks within the southwest boundary, the Mile Rocks within the northwest boundary, and the Tonyeal Rocks just outside the northeast boundary (See Fig. 1).

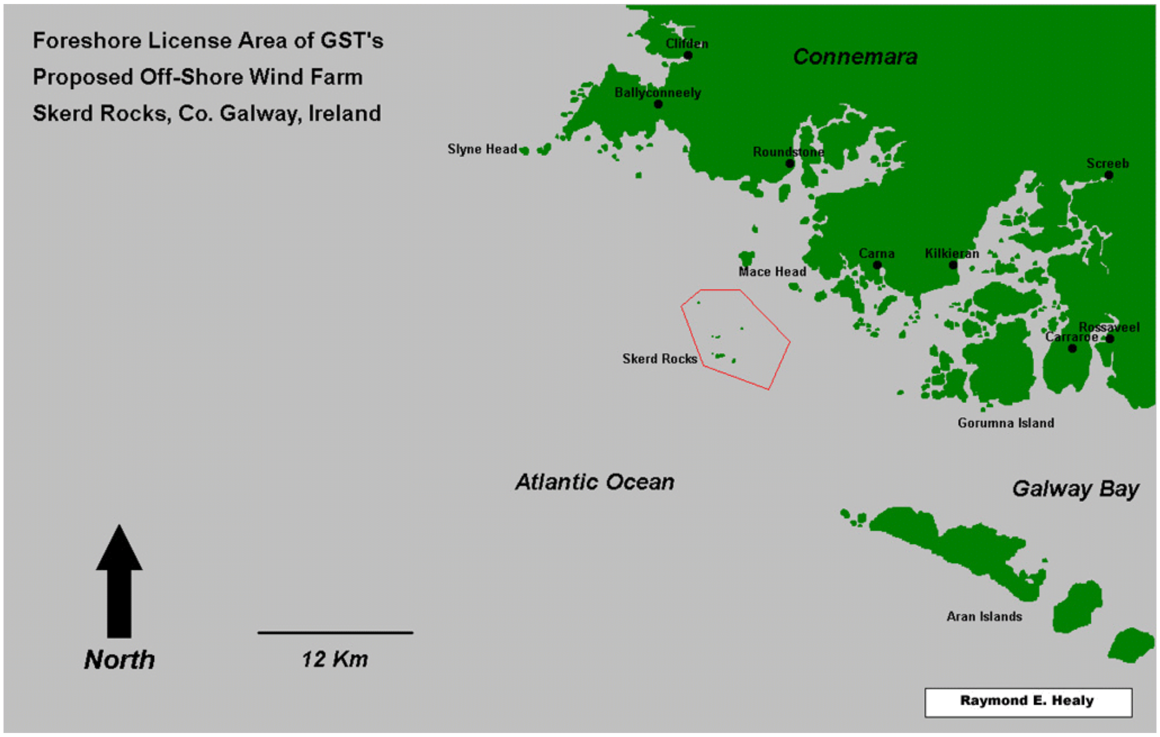

Figure 3 Location map showing the position of the Foreshore License Area (polygonal outline) northwest of the Aran Islands in the northern approaches of Galway Bay. Scale Bar = 12 km.

2 When the FLA was registered with the Department of Marine, there were errors in the registration of two of the coordinates. The registered values for the two erroneous bounding coordinates in decimal degrees longitude and latitude are coordinate **No. 3:** 10.20000 W, 53.25000 N; and coordinate **No. 5:** 9.91833 W, 53.26833 N. These errors were realized only after the study was complete and the report was in final draft form. Consequently, the area studied does not exactly correspond to the official FLA.

METHODS

1. Literature Review

All relevant references to previously published technical reports, journal papers, monographs and theses, pertaining to the geological units occurring in the area of the Skerd Rocks are listed in the **Bibliography**, except those actually used in the preparation of, and which are cited in, this report. The latter works are listed under **References**. Given the limited scope of the project, works published prior to the mid 1960's were not sought, as these are typically difficult to locate and are invariably superseded by later work.

It is important to allude to the prodigious amount of geological research that has been done on several of the geological units occurring within the FLA. This reflects the geological significance of the area, which now incorporates a major accreted fragment of the leading edge of the North American continent (then including northwest Ireland), which collided with the European continent (then including southeast Ireland) roughly 410 million years ago. Indeed, *Friedrich et al.* (1999b) note that the Connemara region is one of the best studied continental magmatic arcs in the northern hemisphere. Importantly, the most intensively studied units within the FLA are the Galway Granite and the Metagabbro, which fortuitously are the aerially predominant rock types in the FLA. In light of the profusion of published research and the limited scope and budget allocated to this study, the literature search and review should be considered as being somewhat cursory, and not wholly doing justice to the body of available research. Consequently, the **Bibliography** should also be regarded as incomplete.

Information other than that published in the scientific literature was also acquired through discussions with:

A. Michael Geoghegan, Project Manager, National Seabed Survey, GSI: discussion pertaining to the geological mapping and seabed sediment distribution in the vicinity of the Skerd Rocks. A discussion on the status of the on-going national seabed survey prompted Mr. Geoghegan to offer to conduct a test survey over part of the FLA. After consultation with Mr. G. Healy, the test survey was subsequently done using the *Celtic Voyager* research vessel initiating Zone 2 of the national seabed survey (i.e., survey of the 50-200 m depth interval).

B. Brendan O'Connor, Aqua-Fact International Services Ltd, Liosbaun, Galway: discussion pertaining to the type and thickness of seabed sediments in the vicinity of Galway Bay in general, and the Skerd Rocks in particular.

C. Prof. Paul Ryan, Department Head, Dept. of Geology, University College Galway: discussion pertaining to resolving the nature of the major faults in the area, and current research on the Carboniferous rocks and general tectono-stratigraphic model of the area.

2. Sampling

A suite of 14 representative rock samples of constituent geological units in the FLA were collected by Messrs R. Healy and G. Healy for geotechnical testing. That testing is beyond the scope of this study, and it is expected LIC Engineering A/S will conduct the testing. *Ottesen Hansen* (2002a and b) states that during the preliminary or primary phase of the project it is sufficient to collect samples from strata that belong to the same geological formation as the underground of the wind farm, and not necessarily from the FLA *sensu strictu*. All but one of the rock samples was collected in the field from mainland onshore outcrops.

The sampling campaign was done by the quick and convenient method known as "highway geology", which contrasts markedly from the conventional method of running linear traverses at 90^{O} to the strike or general trend of the geological strata. Approximate sampling stations were preselected from the geological map in order to permit: (1) easy access from roads; (2) sampling of the geological units in rough proportion to their relative areal extent within the FLA; and (3) a crude traverse across the Errisbeg Townland granite, the areally predominant geological unit within the FLA and the most likely host of the installation, as will be discussed later. The minimum dimension of the samples to be collected was defined as one capable of yielding a 40 mm plug for geotechnical testing (*G. Healy*, pers. comm. 2002). The samples were given a brief description to confirm the sample integrity, and were then catalogued and placed in storage for later shipment to LIC Engineering A/S (See **Appendix 1**).

The following geological units occurring in the FLA were sampled:

A. Ordovician Metagabbro (Mg)
B. Devonian Errisbeg Townland Granite (GaEb)
C. Devonian Cuilleen-Type Granite (GaCu)

where the latter two are subunits of the Galway Granite.

The Devonian Carna-Type Granite (GaCn) is also a subunit of the Galway Granite, which occurs immediately east of the FLA. Because it is transitional with the Cuilleen-Type Granite (GaCu) the Carna-Type was also sampled.

The following geological units occurring within the FLA were not be sampled:

A. Ordovician Skerd Formation (SI)
B. Carboniferous Limestones (Carb)

The SI is a heterogeneous package of rocks, and thus could not be representatively sampled with a small number of samples. In addition, the SI: (a) does not outcrop onshore, but only at the Skerd Rocks, precluding its sampling within the scope of this work; (b) only occurs in a very small portion of the southwest corner of the FLA; (c) being steeply dipping, heavily faulted and prone to weathering, probably provides poor footing for pier foundations, and (d) occurring in the immediate vicinity of the Skerd Rocks is likely an unsuitable location for siting turbines because of shallow depths impeding installation and generating excessive wave action, as well as additional environmental considerations.

The Carb only occurs along the very southern boundary of the FLA in relatively deep water south of a major WNW trending fault, and is thus rejected as a target for sampling, even if accessible at nearby mainland onshore outcrops (*G. Healy*, pers. comm. 2002).

Additionally, sampling of further geological units occurring along the probable path of the proposed submerged high voltage cable with landfall at either Kilkieran or Carna harbours is beyond the scope of this study.

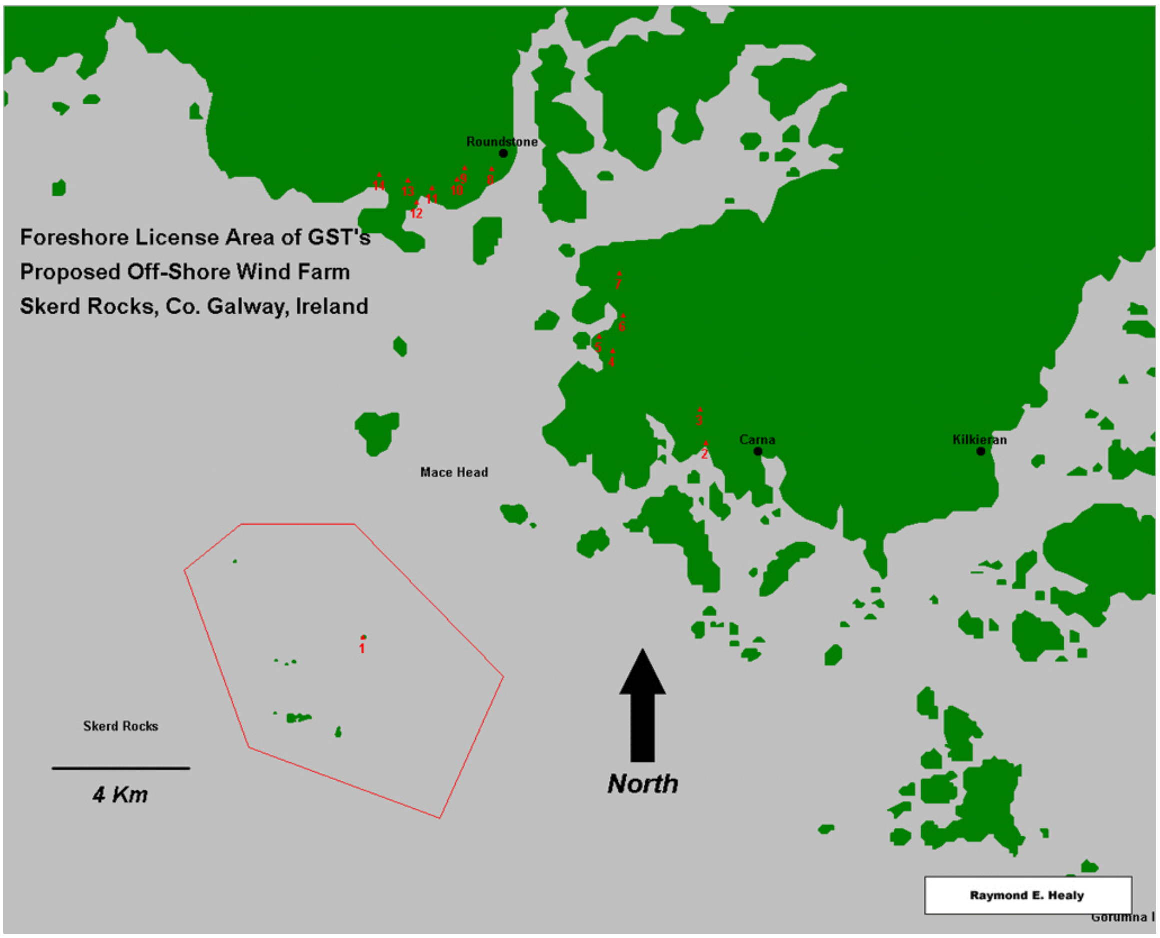

Figure 4 Location map showing one sampling point on Doolick Island and 13 other sample stations on the mainland in the vicinity of Carna and Roundstone. Scale Bar = 4 km.

Table 1. List of Samples for Geotechnical Testing

Sample No.	Location	Geological Unit	Date of Sampling
GST-02-01	Doolick Island	GaEb	37448
GST-02-02	Shoreline at Carna quay	GaCu	37479
GST-02-03	30 m north of road, 1.5 km west of Carna (opposite Cuilleen Hill)	GaCn	37479
GST-02-04	Moyruss crossroads	GaCn	37479
GST-02-05	Moyruss jetty	GaCu	37479
GST-02-06	Moyruss well	GaCu	37479
GST-02-07	40 m south of road at Leitirard	Mg	37479
GST-02-08	10 m south of road at Cregduff Lake	Mg	37479
GST-02-09	150 m north of Cregduff crossroads	Mg	37479
GST-02-10	300 m west of Cregduff crossroads	GaEb	37479
GST-02-11	Bend in road 50 m east of Gurteen crossroads	GaEb	37479
GST-02-12	Shoreline at Gurteen Beach	GaEb	37479
GST-02-13	Dogs Bay crossroads	GaEb	37479
GST-02-14	300 m west of Dogs Bay crossroads	GaEb	37479

Note: GST-02-01 sampled from a fissure in the centre of Doolick island by Mr. G. Healy.

GIS MODEL

1. Introduction

One of the principal objectives of the study was the generation of a Geographic Information Systems (GIS) model to integrate the various data sets collected during the course of the study. The GIS model allows manipulation and comparative analysis of these different data sets and the production of multimedia displays of generated maps.

The FLA, the Skerd Rocks, the town of Roundstone, the trace of a geological fault, the 20 m bathymetric contour, for example, all refer to locations in the physical world and as such are deemed to be geographical information. One way of representing geographical information is to present it visually – on a map. The map acts as a visual representation of objects in the real world. Thus for example, physiographic data is represented on topographic maps (e.g., Ordnance Survey maps), geological data is represented on geological maps, and bathymetric data is represented on marine maps. These three types of maps are all forms of geographic information. By converting the geographic information into digital form the differing information can be juxtaposed, queried and processed more efficiently than otherwise possible with disparate analogue (i.e., physical) data.

2. Agis & Windig Software

A GIS is a suite of computer technologies which, to varying degrees, allows a user the opportunity to capture, edit, manipulate, display, analyse and export geographic information (*Cadcorp* 2002). Thus, GIS presents us with the opportunity to manipulate and analyse geographic information. Data can be introduced into a GIS by: (1) acquiring free data in the public domain supplied by agencies; (2) purchasing 'off the shelf' data from vendors; and/or (3) the user generating his or her own data. The latter is done by converting paper or textual records into a digital format, typically by digitizing data from maps using digitizing software.

GIS vary in functionality and complexity from basic systems with a limited set of functions which may be as simple as displaying topographic (base mapping) data and allowing the printing of maps, whilst more sophisticated GIS will allow extremely complex calculations and processes to be performed. For this study, the author downloaded the Windig 2.5 digitizing and Agis GIS 1.71 shareware from the on-line website http://www.agismap.com/. All of the data used in the GIS model were digitized using Windig and imported into Agis. The latter is considered a basic to intermediate level GIS software, but incorporates adequate functionality for the data manipulation required in this study.

In order to introduce data into the GIS model it must first be digitized. Legends, labels and other features used strictly for presentation purposes, are simply entered by typing the feature name and field display coordinates into display options. However, point (i.e., non-linear) features with fixed or specified coordinates such as the bounding coordinates of the FLA, the coordinates of towns and villages in Connemara, places, areas or regions (i.e., names of islands or geological units) are entered by typing the feature name and feature label and its longitude and latitude in decimal degrees into databases (i.e., Agis datafiles with file extension *.dat*). Point features can also be entered by digitizing the points from bitmap images using Windig. The feature coordinates are again stored in Agis datafiles as longitude and latitude in decimal degrees, and feature names and labels are assigned to each feature. Thus, the coordinates for the town of Roundstone are assigned the feature name Roundstone and a feature label identifying it as a town, which assists in manipulation during map production and presentation (i.e., whether and how to display the feature). Point feature data are incorporated into Agis GIS models as data layers, which are composed of the datafile and an associated data display format file (i.e., Agis file extension *.agd*).

Linear features such as shorelines, geological contacts, bathymetric contours, etc. are entered into databases (i.e., Agis mapfiles with file extension *.mpa*) by digitizing the features from bitmap images in terms of their longitude and latitude in decimal degrees. Thus, a bathymetric contour may be represented by 50 points in a database with a feature name (e.g., 20 m depth contour) and feature label to identify it as a bathymetric contour. The larger and more irregular the feature the greater the number of points digitized in order to reproduce the shape and character of the feature. For example, a straight line can be adequately represented by simply digitizing the two end points, whereas the mainland shoreline of Connemara is represented by approximately 1,456 digitized points. An additional feature code is assigned to linear features to distinguish lines from polygons, where the latter are essentially lines that enclose an area, and determine how the feature is displayed. Thus, each feature in mapfiles is represented by a header record followed by a list of longitudes and latitudes for each point that describes that feature.

The mapfiles are subsequently converted to binary map files (i.e., Agis file extension .*mpb*), which are the binary files containing polygons and lines used in a map layer to display a map. These are associated with a map display format file (i.e., Agis file extension .*agf*), which determines display characteristics of the features based on feature codes. The binary files are created using a specific map projection and origin, such that the data is pre-processed in this projection facilitating rapid display and minimizing disk storage space. Linear feature data is incorporated into Agis GIS models as map layers, which are composed of the binary map file and an associated map display format file (i.e., Agis file extension .*agf*).

In order to digitize accurate longitudes and latitudes from a map image (i.e., bitmap image with file extension .bmp) of the area of interest, it is essential to define the coordinate system of the map. The coordinate system is defined by establishing the correct X (longitude) and Y (latitude) coordinates of three points on the map. These three reference points must have accurately known longitudes and latitudes, should be widely spaced, and occur in the shape of a triangle, and not on a straight line. Suitable reference points include the intersection of map grid lines, towns and villages of known coordinates, and other distinctive physiographic features whose coordinates can be accurately determined and which can be readily and accurately located. All points that are subsequently digitized from the bitmap image are given longitudes and latitudes by reference to a transformation matrix established by Windig using the three reference points. Because error is cumulative, all errors in defining the precise location of each reference point and in determining their exact longitude and latitude propagate into the derived data (i.e., the digitized features from that map image). Importantly, for global longitude (X) and latitude (Y) coordinates, degrees west or south need to be assigned negative values to be correctly placed.

3. Data Sources

Physiographic, geological and bathymetric data were incorporated into the GIS model, whereas regrettably, quantitative data on seafloor sediment types and thicknesses are currently unavailable and could not be incorporated into the model. By bringing data from various sources together within a GIS, the richness of the generated GIS model is amplified. The data sources are:

A. Physiographic data of the mainland and island coastlines - digitized from image downloaded from on-line coastline extractor, National Oceanic and Atmospheric Agency (NOAA), USA at http://rimmer.ngdc.noaa.gov/coast/

B. Physiographic data of towns and of the coastlines of both the mainland and islands - digitized from 1:30,000 scale marine map no. 2709 (*Haslam* 1983).

C. Physiographic data of the FLA were received from Mr. G. Healy in the form of the six bounding coordinates in decimal degrees longitude and latitude.

D. Bathymetric data - digitized from 1:30,000 marine map No. 2709 (*Haslam* 1983).

E. Geological data - digitized from 1:100,000 scale geology map of Connemara (*Morris et al.* 1995).

The geological and marine maps were scanned using a desktop flatbed scanner and the resulting high resolution images were saved as bitmaps (i.e., files with *.bmp* extensions). Physiographic data of the mainland and island coastlines were digitized from a bitmap image downloaded from the on-line coastline extractor of NOAA (See Fig. 3). Because of the low order resolution of the precursor data in the latter image, the physiographic data of the islands and rocks in the vicinity of the FLA were re-digitized from the higher resolution scanned image of the marine map. Thus, the physiographic data for the island coastlines were combined from two sources into a single data set. The towns were also incorporated into the GIS model by determining the coordinates of the towns from the marine map, and creating a separate data set with unique feature labels. The fourteen sampling stations were similarly incorporated into the GIS model. By assigning different features unique labels, the features can be distinguished for the purpose of manipulation and presentation.

The geological data were acquired by digitizing the fault traces and geological contacts in the vicinity of the FLA from the scanned image of the geological map. The data for faults and geological contacts were again assigned different feature labels. Importantly, the geological map is plotted on the Irish National Grid, such that the position in terms of degrees longitude and latitude of three widely spaced fixed points used during digitizing were determined by reading off intercepts on the scale rule at the map margin. Because of the coarseness of this scale rule the coordinates of the three fixed points and consequently of the digitized geological contacts derived therefrom have estimated accuracies of approximately ±0.0015 degrees longitude and latitude.

The bathymetric data were acquired by digitizing the 5, 10, 20, 30 and 50 metre depth contours in the vicinity of the FLA from the scanned image of the marine map. The data set for each depth contour was again assigned a unique feature label. Ideally however, the bathymetric data would consist of a data set with depths for each point in the area of interest, from which arbitrarily selected depth contours could be extracted, or surface projections could be rendered. Digital bathymetry data for Irish marine waters, from coastal to delineation of the current continental shelf claim and 200 nautical mile limit can be purchased from the Marine Data Centre, Marine Institute, 80 Harcourt Street, Dublin 2 (See http://www.tcd.ie/Geography/GIS/Geoid/). However, this was considered beyond the scope and budget of this study.

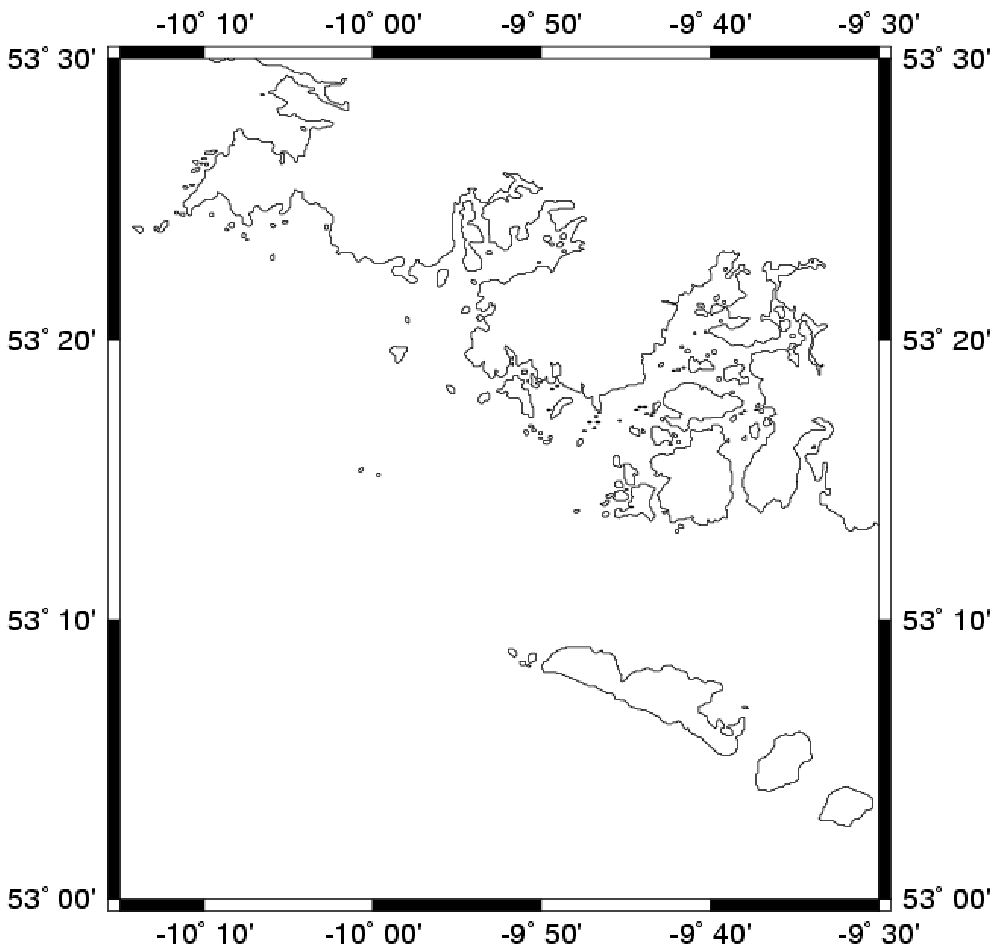

Figure 5 Mainland and island coastlines of the general locality in bitmap image downloaded from on-line coastline extractor, National Oceanic and Atmospheric Agency (NOAA), USA. Note scale bar on image margins allows accurate positioning of three reference points during digitizing of physiographic data.

4. Output Maps

Once all the data are entered into the Agis GIS model, maps are generated by manipulating which data are incorporated and how the data are displayed. Each map is described by a primary file known as the map specification file (i.e., Agis file extension *.agi*), which specifies everything needed to display a map and associated data. The specification file controls the map window position, border and background line style and colours, zoom level, grid size/position, text to appear in the map window, and the area of the globe to be displayed. The number of map layers and data layers used to construct a given map, and the identity of the files used in each layer are also defined in the map specification file. Thus, the content and appearance of a map is controlled by which data and display settings are utilized in the map specification file. In the case of the location map (See Fig. 1), a low magnification and unique map window position was used, whilst data pertaining to the geology, bathymetry and sampling stations were excluded from the map. In the case of the geology map (See Fig. 3), a higher magnification and a map window position standard to most other maps was used, whilst data pertaining to the bathymetry and sampling stations were excluded.

Only in the case of the depth interval maps (See Figs. 11 and 12), where areas within the FLA and occurring within specific depth intervals were sought, were data manipulated in the form of thematic mapping. In these two maps, areas satisfying the 5-20 m and 5-30 m depth intervals, respectively within the FLA were extracted. Thus, enclosed areas (i.e., polygons) bounded by the upper (i.e., 5 m) and lower (i.e., 20 or 30 m) depth contours, but only occurring within the FLA, were identified, extracted and displayed. The optimum water depth interval for installation of the turbine pier foundations is 5-25 m (*G. Healy*, pers. comm. 2002). As stated earlier however, the bathymetric data are such that arbitrarily selected depth contours (e.g., 25 m contour) could not be extracted. Because a depth interval map in the 5-25 m depth interval could not be generated, maps of the 5-20 m and 5-30 m depth intervals were generated to help identify those areas within the FLA suitable for installation of the pier foundations. Importantly, because the 5 m depth contour is in places discontinuous (See *Haslam* 1983), presumably because of the difficulties navigating vessels at these shallow depths in treacherous waters, the extracted areas corresponding to the depth intervals are exaggerated around some islands, rocks and shallows (See legends in Figs. 11 and 12).

The GIS model generated six output maps in the form of JPEG image files (i.e., Joint Photographic Experts Group), which is the standard Internet image file format, offering excellent data compression. The JPEG's can be imported into: (a) wordprocessors as imbedded graphics, as in this report; (b) computer-based multimedia graphic displays; (c) desktop film recorders for reproduction as photographic slides or prints; or (d) simply printed as hardcopies from a wide variety of proprietary software. These six output maps are presented throughout the text and are as follows:

1. General location map showing northwestern approaches to Galway Bay, with the boundary of the FLA superimposed, and with the location and identification of the principal towns (See Fig. 1).
2. Sample location map showing the location of each of the 14 sampling stations, the boundary of the FLA, and the location and identification of the principal towns (See Fig. 2).
3. Geological map showing the boundary of the FLA, and the principal geological features in the vicinity of the FLA (See Fig. 4).
4. Bathymetric map showing the boundary of the FLA, and the 5, 10, 20, 30 and 50 metre bathymetric contours in the vicinity of the FLA (See Fig. 8).
5. Depth interval map showing the boundary of the FLA, the area in the vicinity of the FLA occurring within the 5-20 metre depth interval, and superimposed geological contacts (See Fig. 11).
6. Depth interval map showing the boundary of the FLA, the area in the vicinity of the FLA occurring within the 5-30 metre depth interval, and superimposed geological contacts (See Fig. 12).

CONSTITUENT GEOLOGICAL UNITS

The geological units in the vicinity of the FLA were established from the 1:100,000 scale, Sheet 10, geology map of Connemara (*Morris et al.* 1995). As stated earlier, the geology was digitized and incorporated into the GIS model, from which a geological map of the vicinity of the FLA was generated (See Fig. 4). The latter shows the contacts of the geological units in the vicinity of the FLA. The Ordovician Skerd Formation (SI) occupies a triangular shaped area centred on the Skerd Rocks. The SI is bounded to the south by the Carboniferous Bounding Fault (CBF), a major WNW trending fault that separates the SI from Carboniferous limestones (Carb), and to the north by the EW trending Skerd Rocks Fault (SRF), which separates the SI from the Metagabbros (Mg) of the Ordovician Connemara Metagabbro and Gneiss complex. To the east, the SI is bounded by a discordant contact with the Errisbeg Townland Granite (GaEb) of the Devonian Galway Granite. The Cuilleen-Type Granite (GaCu) occurs within the FLA to the east of the GaEb, whilst the Carna-Type Granite (GaCn) occurs further east and immediately outside of the FLA. The latter two units are repeated to the northeast towards St. Macdara's island. The contacts between the granite types (i.e., GaEb, GaCu and GaCn) generally conform to a concentric ring pattern within the domal structure of the parent Galway Granite intrusion.

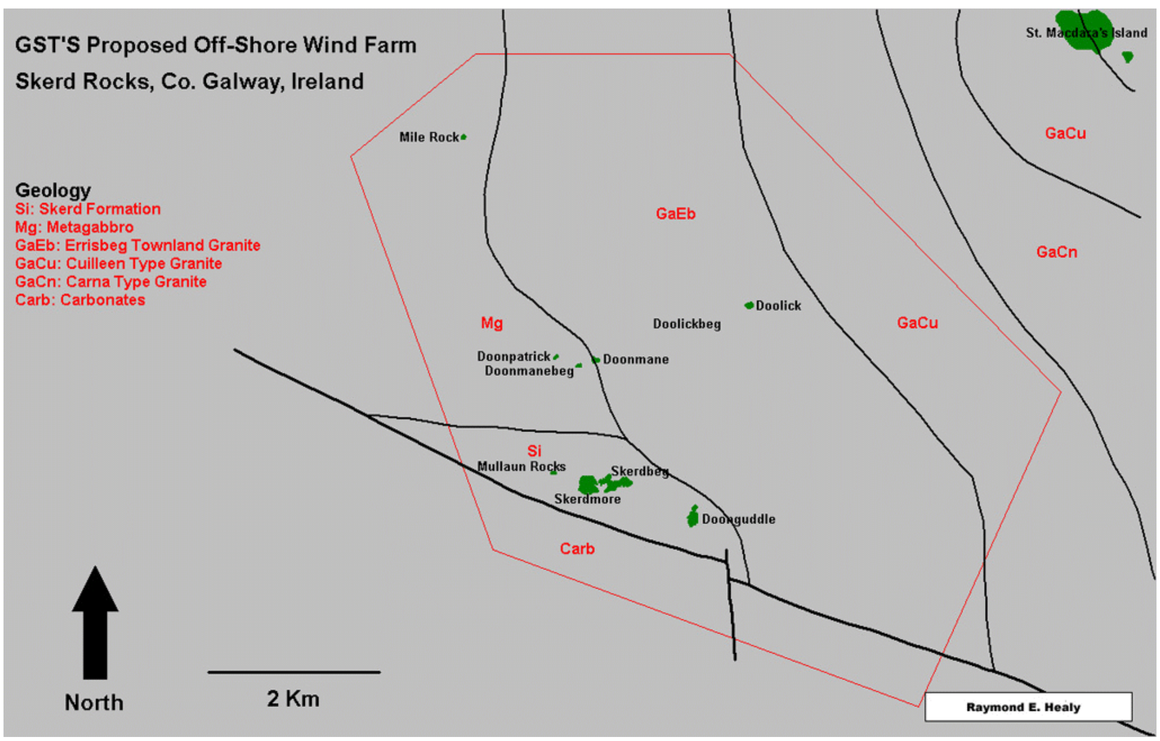

Figure 6 Geological map showing the contacts of the principal geological units in the vicinity of the FLA. The principal units within the FLA are GaEb, Mg, GaCu, Carb and SI, in order of approximate areal predominance. Note the GaCn lies immediately east of the FLA. Scale Bar = 2 Km.

1. Skerd Formation (SI)

The following description of the Skerd Formation is based principally on those of *Ryan & Max* (1975) and *Long et al.* (1995) with lesser contributions from other sources cited in the text.

Exposure of the SI is restricted to offshore occurrences in the vicinity of the Skerd Rocks, where it occupies a relatively small (i.e., approx. 3.5 km^2 corresponding to 9% of the FLA) triangular shaped area in the southwest corner of the FLA. The SI outcrops in the Skerd Rocks, including Skerdmore, Skerdbeg, Doonguddle and Mullaun Rocks (See Fig. 4). The SI is bounded to the east by the Galway granite, to the south by Carboniferous limestones in fault contact, and to the north by the Skerd Rocks Fault (SRF), which separates the SI from the Ordovician Connemara Metagabbro and Gneiss complex. The SRF is interpreted to be the western extension of the Southern Uplands Fault (SUF) in Scotland, representing a major Caledonian crustal lineament along which the Galway granite intruded (*Max et al.* 1975, *Ryan* & Max 1975, *Ryan et al.* 1983, *Leake* 1978, 1989, *Hutton* 1987, *Long et al.* 1995).

The Skerd Formation (SI) is the oldest of six formations that comprise a thick sequence of Ordovician metasediments and metavolcanics designated the South Connemara Group (SCG) by *Ryan & Max* (1975). The SCG locally forms the southern margin of the Galway granite, possibly as a roof pendant, and occurs in the southern parts of Gorumna and Lettermullen islands, and less extensively in the area of the Skerd Rocks. All lithologies of the SCG consistently exhibit ESE trending strike, with moderate to steep southerly dips, and which young to the north and are thus overturned. The indicated minimum thickness of the SCG is 7,000 m.

Metabasalts of the SCG have a predominantly sub-alkaline, slightly LIL-enriched character typical of ocean floor basalts, whereas some of the interstratified sediments have a continental provenance, indicating that the SCG has origins early in the formation of a marginal basin (*Ryan et al.* 1983). However, the SCG is more probably a trench fill sequence that was scraped-off subducting oceanic plate and built up as an accretionary wedge in the fore-arc region, analogous to the tectonic model for the Southern Uplands (*Legget et al.* 1979, *Ffrench & Williams* 1984). Indeed, the SUF, which forms the northern boundary of the Southern Uplands, and whose western expression is the SRF, represents the northern limit of that trench. The SCG is correlated with the Longford-Down Massif and the Northern Belt of the Southern Uplands in Scotland, which represent terranes deposited on the NW margin of the Iapetus ocean on the Laurentian (i.e., North American) continental margin (*Legget et al.* 1979, *Hutton* 1987).

Long et al. (1995) report that the lower units of the SCG are probably of Arenig to Llanvirn age, whilst the upper units are possibly of Caradoc or younger age, thus spanning most of the Ordovician from approximately 495 to 440 Ma. As the lowermost formation in the SCG, the SI has thus a probable depositional age of approximately 490 Ma. The grade of regional metamorphism exhibited by the SCG is possibly in the epidote-amphibolite or amphibolite facies, whilst thermal metamorphism associated with the Galway granite produced hornfelsing adjacent to the discordant contact. Typical assemblages consist of hornblende + plagioclase + biotite + ilmenite + Cu-Fe-sulfides ± quartz, and hornblende + plagioclase + ilmenite + epidote, with plagioclase feldspar compositional range from An_{35} to An_{51} (*Ryan et al.* 1983).

Although the SI has an exposed thickness of 950 m, the indicated minimum thickness is 1,400 m (*Ryan & Max* 1975). Where exposed, the SI is steeply dipping, heavily faulted, and consists of a mixed sequence of volcanics, intrusive sills and clastic sediments (See Fig. 5). The rocks exhibit a well developed cleavage, which is axial planar to gently west-plunging F2 folds. The SI is subdivided into two members:

1A. Skerdmore Member

The Skerdmore Member is the lithologically lower or oldest of the two members, and occurs in the more southwesterly tracts of the Skerd Rocks. Lithologically the member is moderately heterogeneous unit, consisting mainly of basic volcanics, pillow lavas and massive amphibolite sills, as well as tuffs associated locally with black and grey slates and graywackes, and rare, thin and discontinuous beds of acid volcanics. The pelitic sediments are rhythmically banded and commonly well graded.

1B. Moyrus Member

The Moyrus Member is the lithologically upper or youngest of the two members, and occurs in the more northeasterly tracts of the Skerd Rocks. It is a lithologically heterogeneous unit, consisting mainly of black and grey slates, green tuffaceous slates and tuffs, acid to intermediate volcanics, pillow lavas and massive amphibolite sills, and minor micro-conglomerates and graywackes. The pelitic sediments are commonly well graded, though some slumping and intraformational deformation are associated with acid volcanics.

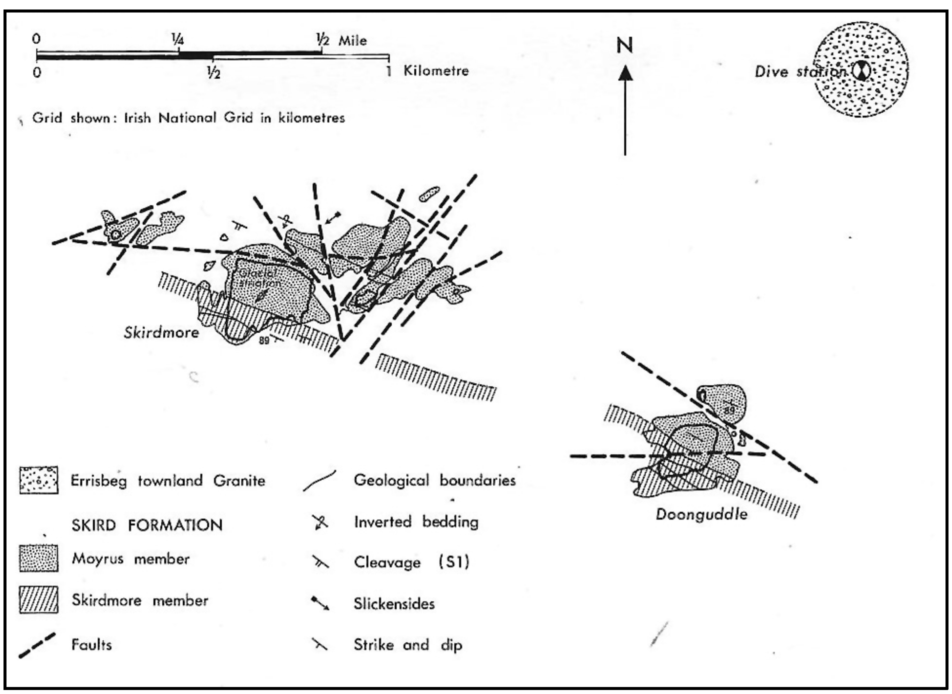

Figure 7 Simplified geological map of the Skerd Rocks area, showing the configuration of the Moyrus and Skerdmore members. Reproduced from Figure 14 of *Ryan & Max* (1975).

2. Metagabbro (Mg)

The following description of the Metagabbro is based principally on those of *Leake* (1989) and *Long et al.* (1995) with lesser contributions from other sources cited in the text. The term metagabbro is used to encompass all of the metamorphosed gabbroic rocks within the ultramafic - mafic series of rocks (*Long et al.* 1995).

The Metagabbro (Mg) occupies a large tract (i.e., approx. 7 km^2 corresponding to 17% of the FLA) in the northwestern part of the FLA, and outcrops at Mile Rock, Doonpatrick, Doonmanebeg, and possibly Doonmane (See Fig. 4). The latter is indeterminate because the contact of the Mg with the Errisbeg Townland Granite is projected to traverse Doonmane, whilst the accuracy of the coordinates of the geological contacts incorporated into the GIS model is estimated to be approximately $\pm 0.002^{O}$ (See **GIS Model**).

The Mg belongs to a regionally extensive Ordovician syntectonic intrusive complex known as the Connemara Metagabbro and Gneiss Complex (See Fig. 6). This EW trending complex extends from Slyne Head to at least Galway City, and is a fragment of a disrupted Ordovician continental magmatic arc on the southeast edge of the Laurentian (i.e., North American) continent. These rocks represent the gabbroic root zone of a now eroded calc-alkaline batholith emplaced into the continental margin above a northwest dipping subduction zone during Grampian orogenesis. The complex together with the Dalradian rocks into which it intruded comprise the Connemara massif, which is an allochthonous piece of the Dalradian miogeocline that was thrust south over rhyolitic rocks of the Delaney Dome Formation along the Mannin thrust during the late Ordovician (*Hutton* 1987). The complex is truncated to the south by the EW trending Skerd Rocks Fault (SRF), and to the east is engulfed by the younger Devonian Galway Granite (*Leggo et al.* 1966).

The Mg consists of several distinct, geographically separate bodies that once comprised a single layered ultramafic-mafic intrusion that has since been tectonically disrupted. Soon after its emplacement, possibly contemporaneous with D2 deformation, the Mg was disrupted by D3 deformation (See **Appendix 2** for details of deformation events). The Mg was ubiquitously injected by intrusion of primarily quartz diorite, which was syntectonically converted to orthogneiss by the contemporaneous deformation. This intrusion of the quartz diorites largely coincides with the D3 deformational event and peak regional metamorphism, which reached upper amphibolite facies with associated migmatization of the Dalradian sediments. Syntectonic development of paragneisses occurred where the intrusions produced migmatization and recrystallization of enveloped and adjacent Dalradian sediments. The complex was folded and metamorphosed during ongoing D3 and D4 deformation, resulting in a large part of the Mg being tectonically inverted. Immediately above the Mannin Thrust, the Mg was tectonically pulverized and recrystallized during thrusting to form a 250 m thick, schistose, mylonitized equivalent of the Mg, called the Ballyconneely Amphibolite. In eastern Connemara, emplacement of the Oughterard Granite occurred post D4, and represents the final phase of synorogenic magmatic activity within the magmatic arc during late Grampian orogenesis (*Cliff et al.* 1996, *Tanner et al.* 1997, *Friedrich et al.* 1999b). The magmatic arc was thus active for a short period in the mid-Ordovician, starting with the emplacement of the gabbros at about 473 Ma, the quartz diorites at about 467 Ma, and culminating with the Oughterard Granite at about 463 Ma (*Friedrich et al.* 1999b).

Geochemically, the gabbroic rocks display tholeiitic to high alumina, LREE-enriched character, whilst the slightly younger orthogneisses display calc-alkaline character, a petrological sequence typical in island arcs (Windley 1977). The geochemical trends of the gabbroic rocks are consistent with igneous fractionation from a single mantle-derived magma with contamination by LREE-enriched crustal material, possibly Dalradian metasediments. The fractionation and contamination occurred at depth in an unexposed magma chamber below the currently exposed batholith. The differentiation trends of the gabbroic rocks and orthogneisses superficially suggest that the gneisses fractionated from the metagabbro. The trends in chemical variation, particularly the Na versus Si contents, show that the gneisses did not fractionate from the Ballyconneely Amphibolite, the end differentiate of the metagabbros. Nonetheless, the similar isotopic Sr and Nd signatures suggest that the gneisses fractionated from the same gabbroic parent magma at depth (i.e., not *in situ*) prior to intrusion into the gabbroic rocks.

The complex is characterized by an early tholeiitic to high alumina gabbroic component, followed by a slightly later calc-alkaline component derived from a single parent magma. This is suggestive of the geochemical trend in island arc volcanism, where more immature series of volcanics (i.e., tholeiitic and calc-alkaline) are found on the oceanic or fore-arc side of island arcs, with more mature series of volcanics (i.e., calc-alkaline and alkali) on the continental side (Windley 1977). Because plutonic rocks in magmatic arcs are generally associated with volcanism, it is probable that volcanics associated with the Metagabbro and Gneiss Complex were deposited in Connemara, but have since been eroded. The LREE-depleted signature of the near-contemporaneous Lough Nafooey volcanics indicate that these are not consanguineous (i.e., co-magmatic) with the Metagabbro and Gneiss complex.

The Mg consists predominantly of metamorphosed hornblende gabbro and hornblende gabbro-norite[3], with less than 10% of other mafic-ultramafic lithologies, such as peridotite, anorthosite, dunite and pyroxenite. The minor ultramafic lithologies represent the earliest intrusions and tend to occur near the lithological base of the complex. Xenoliths of both country rock and earlier gabbroic phases occur in the Mg. *Friedrich et al.* (1999b) note that the Mg underwent an intense D3 and M3 overprint, suggesting that the Mg exhibits strong schistosity. However, *Leake* (1989) states that igneous layering and textures are poorly preserved, and that the Mg tends to be massive and weakly metamorphically foliated.

The gabbroic rocks consist principally of hornblende and plagioclase with relict pyroxenes and accessory magnetite, apatite and pyrite. Hornblende is principally igneous, but partly metamorphic in origin, with igneous megacrysts and late-stage magmatic and metamorphic varieties. The hornblende compositions vary widely from calcic-amphiboles (e.g., pargasitic hornblende and tremolite) to iron-magnesian amphiboles (e.g., anthophyllite), and thus the term hornblende is used in the wider generic sense (*Hawthorne* 1983). Metamorphic replacements of orthopyroxene by anthophyllite, clinopyroxene by tremolite-actinolite, pyroxene + plagioclase by actoniltic- and magnesio-hornblendes are common. Hornblende contains relict cores of plagioclase, clinopyroxene (diopside-salite), orthopyroxene (commonly En_{65-85}) and olivine (commonly Fo_{78-90}). The plagioclase is predominantly very calcic (i.e., An_{80-92}), typically

3 In the IUGS classification, gabbro is defined as a plutonic rock with Q between 0 and 5, P/(A+P) greater than 90, and plagioclase more calcic than An_{50}, whilst gabbro-norite is defined as rock satisfying the definition of gabbro, in which pl/(pl+px+ol) and pl/(pl+px+Hbl) are between 10 and 90, and ol/(pl+px+ol) and hbl/(pl+px+hbl) are less than 5 (*Bates & Jackson* 1987).

bytownite, but ranging from labradorite to anorthite (i.e., An_{50-96}). Late-stage hydrous alteration is ubiquitous producing alteration of hornblende to chlorite and epidote; plagioclase to sausserite and sericite; pyroxene to chlorite and serpentine; olivine to serpentine and magnetite; and biotite to chlorite and prehnite.

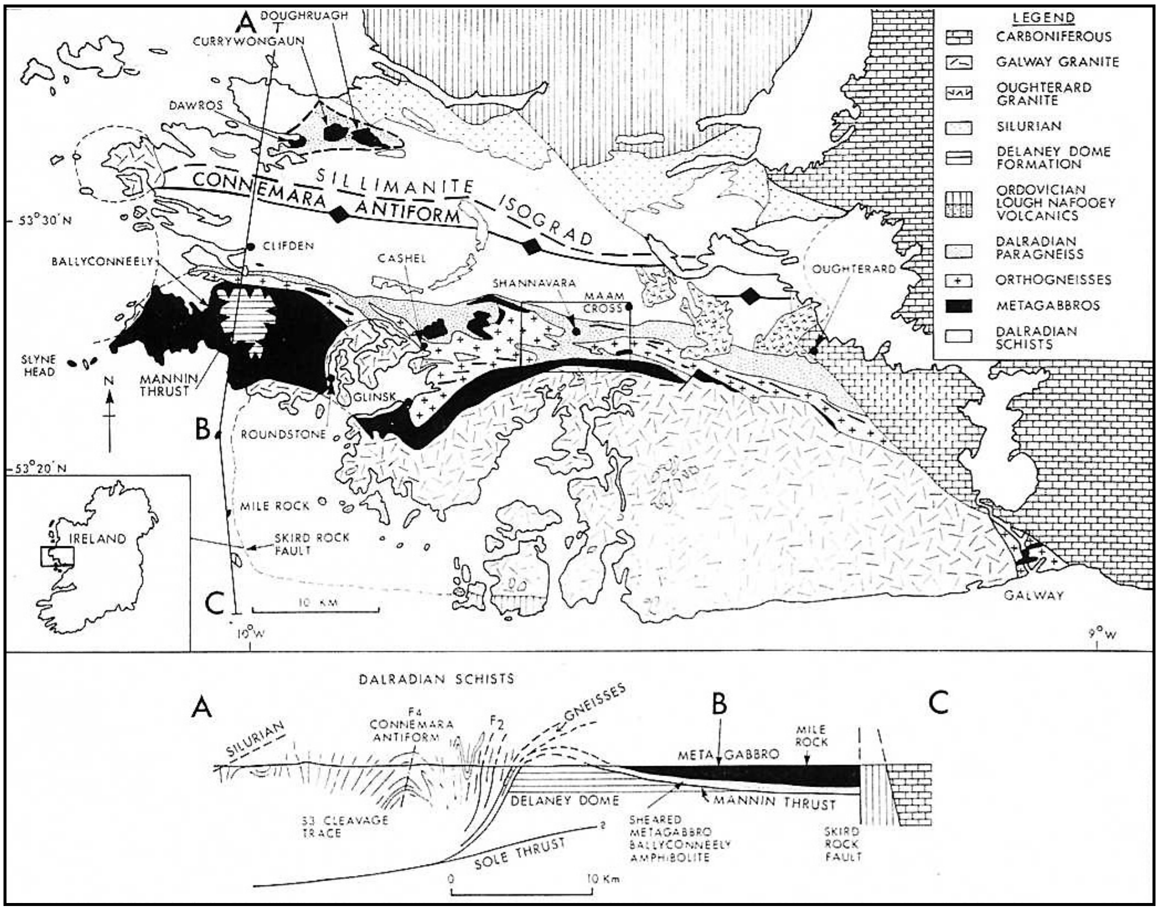

Figure 8 Simplified geological map of Connemara showing the metagabbro-orthogneiss complex, the fringing paragneiss and the sillimanite isograd with sillimanite occurring to the south. The true scale north-south cross-section shows the thrust bottom of the complex, although the metagabbro sequence is inverted. Note Carboniferous limestones are downthrown south of Skerd Rocks near C in cross-section. B is the Wild Bellows Rock. Ornament in section si as in map, except Ballyconneely Amphibolite which is shown stipple with ortho- and para-gneiss grouped together. Reproduced from Figure 1 of *Leake* (1989).

3. Galway Granite

The following description of the Galway Granite is based principally on those of *Max et al.* (1975, 1978) and *Long et al.* (1995), with lesser contributions from other sources cited in the text. *Long et al.* (1995) refer to their description of the Galway Granite as a summary overview only. Because the Galway Granite occurs primarily in Sheet 14, a fuller description is provided in the report accompanying Sheet 14, which unfortunately is to date unpublished.

Subunits of the Galway Granite occupy a large tract of the FLA (i.e., approx. 26.5 km^2 corresponding to 64% of the FLA), principally in the central and eastern parts, but not the western or extreme southern parts, of the FLA (See Fig. 4). In addition, the Galway Granite extends uninterrupted east to Galway City from its approximately NNW trending discordant contact with the SI and Mg near the centre of the FLA. Thus, the bedrock along potential paths of the proposed submerged high voltage cable with landfall at either Kilkieran or Carna harbours consists exclusively of subunits of the Galway Granite.

The Galway Granite is a major post-tectonic Caledonian intrusion emplaced during the lower Devonian with an age of about 405 Ma (*Leggo et al.* 1966, *Pidgeon* 1969). The granite was intruded along, and now largely obscures, the trace of the Southern Uplands Fault (SUF) in western Ireland, which does re-emerge further west as the Skerd Rocks Fault (SRF). The intrusion is exposed over an area of approximately 600 km^2, and occurs as a main batholith with four related discrete satellite plutons, the Omey, Letterfrack, Inish and Roundstone Granites, where the latter actually abuts the main batholith. Both magnetic and gravity anomalies indicate that the main batholith extends at depth south-east across Galway into north Co. Clare (*Morris & Max* 1995, *Ryan et al.* 1995).

The main batholith consists of at least two coalesced, contiguous domes: (1) the Carna dome; and (2) the larger Galway-Kilkieran dome. The Carna dome is separated from the Galway-Kilkieran dome by the Kilkieran septum, which is represented by the Murvey Granite (characteristically occurs on dome margins) and associated Callowfinish variety of the Errisbeg Townland Granite. The contact of the Carna and Galway-Kilkieran domes is characterised by a zone of interaction, where a multiplicity of inter- and intra-magmatic relationships are observed. A possible septum is also recognised within the Galway-Kilkieran dome suggesting the possible occurrence of separate Galway and Kilkieran domes. Furthermore, the Spiddal dome is recognised as an internal dome within the Galway-Kilkieran dome, as evidenced by roof pendants of Galway-Kilkieran granite within the Spiddal Granite. Septa are near roof structures indicating the position of now eroded, overlying roof pendants. The occurrence of one or more septa in the granite indicate that the present erosional surface lies close to the roof of the batholith.

The batholith is composed principally of adamellite, granodiorite and leucogranite. All of the granite varieties are interpreted as being co-magmatic, forming a semi-continuous igneous series derived from a single parent magma (*Leake* 1974). Unusually, the Galway Granite exhibits a reverse zonation (i.e., relative to that observed in most zoned granites). As illustrated in the Carna dome particularly, leucogranite (i.e., Murvey Granite: GaMu) occurs on the margins and passes inwards to adamellite (i.e., Main Errisbeg Townland Granite: GaEb), and then granodiorite (i.e., Carna Granites: GaCn and GaCu). The GaEb exhibits distinct magmatic layering (i.e., graded bedding and current bedding) produced by crystal settling and gravity grading, but which commonly dips at 20-45^{O} outwards from the Carna centre. This indicates that after crystallization of GaEb, it was intruded, domed, and the layering tipped up by the older and more basic Carna Granite. The GaEb is locally gradational with Carna Granite over a transitional zone of 300 m, in which K-feldspathization of the granodioritic Carna Granite occurs. The GaMu, which is always in contact with GaEb, formed as an aplite-like, late differentiate of the GaEb that crystallised above the GaEb and in the spaces created by stoping at the margins of the intrusion.

The Carna Granite occupies the centre of the Carna dome, and exhibits a discontinuously concentric ring pattern of mutual gradational, alternating K-feldspar-rich and -poor varieties (i.e., GaCu and GaCn, respectively). These granites were largely crystallised prior to being emplaced by near-vertical, concentric, upward movement, with the ring structure accentuated by injection and K-feldspathic metasomatism (*Leake* 1978, *Max & Talbot* 1986). Thus, consistent with the gradational contact between the GaEb and Carna Granite, the circumcentric internal structure of the latter reflects K-feldspatization of Carna granodiorite (i.e., GaCn) that was marginally flooded by GaEb, to form GaCu.

All of the granite varieties that exhibit mutually gradational contacts may exhibit locally sharp contacts. The GaMu and Carna Granites (i.e., GaCu and GaCn) do not exhibit a direct relationship. Where the GaEb is in contact with country rock (i.e., no marginal GaMu) a zone up to 10 m wide containing xenoliths is observed. Nonetheless, country rock xenoliths are rare, suggesting that stoped blocks of Connemara Metagabbro and Gneiss Complex sank rapidly before being assimilated and contaminating the granite. Interestingly, micro-diorite xenoliths varying from a few mm to 3 m, and commonly occurring in 'trains' are observed in all the granite varieties, except GaMu. Their distribution and character probably reflects injection of micro-diorite dykes while the granite was sufficiently fluid to allow subsequent disruption, but not assimilation.

The distribution of faults in the area, and including submarine exposures to depths of 20 m, was to a large extent determined from aerial photographs (*Williams* 1975, *M. Geoghegan*, pers. comm. 2002). The faulting is largely related to two major and one minor set of regional faults. The principal faults occur as an early set of partially annealed, discontinuous, curved, closely-spaced faults with a general NE trend, followed by a later set of near vertical, NW trending faults. A third, younger set of SW trending faults is also observed, and these faults are deflected (i.e., due to strain relief) at the intersection with the NW trending faults. *Max & Talbot* (1986) note that younger faulting and jointing are common, but have not been resolved into a pluton-wide system. Because much of the FLA lies in water deeper than 20 m, the distribution of faults in the FLA is largely indeterminate. Where faulting has been mapped within the FLA (i.e., on and around islands), it is both pervasive and intensive (See Fig. 4 of *Max et al.* 1975).

Sheet jointing is common throughout the batholith, and is generally low angle and undulating with minor variations in degree of blastesis, particularly in the GaEb. This jointing does not divide granite types, but rather appears to follow a regional pattern, most probably reflecting the near-synchronous character of final cooling and unloading throughout the batholith. P. *Ryan* (pers. comm. 2002) notes that the near horizontal joints widespread near the roof of the granite are potentially detrimental to turbine foundation piers. However, the near vertical orientation of the granite contacts in the FLA indicates that the erosional surface has intersected the granite well below the roof zone. In the Mace Head area, which lies close to the approximate centre of Carna dome, the jointing coincides with the major fault trends (i.e., NE and NW), with the NE trend being dominant (*Derham* 1986). The latter author also notes that both the faulting and jointing tend to be compartmentalized, being more intensely developed in some areas. Because the FLA straddles the Carna dome only, the following descriptions deal solely with the geology of sub-units of the Carna dome, but excluding the Murvey Granite.

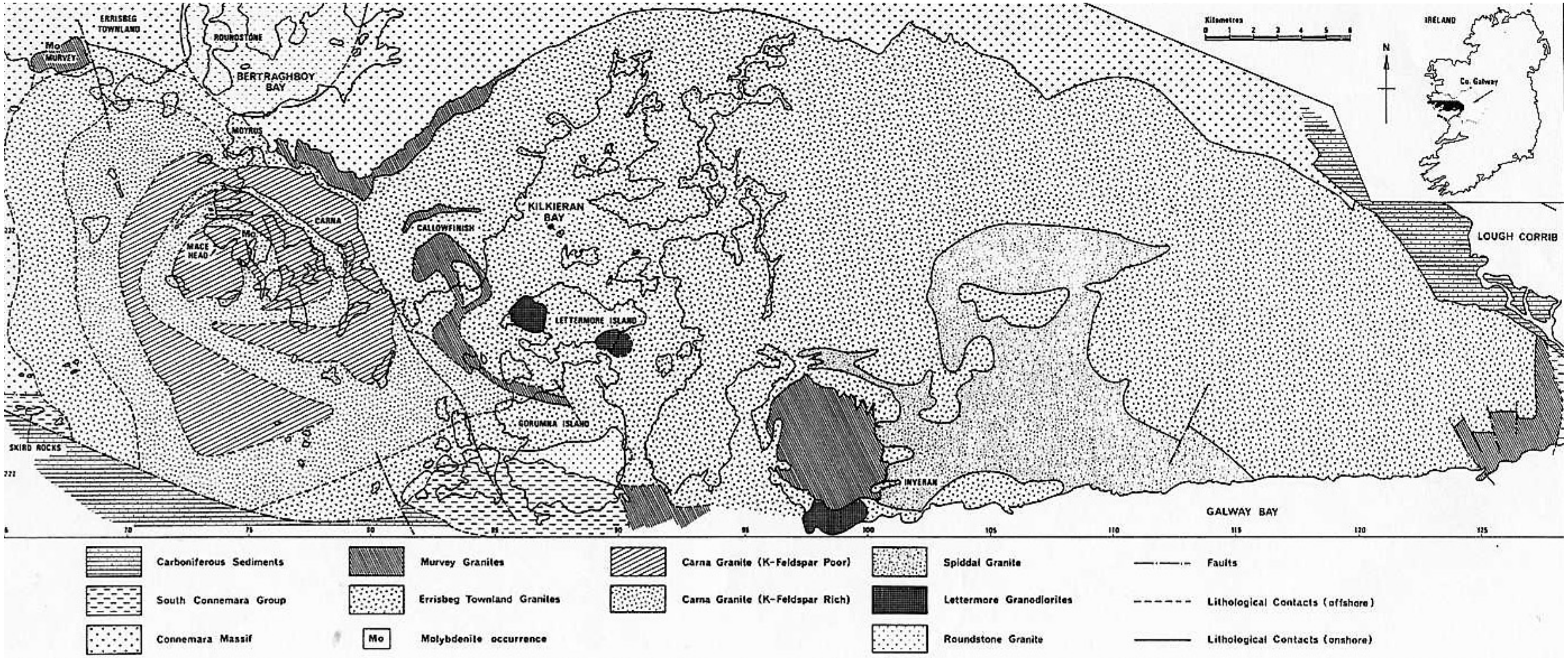

Figure 9 Map of the Galway Granite. Reproduced from Figure 1 of *Max & Talbot* (1986).

3A. Main Errisbeg Townland Granite (GaEb)

The GaEb occupies an extensive NNW trending tract (approx. 20 km^2 corresponding to 49% of the FLA) in the central FLA, which outcrops at Doolick, Doolickbeg, and possibly Doonmane (See Fig. 4). The latter is indeterminate because of: (1) the low spatial resolution inherent in the regional geological map of *Morris et al.* (1995); and (2) the contact between the Mg and GaEb is projected by the GIS model to traverse Doonmane, whilst the accuracy of the coordinates of the geological contacts incorporated into the GIS model is estimated to be approximately $\pm 0.0015^{O}$ (See **GIS Model**). However, the occurrence of Mg and/or GaEb on Doonmane can be readily determined by a simple survey of the island, as the Mg is greenish whilst the GaEb is pink to grey.

The GaEb has an average silica content of 71% SiO_2, and consists of 33% plagioclase feldspar (i.e., oligoclase or oligoclase-andesine), 30% quartz, 30% K-feldspar, 6% partly chloritized biotite, and minor hornblende, sphene, magnetite and apatite (*Leggo et al.* 1966). The GaEb is the most abundant granite type in the batholith, and is classified as an adamellite. There are several varieties recognised (i.e., Main Errisbeg Townland, Callowfinish, Shannawona and Mafic Errisbeg Townland Granite varieties), but only the main variety is observed in the Carna dome. The GaEb is a pink to pale grey, inequigranular, coarse-grained, porphyritic biotite-hornblende adamellite characterised by coarse (i.e., 2-5 cm) greenish saussuritised plagioclase and pink K-feldspar megacrysts set in a medium-grained matrix. Rapakivi textures are widespread.

The GaEb is gradational with the GaCu over a transitional zone of 300 m, although locally the contact is sharp. Where GaEb is in contact with country rock (i.e., no marginal GaMu) granitic apophyses invade the country rock, whilst a 10 m wide zone containing xenoliths of country rock is observed. The GaEb exhibits the most pronounced foliation of the granites, with extensive magmatic layering, suggesting that the GaEb is mechanically anisotropic.

3B. Cuilleen-Type Granite (GaCu)

The GaCu occupies a moderately large tract (approx. 6.5 km^2 corresponding to 15% of the FLA) in the eastern FLA, but does not outcrop within the FLA (See Fig. 4).

Leggo et al. (1966) reports that Carna Granite (which includes both the GaCu and GaCn) has an average silica content of 68% SiO_2, and consist of approximately 40% plagioclase feldspar (i.e., oligoclase-andesine), 25% quartz, 25% K-feldspar, 7% partly chloritized biotite, 2% hornblende, and minor amounts of sphene, magnetite and apatite, although the GaCu is more K-feldspar-rich. The GaCu is classified as a monzogranite, but is locally an adamellite. The GaCu is generally pink in colour, medium- to coarse-grained, and contains coarse K-feldspar megacrysts (i.e., up to 2 cm) and clots of biotite and hornblende.

The contacts of GaCu with GaCn are usually gradational, but can be sharp, and invariably the relationship reflects K-feldspathization. The GaCu is also gradational with GaEb over a transitional zone of 300 m, although locally that contact is also sharp. The GaCu is only weakly foliated with minimal magmatic layering, suggesting that the GaCu is largely mechanically isotropic.

3C. Carna-Type Granite (GaCn)

The GaCn neither occurs nor outcrops within the FLA, notwithstanding the reduced accuracy of the coordinates of the geological contacts incorporated into the GIS model (i.e., approx. ±0.002^{O}; See Fig. 4 and **GIS Model**). However, the GaCn is transitional with respect to the GaCu, and because of its discontinuous and patchy development, definition of the GaCn/GaCu boundary is comparatively arbitrary. Thus, Carna Granite mapped as GaCu, but more characteristic of GaCn, may occur locally within the FLA.

Leggo et al. (1966) reports that Carna Granite (which includes both the GaCn and GaCu) has an average silica content of 68% SiO_2, and consist of approximately 40% plagioclase feldspar (i.e., oligoclase-andesine), 25% quartz, 25% K-feldspar, 7% partly chloritized biotite, 2% hornblende, and minor amounts of sphene, magnetite and apatite, although the GaCn is less K-feldspar-rich. The GaCn is generally a homogeneous, medium-grained, grey granodiorite with occasional coarse plagioclase megacrysts (i.e., up to 2 cm) and rare K-feldspar megacrysts and clots of hornblende. Steeply dipping biotite layering occurs intermittently throughout the GaCn.

The contacts between the GaCn and GaCu are usually gradational, but can be sharp, and invariably the relationship reflects K-feldspathization. Although the GaCn is only weakly foliated, the steeply dipping biotite layering suggests that the GaCn is somewhat mechanically anisotropic.

4. Carboniferous Limestones (Carb)

The following description of the Carb is based principally on those of *Williams* (1975) and *Long et al.* (1995) with lesser contributions from other sources cited in the text. Importantly, there is a paucity of research on the Carb in this locality due to the lack of onshore exposure.

The Carb occupies a relatively small, narrow, WNW trending tract (approx. 4 km^2 corresponding to 10% of the FLA) within and parallelling the southern boundary of the FLA. The Carb does not outcrop within the FLA, the closest onshore outcrop being the Aran islands. The Carb is bounded to the north by the SI on the west side of the southern FLA, and by the GaEb of the Galway Granite on the eastern side of the southern FLA. This contact is the northern limit of the Carb in the locality, and constitutes a major fault, with the Carb downthrown against the Galway Granite and the SCG. For convenience and consistent with the usage of *Williams* (1975), the fault is here termed the Carboniferous Bounding Fault (CBF). The fault has a WNW strike west of Lettermullen island. To the east, the fault swings around to an EW strike, extending to at least Galway City and defining much of the sharp northern boundary of Galway Bay, and is clearly post-Caledonian. The fault exhibits several minor offsets by later, roughly NS striking sets of faults, one of which occurs just southeast of Doonguddle (See Fig. 4). The fault delineates a line south of which deep water is encountered within and beyond the FLA. *Williams* (1975) interprets the CBF as a hinging fault with increased throw to the west, which may be the western expression of a line extending from near Galway City through the Strokestown area, and which acted as a major hinge line related to accumulation of sediment on the continental shelf to the west during the Carboniferous.

Williams (1975) notes that no rocks younger than Carboniferous were recovered during grab sampling of the seabed in the study area. *Morris et al.* (1995) indicate that the Carb in the vicinity of the Skerd Rocks consists of limestones of Dinantian age (i.e., lower Carboniferous), but provide no further details or descriptions. The Carb has been downthrown against the older Galway Granite, SCG and Mg by the CBF, but the amount of throw is indeterminate, although probably substantial. *A* transit sonar scan from a track running southwest from Namackan Rocks indicates seafloor bedrock consisting of granite and limestone, as well as mud (See track 9 in Fig. 1 of *Geoghegan et al.* 1975). The latter authors interpret that the limestone is Visean (i.e., late Dinantian), based on the pattern of jointing, (i.e., strike NS and EW) and bedding (i.e., dip gently SW), which are similar to the features of Visean limestones lying along strike on the Aran islands and the mainland in Co. Clare (See Fig. 4 of *Max et al.* 1975). Interestingly, the granite-limestone contact along track 9, approximately 5 km south of Namackan Rocks, was obscured by mud and had to be extrapolated.

During the Lower Carboniferous the study area lay at approximately 5^{O} south of the equator in tropical latitudes. By Visean times, the shallow sea that had lain to the south of the Devonian continent at the start of the Carboniferous had transgressed northward as far as southern Ulster. Much of Ireland was thus covered by warm tropical seas, not unlike the present day Carribean, and resulted in the deposition of carbonate sediments on a shallow continental shelf. Sedimentation during the late Courceyan stage (i.e., pre-Visean) is characterized by a thick blanket of Waulsortian carbonate 'reefs' composed of grey coloured, poorly fossiliferous, fine-grained, micritic limestone containing stromatactis structures, which formed in deep-water mudbank complexes (*Phillips & Sevastopulo* 1986, *Hitzman & Large* 1986).

The Waulsortian gave way during the Chadian an Arundian (i.e., early Visean) to deposition of oolitic, peloidal and skeletal sand and muddy sand in shelf facies, and dark, argillaceous, fine-grained and cherty carbonates, termed 'Calp', in basinal facies (*Phillips & Sevastopulo* 1986). Carbonate 'reefs' similar to the Waulsortian did re-emerge as a widely distributed facies in the Asbian stage (i.e., late Visean). Nonetheless, this pattern of carbonate sedimentation in shallow-water shelf facies separating deep-water basinal facies persists for most of remaining Visean times. Basin formation was related to a contemporaneous regime of extensional tectonics with associated active faulting and volcanicity. *Phillips & Sevastopulo* (1986) note that the margins of these basins were commonly fault controlled, consistent with CBF possibly forming the northern margin of a Carboniferous basin. As stated earlier, *Max et al.* (1975) noted that the CBF probably acted as a major hinging fault related to sedimentary accumulation during the Carboniferous. *Gallagher* (1996) recognises three principal basins in southern and western Ireland: (a) the Dublin Basin; (b) the South Munster Basin; and (c) the Shannon Basin or Trough. However, *Gallagher* (1996) and *Cope et al.* (1992) show that the Shannon Basin did not extend northward to encompass north Clare or Galway, including the study area. Notwithstanding the latter, the northern margin of the continental shelf terminated at the Galway-Mayo High in the vicinity of the FLA during most of the Visean stage (*Cope et al.* 1996), and suggests that on a regional scale the CBF controlled the northern limit of carbonate deposition on the Clare shelf.

Despite the almost complete lack of published research pertaining directly to the character of the limestones occurring within the southern part of the FLA, it may be inferred that the Carb corresponds to limestone deposited on a shallow marine continental shelf during the Visean stage of the Lower Carboniferous. The Burren section consists of limestones deposited during the Visean stage from the Arudian to Brigantian. The Arundian to Holkerian age Tubber Formation overlies the Waulsortian and consists of grey crinoidal packstones, which are cherty at the base with peloidal and oolitic facies at some horizons (*Sevastopulo & Wyse Jackson* 2001). This is overlain by the Asbian age Burren Formation, which consists of non-cyclic and cyclic limestones with palaeokarst surfaces and shales (*Gallagher & Somerville* 1997). The 400 m thick formation can be divided into two parts: (1) a lower part of grey, skeletal to peloidal, chert-free, non-cyclic limestones with some dark cherty lithologies and oolitic limestones; and (2) an upper part of cyclic limestones consisting of thickly bedded to unbedded, massive, dark steely-blue, skeletal, grainstone and packstone (*Gallagher* 1996). The upper part contains up to twelve cycles, which control the scarp and terrace geomorphology of both the Burren and the Aran Islands (*Gallagher* 1996, *Sevastopulo & Wyse Jackson* 2001). The cycles represent shallowing-up sequences from deep, subtidal conditions culminating with emergence and development of palaeokarst surfaces and palaeosols (*Gallagher* 1996). The Burren Formation is overlain by the Brigantian age Slievenaglasha Formation, which consist of two developments of crinoidal limestone with an intervening unit of intraclastic limestone (*Sevastopulo & Wyse Jackson* 2001). These crinoidal limestones also exhibit cycles, and vary from thickly bedded, crinoidal packstone and grainstone at the base, to fine- to medium-grained, crinoid-poor, peloidal limestones. These cycles represent shallowing-up sequences from deep to shallow subtidal conditions, but without the emergence that occurred during the Asbian.

Assuming consistency in the gentle SW dip of the limestones in the FLA, the Carb may be structurally lower, and hence somewhat older, than the Visean limestones exposed at the Aran islands and the Burren. We can infer that the Carb in the FLA is probably composed of middle to late Visean strata, most probably shallow marine limestones of the Burren or Tubber Formations.

5. Seafloor Sediments

The following discussion contrasts with the previous four sections, which dealt with Palaeozoic bedrock geology, in that this section deals with recent unconsolidated surficial sediments that potentially blanket part or all of the FLA. Importantly, there is an almost complete dearth of research on the seafloor sediments occurring in the locality. The possible occurrence of substantial thicknesses of unconsolidated sediments, which are mechanical unstable, clearly has significant influence on the boring, design and installation of turbine foundation piers.

The distribution of sediment in the northern approaches to Galway Bay is irregular, but bedrock exposure in the critical areas is over 75% (*Keary* 1975). The three critical areas studied by side-scan or transit sonar were: (a) the area of the Skerd Rocks and Mile Rocks; (b) the area west and southwest of Golam Head; and (c) the area of the approaches to Kilkieran Bay extending south to Namackan Rocks. Thus, it may be inferred that bedrock exposure in the FLA is indeed 75% or greater.

The FLA lies in a high energy marine environment directly exposed to long waves produced in the Atlantic ocean, and which are characterised by a deep wave base. Turbulence and high water velocities yield only minimal sediment accumulation above at least 20 m water depth within the vicinity of the FLA (*B. O'Connor*, pers. comm. 2002). Sedimentation occurring above this water depth is probably restricted to steep topographic depressions, related to joints, faults and geological contacts. Thus, seafloor sediment encountered above the 20 m water depth within the FLA is likely to occur as sedimentary drapes in steep topographic depressions, which are in any case unsuitable locations for siting turbine foundation piers. Sediment occurring below 20 m and above 30 m water depth is most likely in areas with reduced wave base and water velocities. Such sediment accumulation are expected within the FLA, particularly in the shallow trough northwest of Fools Shoal and northeast of Doolick. The trough runs along the northeastern boundary of the FLA between the bounding coordinates 5 and 6, and lies east of the Kelly Rock plateau (See Fig. 7). The trough encompasses a large tract in the 20-30 m depth interval, which occurs within the shadow of the energy dissipation produced by wave-breaking and shoaling as waves travel through the cluster of shallows, rocks and islands (*Aqua-Fact* 2002). Because the prevailing wind in the area of greater Galway Bay is west-southwest (*O'Connor* 1993), the wind height plot corresponding to that wind direction of *Aqua-Fact* (2002) is reproduced here to illustrate the extent of the wave shadow (See Fig. 8). Thus, the highest likelihood of sediment accumulation in areas with water depths of less than 30 m within the FLA are thus predicted to occur along the southern two thirds of the northeastern boundary.

O'Connor et al. (1993) studied the sediments and associated macrobenthos in greater Galway Bay, where the study area encompassed the entire bay east of a line running south from Namackan Rocks. The study included qualitative descriptions of the seafloor, whether it be exposed rock or sediment, as well as granulometric analysis of the sediments. Neither geochemical nor mineralogical analysis were done on the sediments. The distribution of seafloor types were classified in terms of the following: (a) fine sand; (b) sand; (c) mixed; (d) maerl; (e) pebbles; (f) gravel; and (g) exposed rock. Maerl is biogenic in origin, consisting of calcareous marine algal remains, typically in the size range of 0.5-6 cm in diameter (*B. O'Connor*, pers. comm. 2003). Sand and fine sand predominate over most of the inner and mid Galway Bay, South Sound, as well as the deep waters (i.e., approx. > 60-70 m depths) south of the Aran Islands. This pattern of sedimentation reflects the low energy environment in the wave shadow of the Aran Islands. In the outer North Sound (i.e., area south and west of

Namackan Rocks), unprotected by the wave shadow of the Aran Islands, exposed bedrock predominates with lesser tracts of sand and silty sand. Bedrock is exposed in water depths down to 60 m, indicating that sedimentation is minimal in shallower areas directly exposed to full Atlantic waves. Thus, it is considered unlikely that there are significant thicknesses of sediment accumulation in areas within the FLA with water depths of less than 30 m.

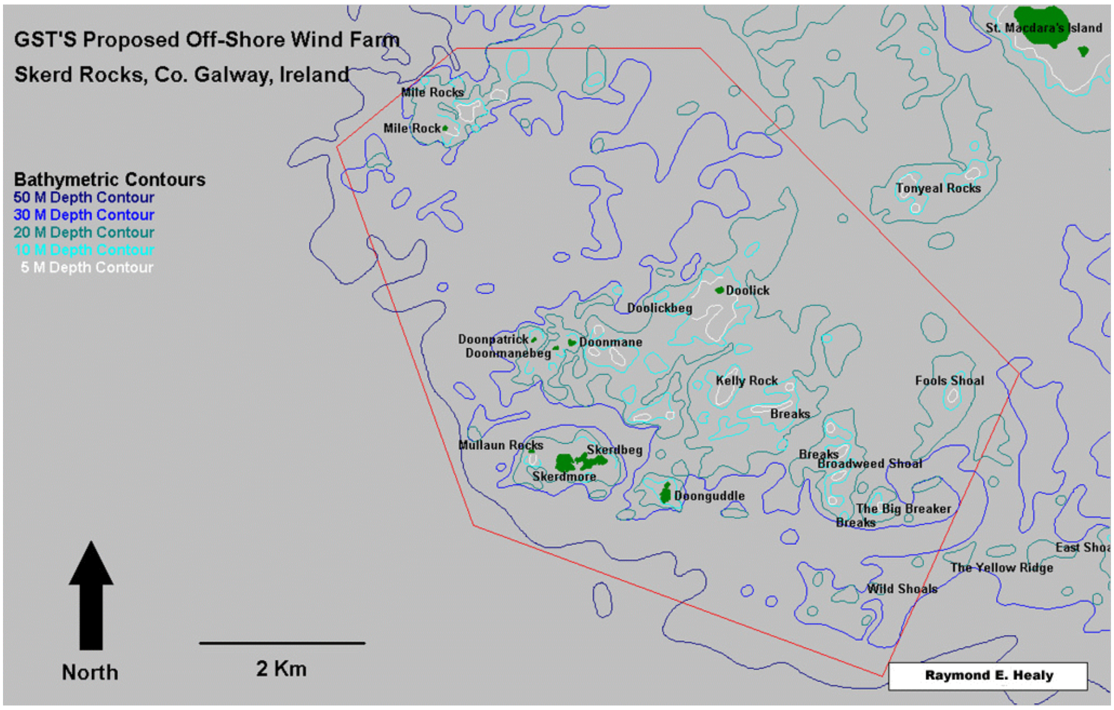

Figure 10 Bathymetric map in the vicinity of the FLA, showing the 5, 10, 20, 30 and 50 m depth contours. Note the 5 m contour is discontinuous in several locations. Bar scale = 2 km.

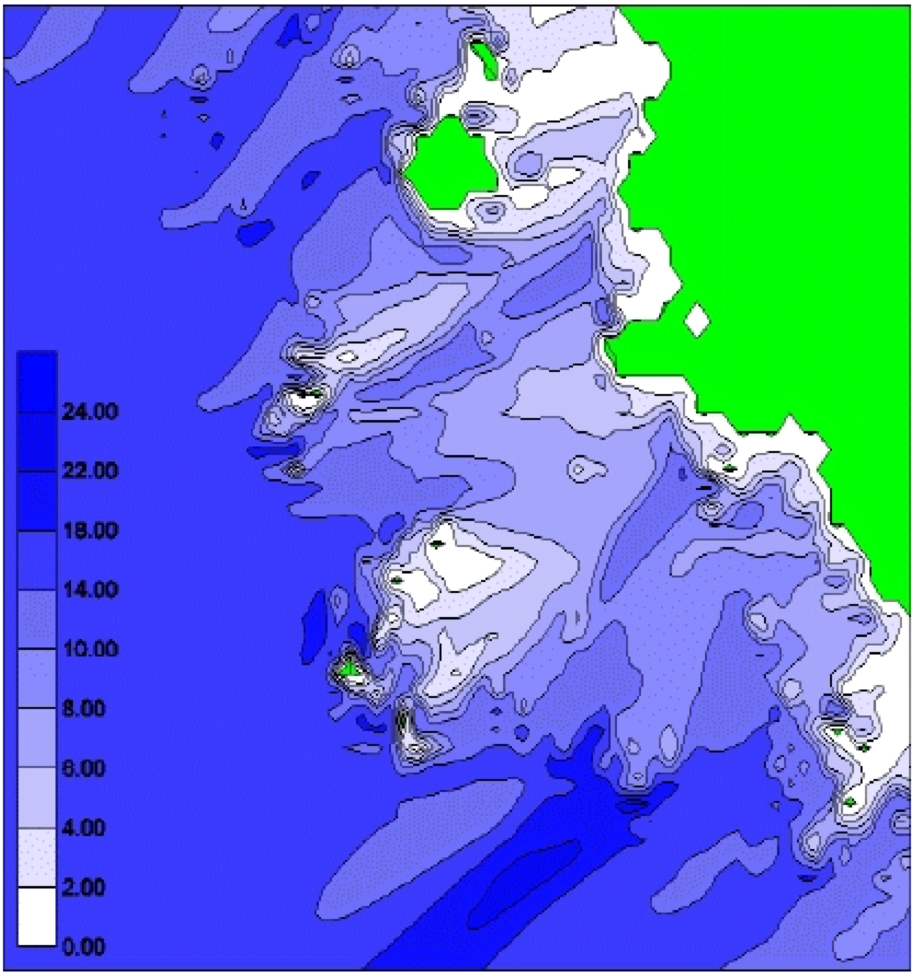

Figure 11 Predicted wave heights for 50 year maximum west-southwest winds in the Skerd Rocks locality. Reproduced from Figure 2.2 of *Aqua-Fact* (2002).

GEOLOGICAL HISTORY

Introduction

The geological history of the Skerd Rocks area, including the FLA, is actually the story of how the North American (i.e., Laurentian) plate collided with European plate, leaving behind a vestige in the form of accreted terranes, prior to being rafted away after opening of the Atlantic ocean. The FLA cannot be viewed as a single discrete place in time and space, but rather only as a contemporary snapshot in an ever evolving time-space continuum.

The Iapetus ocean, commonly referred to as the proto-Atlantic, separated the Laurentian and European continents from late PreCambrian to late Ordovician times. During this time areas comprising present day Ireland lay on opposite sides of the ocean, with northwest Ireland on the Laurentian continental margin, and southeast Ireland on the European continental margin. Mafic dyke swarms produced during rifting in the tensional environment associated with the opening of the Iapetus have U-Pb ages of about 615 Ma (*Kamo et al.* 1989). Subduction of all intervening oceanic plate at the end of the Ordovician, about 450 Ma, heralded the closure of the Iapetus in the British Isles sector. The Iapetus ocean thus spanned a cycle from opening to closing of some 170 My. It was not until about 65 Ma in early Tertiary times that the Atlantic ocean finally opened and spread away to its current location (See Table 2).

Table 2. Geological Time Scale and Major Events Affecting the Area

Age (Million Years)	Period	Major Events	Orogeny
1.6	**Quaternary**	A series of ice ages, followed by spread of vegetation, growth of lowland bogs, arrival of man. Reached approximate current latitudes.	
65	**Tertiary**	Erosion. Spreading open of north Atlantic from about 65 Ma, with generation of oceanic crust. Intrusion of dolerite dykes.	
135	**Cretaceous**	Erosion. Probable incursion of chalk sea, with chalk deposited widely. Continuing deposition in offshore basins. Latitude close to 30^{O} North.	
205	**Jurassic**	Erosion and uplift. Sediments deposited in offshore rift basins and in N. Ireland.	
250	**Triassic**	Desert conditions on land, with sand and gypsum deposited in east of Ireland. Initial rifting between Europe and future N. America in the Triassic. Close to equatorial latitudes.	
290	**Permian**		
355	**Carboniferous**	Land progressively submerged; coastal sand delta building, limestones deposited in tropical seas, followed by deposition of nearshore then deltaic mud and sands. Late Carboniferous intrusion of dolerite sheets and effects (gentle folding and block faulting) of distant Variscan mountain building continuing into Permian. Latitude close to 5^{O} South.	D6 Variscan/ Hercynian
410	**Devonian**	Acadian mountain building episode, rapid erosion and deposition of red beds in semi-arid conditions. Early Devonian intrusion of Corvock Granite, Galway Granite and related plutons.	D5 Acadian & Caledonian
438	**Silurian**	Sedimentary deposition in shallow remnant sea and its margins following closure of Iapetus Ocean. Major sinistral shearing and Caledonian mountain building.	
510	**Ordovician**	Peak regional metamorphism and major deformation of Dalradian schists in early Ordovician during Grampian mountain building. Sedimentation, northward ophiolite obduction and development of magmatic arc above initially southward, then northward directed subduction zone as Iapetus begins to close. Taconic mountain building. Cessation of subduction with continent-continent collision, effectively closing Iapetus Ocean. Latitude close to 30^{O} South.	D4 D3 Taconic & Grampian D2
544	**Cambrian**	Spreading of Iapetus Ocean from late PreCambrian with generation of oceanic crust.	
4600	**PreCambrian**	Sedimentary deposition of Dalradian rocks 750-600 Ma, interrupted by an ice age and periods of volcanism. Dalradian sediments contain detrital zircons derived from adjacent landmass of 1700-1300 Ma. Earliest deformation and metamorphism of Dalradian rocks in late PreCambrian Brazilide? mountain building event.	D1 Brazilide?

Notes: Table is not to scale. Reproduced with modifications from Figure 1 of *Long et al.* (1995).

Tectono-Stratigraphic Framework of the Skerd Rocks Area

The Laurentian-European continent-continent collision is considered to have occurred along a line referred to as the Iapetus Suture, also known as the Navan-Silvermines Fault, which runs from Termonfeckin through Navan, Silvermines, Limerick, and the Shannon estuary (See Fig. 10). The Iapetus suture lies in the Central Terrane of the British Caledonides. This terrane represents Silurian rocks deposited in a successor basin between two remnant arcs of opposing polarity after subduction of oceanic crust and effective closure of the Iapetus (*Hutton* 1987).

The Northern Belt Terrane lies north of the Central Terrane across the Silurian-Devonian aged Orlock Bridge Fault (OF), and corresponds to the Southern Uplands of Scotland (*Hutton* 1987). The South Connemara Group (SCG), which includes the Skerd Formation (SI), belongs to the Northern Belt Terrane. This terrane most probably represents a trench fill sequence scraped-off subducting oceanic plate and built up as an accretionary wedge in the fore-arc region (*Ffrench & Williams* 1984, *Hutton* 1987). Thus the Northern Belt represents terrane deposited on the NW margin of the Iapetus ocean on the Laurentian continental margin (*Legget et al.* 1979, *Hutton* 1987). The Southern Uplands Fault (SUF), which forms the northern boundary of the Southern Uplands (i.e., Northern Belt) represents the northern limit of that trench.

In the British Caledonides, the Midland Valley Terrane lies north of the Northern Belt Terrane of the Southern Uplands, across the SUF. In far western Ireland, the Connemara Terrane lies north of the Northern Belt Terrane, across the Skerd Rocks Fault (SRF). It is generally accepted that the SRF is the western extension of the Ordovician-Silurian age SUF (*P. Ryan*, pers. comm. 2002). However, the Connemara Terrane does not correspond to the Midland Valley Terrane of Scotland, but rather corresponds to highly deformed and metamorphosed Dalradian rocks of the Grampian Terrane. These rocks were deposited in the Dalradian miogeocline on the passive margin of the Laurentian continent (east of Newfoundland) during late Proterozoic and Cambrian times (*Hutton* 1987). The Grampian Terrane lies north of the Highland Boundary Fault (HBF), whose western expression in Ireland is the Fair Head-Clew Bay Fault. Thus, the Connemara Terrane has been displaced 30-40 km south of the main Dalradian outcrop and the HBF, and outboard of the Ordovician aged South Mayo Terrane (*Hutton* 1987, *Leake & Tanner* 1994). The Connemara Terrane is thus an allochthonous piece of the Dalradian miogeocline, into which the Connemara Metagabbro and Gneiss Complex intruded. The latter is an Ordovician continental magmatic arc emplaced into the continental margin above a northwest dipping subduction zone. The northern boundary of the Connemara Terrane is the Lough Nafooey-Doon Rock Fault, which similar to the SRF, has a throw of approximately 12,000 m, such that the Connemara massif can be considered a horst.

The Galway Granite is a broad intrusive body exposed over most of the north shore of Galway Bay, and constitutes a post-tectonic Caledonian intrusion emplaced during the early Devonian, about 405 Ma (*Leggo et al.* 1966, *Pidgeon* 1969). The intrusion is a stitching pluton emplaced on the contact of the Midland Valley and Southern Uplands terranes (*Leake & Tanner* (1994), and was emplaced in a dilational bend in the SUF/SRF, which engulfed and now largely obscures the SUF (*P. Ryan*, pers. comm. 2002).

Across much of Ireland, lower Carboniferous sediments form an overstep sequence that unconformably overlies the eroded Devonian 'Old Red Sandstone' continent created by the collision of the Laurentian and European continents. Visean limestones are observed in contact with the Skerd Formation and the Galway Granite on the southern downthrown block of the Carboniferous Bounding Fault (CBF). The limestones underwent synsedimentary downfaulting along the CBF, which acted as a major hinging fault accommodating substantial carbonate sedimentation during the Carboniferous (*Max et al.* 1975). The limestones extend south from the CBF and along strike to the Aran islands and the Burren in Co. Clare (*Geoghegan et al.* 1975), and represent shallow marine carbonate platform deposits.

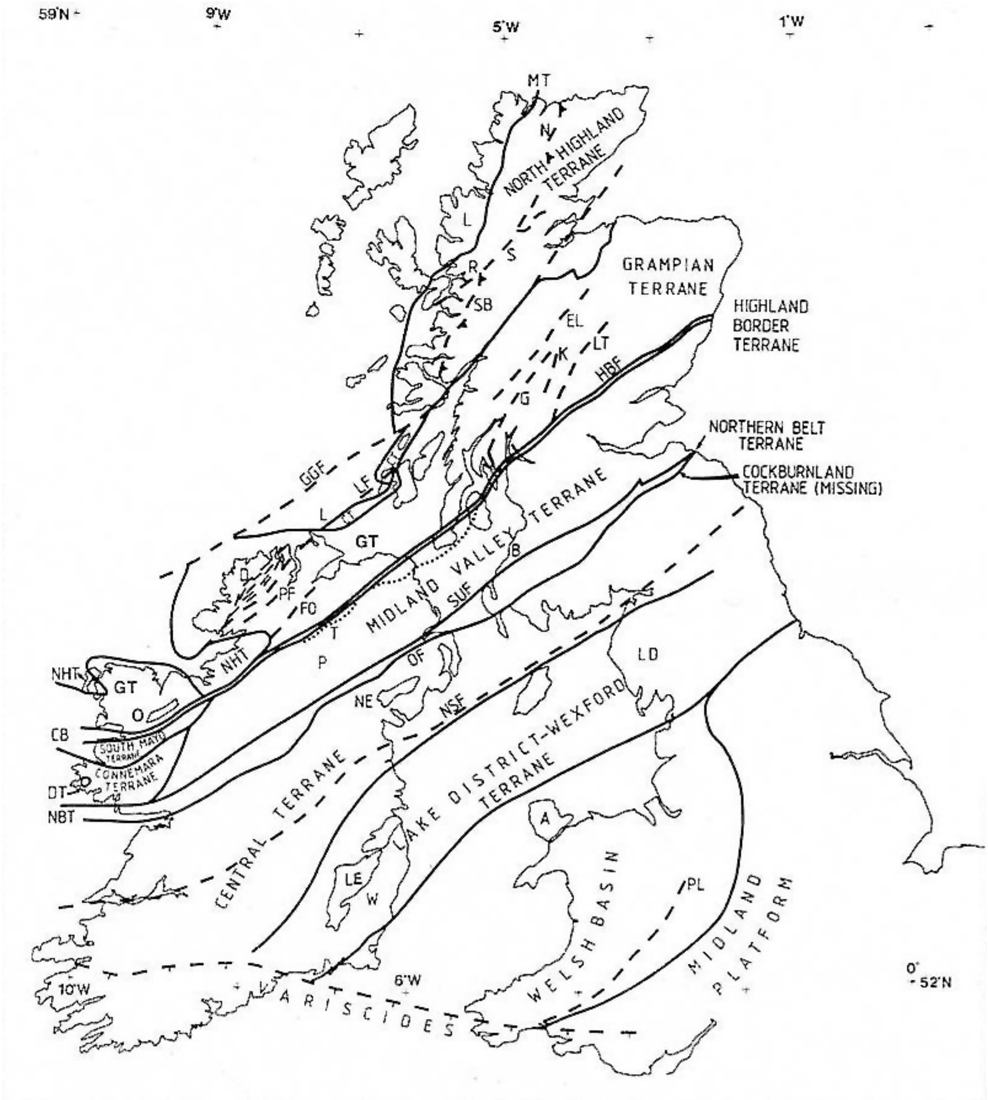

Figure 12 Caledonian terrane map for Britain and Ireland. Heavy lines = terrane boundaries. Dashed lines = other Caledonian faults. Dotted lines along Highland Boundary Fault (HBF) = extension of Grampian Terrane south of end-Silurian/early Devonian HBF. Terrane names: Colonsay Terrane (CT); Delaney Terrane (DT); Grampian Terrane (GT); Northern Belt Terrane (NBT); Northern Highland Terrane (NHT). Fault abbreviations: Donegal Shear Zone (D); Ericht-Laidon Fault (EL); Foyle Fault (FO); Garabal Fault (G); Great Glen Fault (GGF); Killin Fault (K); Leannan Fault (LF); Loch Tay Fault (LT); Moine Thrust (MT); Naver Slide (N); Navan-Silvermines Fault (NSF); Orlock Bridge Fault (OF); Pettigo Fault (PF); Pontesford Lineament (PL); Stratchonnan Fault (S); Sgurr Beag Slide (SB); Southern Uplands Fault (SUF). Geographic and other abbreviations: Anglesey (A); Ballantrae (B); Clew Bay (CB); Lewisian (L); Lake District (LD); Leinster Granite (LE); Newry Granite (NE); Ox Mountains (O); Pomeroy (P); Ratagain Granite (R); Tyrone Inlier (T); Wexford (W). Reproduced from Figure 1 of *Hutton* (1987).

Tectonic History and Palaeogeography

During late Pre-Cambrian and Cambrian times the Iapetus ocean separated the Laurentian and European continents. During this time areas comprising present day Ireland lay on opposite sides of the ocean at approximate latitudes of 30^{O}S. Present day northwest Ireland lay on the Laurentian continental margin, while southeast Ireland lay on the European continental margin. Palaeofaunal evidence shows that distinct Laurentian and European faunal provinces existed, indicating that the two continents were widely separated (*Windley* 1977).

The Dalradian rocks of the Connemara Terrane were deposited in a transgressive sea within an ensialic basin created by stretching and crustal thinning of the NeoProterozoic supercontinent about 750 Ma (*Dalziel* 1994, *Long et al.* 1995). The Dalradian sediments accumulated on this shallow continental shelf, until rifting led to the development of separate, deeper depositional basins, and eventual opening of the Iapetus ocean about 615 Ma (*Kamo et al.* 1989). The extensional setting along the Laurentian margin persisted until mid-Ordovician, when a continental magmatic arc developed above a northwest directed subduction zone, ushering in a compressional tectonic environment (*Long et al.* 1995).

The magmatic arc formed during the Grampian orogeny, the first contractional orogenic phase to affect the Laurentian continental margin, and which was synchronous with the Taconic orogeny of the northern Appalachians (*Friedrich et al.* 1999a). The latter authors state that the timing of orogenesis marks the collision and accretion of outboard island arcs, evidenced by the early to mid-Ordovician South Mayo Terrane, and was followed by short lived continental magmatism. The latter is represented by the syntectonic intrusive complex known as the Connemara Metagabbro and Gneiss Complex. This complex intruded the Connemara Terrane, an allochthonous piece of the Dalradian miogeocline, which has since been displaced south of the main Dalradian outcrop and outboard of the Ordovician age South Mayo Terrane (*Hutton* 1987, *Long et al.* 1995).

The complex is the gabbroic root zone of a now eroded calc-alkaline batholith. It consists of an ultramafic-mafic intrusion of largely gabbroic rocks disrupted and ubiquitously injected by intrusion of calc-alkaline quartz diorite, which was syntectonically converted to orthogneiss. The latter coincided with peak regional metamorphism, which reached upper amphibolite facies with syntectonic development of paragneisses in the adjacent Dalradian rocks (*Long et al.* 1995). The magmatic arc was active for a short period in the mid-Ordovician, starting with the emplacement of the gabbros at about 473 Ma, the quartz diorites at about 467 Ma, and culminating with the Oughterard Granite at about 463 Ma (*Friedrich et al.* 1999a and b).

Cessation of subduction of oceanic plate and associated magmatism near the end of the Ordovician, heralded the final closure of the Iapetus in the British Isles sector. The Iapetus ocean had spanned an interval of approximately 165 My (i.e., 'Wilson Cycle') from opening (about 615 Ma) to closing (about 450 Ma). During the late Ordovician the collided fore-arcs and continental margins underwent deformation and low grade metamorphism, whilst the detached Connemara Terrane was thrust south (*Hutton* 1987).

The Connemara Terrane is truncated to the south by the EW trending SRF, which is the western expression of the SUF. The Northern Belt lies immediately south of the SUF/SRF, and represents terrane deposited on the NW margin of the Iapetus ocean on the Laurentian margin (*Legget et al.* 1979, *Hutton* 1987). The SUF forms the southern limit of the

Laurentian foreland, and the northern limit of the trench above the subducting oceanic plate. Thus, Northern Belt most probably represents a trench fill sequence scraped-off subducting oceanic plate and built up as an accretionary wedge in the fore-arc region (*Ffrench & Williams* 1984, *Hutton* 1987). The South Connemara Group (SCG), including the Skerd Formation (SI) outcropping at the Skerd Rocks, belongs to this terrane, and thus represents early to mid-Ordovician trench fill deposits.

A Silurian successor basin formed from the shallow remnant sea between the remnant arcs of opposing polarity after subduction of oceanic crust, continental margin collision, and effective closure of the Iapetus (*Hutton* 1987). The remnant arcs and continental margins underwent uplift and erosion during the Silurian, with the sediments deposited in the Silurian successor basin, which now comprises the Central Terrane of the British Caledonides.

Major sinistral strike slip movement along the boundaries of the terranes between the opposing continental forelands became widespread during the end-Silurian and early Devonian, culminating in the major mountain building episode of the Caledonian orogeny (*Hutton* 1987). The latter author notes that the resulting anastomosing network of great faults and shear zones can cause 'strike slip shuffling', where terranes are moved inboard or outboard of one another, as well as 'strike slip stripping', where terranes are tectonically degraded and drawn out into long, thin terranes. Rather than there being a single line of suture, the entire zone between the opposing Laurentian and European continental forelands consists of rearranged fragments of the Iapetus palaeogeography.

Continued strike slip movement along the SUF seems to have brought hot mantle material into contact with the lower crust, promoting partial melting and generation of granitic magma during the metamorphic climax, and providing conduits for emplacement of post-tectonic intrusions (*Leake* 1978). The Galway Granite was emplaced during the early Devonian, about 405 Ma, and constitutes a major post-tectonic Caledonian intrusion (*Leggo et al.* 1966, *Pidgeon* 1969). It was emplaced in a dilational bend in the SUF, which engulfed and now largely obscures the SUF/SRF (*P. Ryan*, pers. comm. 2002). The intrusion is regarded as a stitching pluton emplaced on the contact of the Midland Valley and Southern Uplands terranes (*Leake & Tanner* (1994). Emplacement of the Galway Granite thus precluded further sinistral strike slip movement on the SUF/SRF, which had characterised the major Caledonian faults since late Ordovician times.

The Devonian continent created by the collision of the Laurentian and European continents is referred to as the 'Old Red Sandstone' continent. The continent was characterised by desert conditions, with present day Ireland lying at approximately 5^{O} south of the equator in tropical latitudes. At the beginning of the Carboniferous (i.e., earliest Courceyan stage) a shallow sea lay to the south of the continent. This sea transgressed northward covering much of Ireland by warm tropical seas, not unlike the present day Carribean, and resulted in the unconformable overstepping of the underlying eroded continent. During the late Courceyan stage carbonate deposition was dominated by a thick blanket of the distinctive Waulsortian carbonate 'reefs', which formed in deep-water mudbank complexes (*Phillips & Sevastopulo* 1986, *Hitzman & Large* 1986).

During the succeeding Visean stage, a pattern of carbonate sedimentation in shallow-water shelf facies separating deep-water basinal facies developed. This pattern persisted for most of the Visean with deposition of oolitic, peloidal and skeletal sand and muddy sand in shelf facies, and dark, argillaceous, fine-grained and cherty carbonates, termed 'Calp', in basinal facies (*Phillips & Sevastopulo* 1986). Basin formation was related to a contemporaneous regime of extensional tectonics with associated active faulting and volcanicity. On the north shore of Galway Bay (including the Skerd Rocks), Visean limestones are observed in fault contact with the Skerd Formation and the Galway Granite on the southern downthrown block of the Carboniferous Bounding Fault (CBF). The CBF probably acted as a major hinging fault related to limestone accumulation during the lower Carboniferous (*Max et al.* 1975). Although the CBF did not form the northern margin of the Shannon Basin, it nonetheless may have formed the northern margin of the Clare shelf with the Galway-Mayo High (*Cope et al.* 1992). The Visean limestones extend south from the Skerd Rocks area and along strike to the Aran islands and the Burren in Co. Clare (*Geoghegan et al.* 1975). Much of this thick sequence of shallow marine limestones is characterised by repeated shallowing-up cycles, with a platform-wide pattern in the cyclicity that indicates glacio-eustatic control (*Gallagher* 1996). The latter author notes that the calculated duration of these cycles are consistent with Milankovitch climatic cycles and the contemporaneous occurrence of Gondwanan glaciation in late Visean times in the southern hemisphere.

During the late Carboniferous and early Permian, folding and block faulting related to the distant Hercynian orogeny affected the area of Munster, particularly. From the beginning of the Permian period until the late Cretaceous, the area corresponding to present day Ireland was elevated above sea level, and underwent subaerial erosion under arid continental conditions (*Long et al.* 1995). A transgressive sea inundated much of Ireland during the late Cretaceous, giving rise to the deposition of chalk, now preserved only in northern Ireland. Crustal stretching and continental rifting began in the Triassic, preceding the opening of the Atlantic ocean. The initial mid-Atlantic opening in southern latitudes was followed by formation of oceanic crust in the mid-Jurassic. In the early Cretaceous, Newfoundland spread apart from Ireland, whilst the rifting and crustal stretching occurred between the Rockall Plateau and Ireland without the formation of intervening oceanic crust (*Long et al.* 1995). Formation of oceanic crust between Rockall and Greenland heralded true ocean spreading and opening of the Atlantic ocean in the early Tertiary, about 65 Ma.

Quaternary

A series of ice ages occurred during the Pleistocene epoch of the Quaternary period (i.e., between 1.6 Ma and 10,000 yr BP) resulting in extensive ice sheets across the British Isles, including most of Ireland. Ice thickness at the peak of the last ice age (i.e., the late Devensian approximately 20-25,000 yr BP) are estimated to be approximately 250-500 m in the vicinity of the FLA (*Lambeck* 1993a and b). The Irish ice sheet did not extend far beyond the present shoreline on the west coast of Ireland, and the vicinity of the FLA would have been deglaciated by 16,000 yr BP. Ireland was completely deglaciated by 13,000 yr BP (*Lambeck* 1993b).

Glacio-isostatic rebound due to unloading of this relatively short-lived and thin ice mass in the vicinity of the FLA, was substantially less than the rise in sea level due to melting of the worldwide ice sheets. Consequently, a significant positive sea level change is predictable in the vicinity of the FLA. The preliminary glacial rebound model of *Lambeck* (1993a) indicates a sea level change of 25-50 m since 18,000 yr BP in the vicinity of the FLA. The high resolution glacial rebound model of *Lambeck* (1993b) does not encompass western Ireland, but does indicate positive sea level changes of the same order or greater as *Lambeck* (1993a). *Geoghegan et al.* (1975) observed sea cliffs during a transit sonar survey of Galway Bay, which were interpreted to indicate sea levels 52-55 m lower than present during the Pleistocene. Thus, the opposing, but nonequivalent, effects of glacio-isostatic rebound and sea level rise due to glacial melting seem to have caused a sea level rise of approximately 55 m since peak glaciation in the vicinity of the FLA.

Interestingly, Holocene sea levels in eastern Maine have risen by 0.75 mm/yr between 6,000 and 1,500 yr BP, and by 0.43 mm/yr since 1,500 yr BP (*Gehrels* 1999), and indicate the magnitude of change in the global eustatic postglacial sea level regime. Indeed, the latter author notes a sea level rise of 0.5 m in the past 300 years, which thereby commenced prior to the industrial revolution, indicating at least a significant natural (i.e., non-manmade) component to this rapid rise in sea levels. Predicted global warming arising from increasing atmospheric emissions of greenhouse gases, principally CO_2, produced from the burning of fossil fuels, is expected to accelerate this pattern of rising sea levels. Interestingly, rising sea levels of the order of 1 m by 2030/2050 have been predicted by eustatic modelling, with accompanying more turbulent weather including wind speeds, wave heights, storm surges, etc. (*Devoy* 1992).

DISCUSSION

The Skerd Formation (SI) occupies a relatively small triangular shaped area in the southwest corner of the FLA (i.e., approx. 3.5 km^2 corresponding to 9% of the FLA), and outcrops in the Skerd Rocks, including Skerdmore, Skerdbeg, Doonguddle and Mullaun Rocks. The SI is separated from Metagabbro to the north by the EW trending Skerd Rocks Fault (SRF), and from limestone to the south by the WNW trending Carboniferous Bounding Fault (CBF). The SI consists of a lithologically heterogeneous package of Ordovician age metavolcanics and metasediments. The SI is not favoured as a potential site for installation of turbines, as the SI is steeply dipping and heavily faulted, most probably providing poor footing for turbines pier foundations. The SI is also not favoured for siting of turbines because the SI occurs in the immediate vicinity of the Skerd Rocks, where maximum wave heights, treacherous currents and extreme bathymetry (likened to church steeples by *M. Geoghegan* pers. comm. 2002) each present a significant deterrence to turbine installation.

Interestingly, the South Connemara Group (SCG) at Lettermullen is thermal metamorphosed and relatively indurate, whereas at the Skerds the SI (lowermost unit of the SCG) is a lower grade melange that weathers heavily and irregularly (*P. Ryan* pers. comm. 2002). Despite its tendency to weather, the SI remains topographically prominent, probably because the steep southwesterly dip of the SI results in the prevailing wind and wave action being presented against the dip slopes.

The Carboniferous limestones (Carb) occupies a relatively small, narrow, WNW trending tract (i.e., approx. 4 km^2 corresponding to 10% of the FLA) parallelling the southern boundary of the FLA. The Carb only occurs along the very southern boundary of the FLA in relatively deep water south of the CBF, and consists of lower Carboniferous age Visean limestones similar to those on the Aran Islands and the Burren. The Carb is not favoured as a potential site for installation of turbines as it lies in water depths that exceed the optimum water depth for installation of turbines (See Figs. 11 and 12).

The Metagabbros (Mg) occupies a large tract (i.e., approx. 7 km^2 corresponding to 17% of the FLA) in the northwestern part of the FLA, and outcrops at Mile Rocks, Doonpatrick, Doonmanebeg, and possibly Doonmane. Although the Mg has undergone intense metamorphism, it is originally an igneous rock. However, the igneous layering and textures are poorly preserved in the Mg, which tends to be massive and weakly foliated. Late stage metamorphic alteration of the Mg is ubiquitous producing a mineral assemblage composed largely of hydrous sheet silicates, such as micas, clays, chlorites and serpentines. Thus, while the Mg is probably mechanically isotropic, it consists of brittle, platy, micaceous minerals, and most likely exhibits decreased mechanically strength. In addition, because much of the Mg lies in waters deeper than 30 m, and occurs in the northwestern corner of the FLA with resulting increased distances for high voltage cabling, the Mg is generally not favoured for turbine installation (See below).

Subunits of the Galway Granite occupy approximately 26.5 km^2, corresponding to 64% of the FLA. Except for the extreme southern FLA, granite occupies all of the FLA east of a NNW trending sinuous line running just east of Mile Rock, Doonmane and Doonguddle. The Errisbeg Townland Granite (GaEb) occupies an extensive NNW trending tract (i.e., approx. 20 km^2 corresponding to 49% of the FLA) in the central FLA, and outcrops at Doolick, Doolickbeg, and possibly Doonmane. The Cuilleen-Type Granite (GaCu) occupies a moderately large tract (i.e., approx. 6.5 km^2 corresponding to 15% of the FLA) in the eastern FLA, but does not outcrop within the FLA. The Carna-Type Granite (GaCn) occurs immediately to the east of the FLA, but being patchily developed and transitional with the GaCu, may actually occur within FLA. The contacts between the three granite types (i.e., GaEb, GaCu and GaCn) generally conform to a concentric ring pattern within the domal structure of the parent Devonian Galway Granite.

It is probable that the mechanical properties of the granite types in the FLA are not significantly different (*M. Geoghegan* pers. comm. 2002). *Inamdar & McIntyre* (1975) determined some of the physical properties of rock types in the area. The saturated density, grain density, bulk density and porosity for the GaEb and Carna granites (i.e., GaCu and CaGn) are given below in Table 3. If the measured physical properties are any indicator of the mechanical properties of the granites, these data suggest no significant differences.

Table 3. Physical Properties of GaEb and Carna Granites

Rock Type	**Saturated Density (gm/cm^3)**		**Grain Density (gm/cm^3)**		**Bulk Density (gm/cm^3)**		**Porosity (In Volume%)**	
	Mean	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
GaEb (18)*	2.634	0.027	2.667	0.018	2.614	0.037	1.98	1.20
Carna (33)**	2.654	0.024	2.681	0.022	2.638	0.030	1.59	0.96

Notes: *Number of samples. **Carna includes GaCu and GaCn.

The differences in the mechanical properties of the granites are probably less dependant on their gross primary mineralogy than on the extent to which they are affected by weathering, foliation, faulting and jointing. The GaEb and GaCu contain 93 and 90% quartz plus feldspar, respectively, which are hard minerals. On the Mohs scale (where hardness of diamond is 10), the hardness of quartz is 7, and that of both plagioclase feldspar and K-feldspar is 6. Thus, the primary mineral assemblages and granular texture of these granite types indicate that they are extremely indurate. However, K-feldspar is more prone to weathering than plagioclase feldspar, typically being the first feldspar to be eroded in the subaerial environment. Although the GaEb contains higher proportions of K-feldspar than the GaCu, it has a slightly higher content of quartz, which is resistant to weathering. Thus, the GaEb and GaCu are not expected to be significantly different in terms of their susceptibility to weathering and related degradation of mechanical integrity.

The GaCu is only weakly foliated with minimal magmatic layering, suggesting that the GaCu is largely mechanically isotropic. In contrast, the GaEb exhibits the most pronounced foliation of the granites occurring in the Carna dome, with extensive magmatic layering, suggesting that the GaEb is mechanically anisotropic. Layering typically results in the preferred orientation and segregation of felsic minerals such as quartz and feldspar into different layers than the mafic minerals such as biotite and hornblende. The prominent layering in the GaEb has been domed-up by intrusion of the Carna Granite, and is near vertical, and presumed to sub-parallel the margins of the Carna dome. The directions of weakest tensile and compressional strength, are expected to be normal and parallel, respectively to the planarity of that layering.

The principal faults in the granites occur as an early set of partially annealed, discontinuous, curved, closely-spaced faults with a general NE trend, followed by a later set of near vertical, NW trending faults. A third, younger set of SW trending faults is also observed. *Max & Talbot* (1986) note that younger faulting and jointing are common, but have not been resolved within a pluton-wide system. Notably, the distribution of faults in the FLA is largely undetermined, but where faulting has been mapped within the FLA it is intensive. P. *Ryan* (pers. comm. 2002) notes that the near horizontal joints widespread near the roof of the granite could be potentially detrimental to turbine foundation piers. However, the near vertical orientation of the granite contacts in the FLA indicates that the erosional surface in the FLA has intersected the granite well below the roof zone. Nonetheless, sheet jointing is common throughout the batholith, and is generally low angle and undulating. In the Mace Head area, which lies close to the approximate centre of Carna dome, conjugate jointing coincides with the major fault trends (i.e., NE and NW), with the NE trend being dominant (*Derham* 1986). However, faulting and jointing tend to be compartmentalized, being more intensely developed in some areas. The distribution and orientation of faults and joints in the FLA is expected to have a significant influence over the design and siting of turbine foundation piers, and requires detailed study.

The optimum water depth interval for installation of the turbine pier foundations is 5-25 m (*G. Healy*, pers. comm. 2002). However, the bathymetric data incorporated into the GIS model are such that arbitrarily selected depth contours (e.g., 25 m contour) could not be extracted. Because a depth interval map in the 5-25 m depth interval could not be generated, maps of the 5-20 m and 5-30 m depth intervals were generated to help identify those areas within the FLA suitable for installation of the turbine foundations piers. Thus, two depth interval maps were generated by extracting those areas within the FLA occurring within specific depth intervals (i.e., 5-20 and 5-30 m intervals). The boundary of the FLA and the geological contacts were also superimposed on these maps (See Figs. 11 and 12). Importantly, because the 5 m depth contour is in places discontinuous (See *Haslam* 1983), presumably because of the difficulties navigating vessels at these shallow depths in treacherous waters, the extracted areas corresponding to the depth intervals are exaggerated around some islands, rocks and shallows.

Figure 11 shows a large, irregular and discontinuous area occurring in the 5-20 m depth interval that covers much of the central part of the FLA, stretching from The Big Breaker to Doolick, and centred around Kelly Rock. This area is referred to here as the Kelly Rock Plateau, the bedrock of which consists largely of Errisbeg Townland Granite (GaEb). Minor yet significant areas at Doonguddle, the Skerds, Mile Rocks and Fools Shoal are also identified, although those at Doolick, Doolickbeg, Doonguddle and the Skerds are significantly exaggerated due to missing or discontinuous 5 m depth contours. However, the areas at Fools Shoal and Mile Rocks are largely unexaggerated, and thus afford additional potential sites for installation of turbines. The Kelly Rock Plateau, Fools Shoal and Mile Rocks also generally lie within areas of low predicted maximum 50 year wave heights (i.e., < 8 m: See Fig. 9), and thus appear to satisfy both the depth interval and wave height criteria for installation of turbines. However, the Mile Rocks area is not proximate to the main areas of Kelly Rock Plateau and Fools Shoal, such that a turbine installation at Mile Rocks would require extended high voltage cabling.

Figure 12 shows a large, continuous area occurring in the 5-30 m depth interval that includes the Kelly Rock Plateau and extends unbroken to include most of the northeastern and northern boundaries of the FLA. Interestingly, the bedrock of this newly identified area extending east and north of the Kelly Rock Plateau consists largely of Cuilleen-Type Granite (GaCu). The areas of The Big Breaker, Fools Shoal and Mile Rocks are now seen to be continuous with the Kelly Rock Plateau. Again, the area around Doolick and Doolickbeg, as well as the areas at Doonguddle and the Skerds are significantly exaggerated due to missing or discontinuous 5 m depth contours. A significant area around the Wild Shoals is identified as occurring in the 5-30 m depth interval. However, some of the areas newly identified in the 5-30 m depth interval such as Wild Shoals lie within areas of higher predicted wave heights (< 14 m: See Fig. 9), and thus may not satisfy the wave height criterion for installation of turbines.

A substantial area of the FLA lies in 5-20 m water centred on the Kelly Rock Plateau with lesser areas at Fools Shoal and Mile Rocks. However, approximately half of the FLA lies in 5-30 m water, the bulk of which lies as a continuous area, including the Kelly Rock Plateau, Mile Rocks and Fools Shoal, and extending to the northeastern and northern boundary of the FLA. This area generally exhibits low predicted maximum 50 year wave heights, lies on the landward side of the FLA, and is dominated by granitic substrata, with metagabbro only in the extreme north around Mile Rocks. However, accumulation of surficial seafloor sediment is possible in the area of 20-30 m water that forms a shallow trough along the northeastern boundary of the FLA (i.e., landward of the Kelly Rock Plateau).

The critical data investigated and/or reviewed in this study that have a bearing on siting of turbines are: (1) favourable bedrock geology, (2) optimum water depth interval for turbine foundation pier installation; (3) proximity to mainland, with inverse capital costs of high voltage cabling; and (4) maximum 50 year wave height distribution. The convergence of these data indicate that an extensive area of the eastern side of the FLA centred on the Kelly Rock Plateau and extending towards the northeastern and northern boundaries of the FLA is most favourable for installation of the turbines, where the optimum water depth interval for turbine installation is 5-30 m. That area shrinks to the Kelly Rock Plateau, Fools Shoal and possibly northeastern Mile Rocks areas, where the optimum water depth interval for turbine installation is 5-20 m.

Keary (1975) states the distribution of sediment in the northern approaches to Galway Bay is irregular, but bedrock exposure in critical areas is over 75%. From this it is inferred that bedrock exposure in the FLA is 75% or greater. Furthermore, *O'Connor et al.* (1993) showed that the area immediately south and west of Namackan Rocks is dominated by exposed bedrock with lesser tracts of sands, and that bedrock is exposed in water depths down to 60 m locally. The FLA lies in a high energy marine environment, where high water velocities and turbulence produce only minimal sediment accumulation above at least 20 m water depth (*B. O'Connor*, pers. comm. 2002). Seafloor sediment encountered above the 20 m water depth within the FLA is most likely to occur as sedimentary drapes in steep topographic depressions, which are in any case probably unsuitable locations for siting turbine foundation piers.

Seafloor sediment occurring between 20 and 30 m water depths is most likely in areas with reduced wave base and water velocities. Such sediment accumulation is possible within the FLA, particularly in the shallow trough that runs along the northeastern boundary of the FLA east of the Kelly Rock Plateau (See Figs. 11 and 12). The trough encompasses a large tract occurring within the shadow of the energy dissipation produced by wave-breaking and shoaling as waves travel through the cluster of shallows, rocks and islands (*Aqua-Fact* 2002). Thus, the highest likelihood of sediment accumulation in areas with water depths of less than 30 m within the FLA is along the southern two thirds of the northeastern boundary. This extensive area is characterised by granitic substrata, maximum proximity to land, low predicted maximum 50 year wave heights, and is contiguous with the Kelly Rock Plateau and

Fools Shoal. Thus, assuming the optimum depth interval for turbine foundation piers is 5-30 m, this area seems otherwise ideally suited to siting turbines. Consequently, the distribution and character of unconsolidated seafloor sediment in this area requires detailed study. Nonetheless, it is considered unlikely that there are significant thicknesses of sediment accumulation in water depths of less than 30 m within the FLA.

Atmospheric and eustatitc models are predicting increased atmospheric temperatures and rising sea levels of the order of 1 m by 2030/2050 with accompanying more turbulent weather including wind speeds, wave heights, storm surges, etc. Given the latter, it might be propitious to design turbine installations with higher safety factors, such as planning for a 100 instead of 50 year maximum wave height.

Discussions between Messrs R. Healy, G. Healy and Mr. Geoghegan, Project Manager, National Seabed Survey, GSI, lead to a test survey being done over part of the FLA in August 2002. This survey was done using the *Celtic Voyager* research vessel operating on a "shake-down" voyage for both equipment and crew. The vessel is equipped with single-beam echo sounder, side-scan sonar, multi-beam sonar, shallow seismic sub-bottom profiler, as well as a range of other analytical techniques such as magnetic, gravity and seawater salinity, conductivity and temperature. The vessel is also equipped with the capability of collecting grab samples from the seabed for the purpose of seabed ground-truthing.

The test survey represents the initiation of Zone 2 (i.e., 50-200 m depth interval) of the national seabed survey. An approximately 1 km wide, multi-lane tract was surveyed, extending along the northeastern boundary of the FLA between the bounding coordinates 5 (i.e., 9.92500W 53.26666 N) and 6 (i.e., 9.98333 W 53.30250 N). In addition, a second, single-lane tract was surveyed from bounding coordinate 5 into Kilkieran harbour. These proprietary data are available on a partial cost recovery basis, while further surveying of the FLA can be done by GSI on a cost shared basis, or using third parties (e.g., Gotech or Waterborne Geophysics), and possibly including GSI "piggybacking" some techniques on such third party surveys (*M. Geoghegan*, pers. comm. 2002). Interestingly, the GSI also conducted a mini survey (using multi-beam sonar, magnetic and gravity methods) in the North Sound of Galway Bay, south of Gorumna and Lettermullen islands. Further information on this mini survey and the national seabed survey are available at www.marine.ie/scientific+services/surveys/seabed, or www.gsiseabed.ie. Finally, aerial laser bathymetric surveying in Irish coastal waters was also scheduled for 2002.

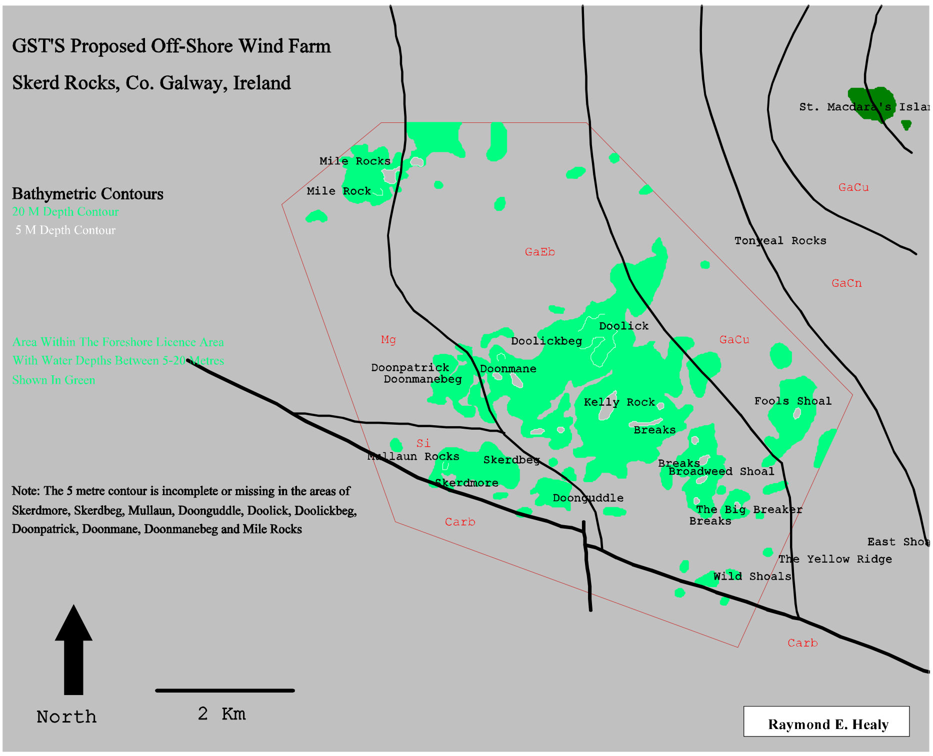

Figure 13 Depth interval map showing the area in the FLA occurring within the 5-20 metre depth interval, and superimposed geological contacts. Bar Scale = 2 Km.

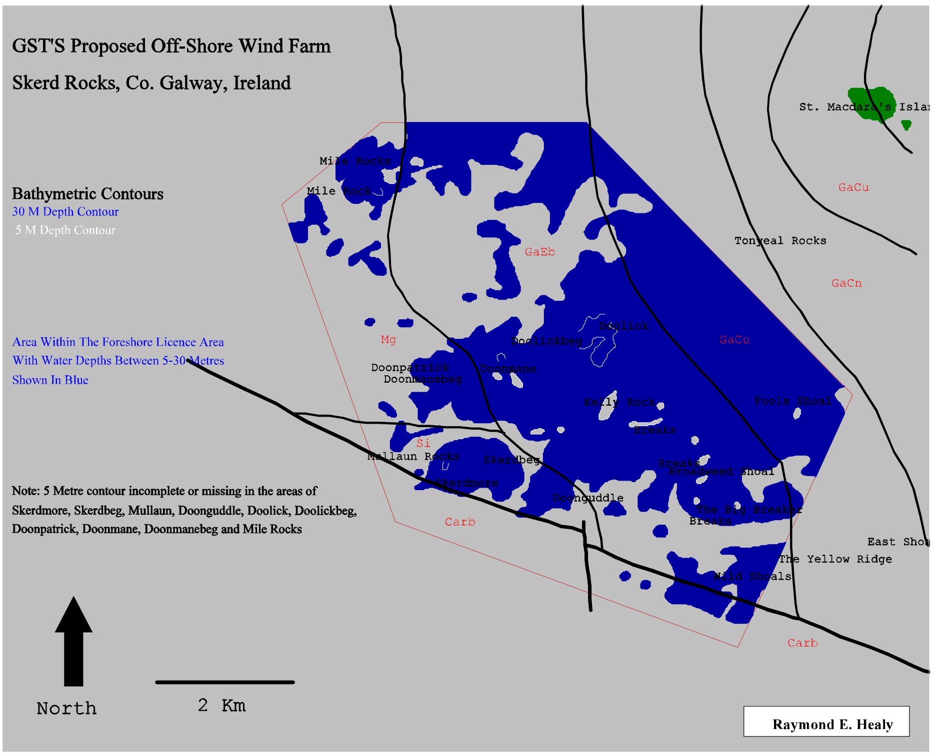

Figure 14 Depth interval map showing the area in the FLA occurring within the 5-30 metre depth interval, and superimposed geological contacts. Bar Scale = 2 Km.

CONCLUSIONS

1. The geological units in the vicinity of the FLA were determined from the 1:100,000 scale geology map of Connemara. These units include: (1) the Ordovician Skerd Formation (SI); (2) the Carboniferous limestones (Carb); (3) the Ordovician Metagabbro (Mg) of the Connemara Metagabbro and Gneiss complex; (4) the Devonian Errisbeg Townland Granite (GaEb); and (5) the Devonian Cuilleen-Type Granite (GaCu).

2. Two regionally important faults occur within the FLA. The EW trending Skerd Rocks Fault (SRF) separates the SI from the Mg to the north. The WNW trending Carboniferous Bounding Fault (CBF), which can be traced along and defines the north shore of Galway Bay, separates the SI and the granites from the Carb. The Carb limestones have been downthrown on the southern block of the CBF against the SI and granite.

3. The Skerd Formation (SI) occupies a relatively small triangular shaped area in the southwest corner of the FLA (i.e., approx. 9% of the FLA), and outcrops in the Skerd Rocks, including Skerdmore, Skerdbeg, Doonguddle and Mullaun Rocks. The SI is a lithologically heterogeneous package of metavolcanics and metasediments. The SI is not favoured as a potential site for installation of turbines, as the SI is steeply dipping and heavily faulted, most probably providing poor footing for turbine foundation piers. The SI is also not favoured for siting of turbines because of the treacherous waters, high maximum wave heights and extreme bathymetry.

4. The Carboniferous limestones (Carb) occupies a relatively small, narrow, WNW trending tract (i.e., approx. 10% of the FLA) parallelling the southern boundary of the FLA. The Carb consists of Visean age limestones similar to those on the Aran Islands and the Burren. The Carb only occurs along the very southern boundary of the FLA in relatively deep water, and is thus not favoured as a potential site for installation of turbines.

5. The Metagabbro (Mg) occupies a large tract (i.e., approx. 17% of the FLA) in the northwestern part of the FLA, and outcrops at Mile Rocks, Doonpatrick, Doonmanebeg, and possibly Doonmane. The Mg tends to be massive and weakly foliated, but is largely composed of hydrous sheet silicates (e.g., micas, clays, chlorites and serpentines). Thus, while the Mg is probably mechanically isotropic, it likely exhibits relatively low mechanical strength. Because much of the Mg lies in waters deeper than 30 m, and occurs distally in the northwestern corner of the FLA, the Mg is generally not favoured as a potential site for installation of turbines.

6. Subunits of the Galway Granite occupy approximately 64% of the FLA (i.e., approx. 26.5 km^2). With the exception of the extreme southern FLA, granite occupies all of the area east of a NNW trending sinuous line running just east of Mile Rock, Doonmane and Doonguddle. The Errisbeg Townland Granite (GaEb) occupies an extensive NNW trending tract (i.e., approx. 49% of the FLA) in the central FLA, and outcrops at Doolick, Doolickbeg, and possibly Doonmane. The Cuilleen-Type Granite (GaCu) occupies a moderately large tract (i.e., approx. 15% of the FLA) in the eastern FLA, but does not outcrop within the FLA. The Carna-Type Granite (GaCn) occurs immediately to the east of the FLA, but being patchily developed and transitional with the GaCu, may actually occur within FLA. The contacts between the three granite types generally conform to a concentric ring pattern within the domal structure of the parent Galway Granite.

7. The GaEb and GaCu exhibit primary mineral assemblages (i.e., 93 and 90% quartz plus feldspar, respectively) and granular textures indicating that the granites are extremely indurate. The susceptibility to weathering of the GaEb and GaCu are probably not significantly different. Thus, differences in the mechanical properties of the granites are probably more dependant on the extent to which they are affected by foliation, faulting and jointing. The GaCu is only weakly foliated with minimal magmatic layering, and is probably mechanically isotropic. The GaEb is strongly foliated with extensive magmatic layering, and is thus probably mechanically anisotropic. The layering is near vertical and probably sub-parallels the outer contacts of the granite.

8. The principal faults in the granites occur as an early set of partially annealed, discontinuous, curved, closely-spaced faults with a general NE trend, and a later set of near vertical, NW trending faults. A third, younger set of SW trending faults also occurs. Although the erosional surface intersects the granite well below the roof zone of the batholith, where near horizontal joints are widespread, low angle sheet jointing is common throughout the granite. The conjugate joints coincide with the major fault trends (i.e., NE and NW) with the NE trend being dominant. The distribution of faults and joints within the FLA is largely undetermined, but where faulting has been mapped within the FLA it is intensive.

9. The 5-20 m water depth interval identifies a large, irregular and discontinuous area covering much of the central FLA extending from The Big Breaker to Doolick, and is here called the Kelly Rock Plateau. Significant areas at Mile Rocks and Fools Shoal are also identified as occurring in the 5-20 m interval, and are also potential sites for siting turbines. The Kelly Rock Plateau, Fools Shoal and Mile Rocks areas generally lie within areas of low predicted maximum 50 year wave heights, and thus appear to satisfy the water depth interval and wave height criteria for installation of turbines. However, the Mile Rocks area is not proximate to the main areas of the Kelly Rock Plateau and Fools Shoal, such that turbines at Mile Rocks would require extended high voltage cabling.

10. The 5-30 m water depth interval identifies a large, continuous area that includes the Kelly Rock Plateau, Fools Shoal and Mile Rocks areas and extends to the northeastern and northern boundaries of the FLA. This extensive area generally exhibits low predicted maximum 50 year wave heights, lies on the landward side of the FLA, and is dominated by granitic substrata, with metagabbro only in the extreme north around Mile Rocks. A significant, separate area around the Wild Shoals is also identified as occurring in the 5-30 m depth interval, but lies in an area of higher predicted maximum 50 year wave heights.

11. The critical data investigated and/or reviewed in this study that have a bearing on siting of turbines are: (1) favourable bedrock geology, (2) optimum water depth interval for turbine foundation pier installation; (3) proximity to mainland, with inverse capital costs of high voltage cabling; and (4) maximum 50 year wave height distribution. The convergence of these data indicate that an extensive area of the eastern side of the FLA centred on the Kelly Rock Plateau and extending towards the northeastern and northern boundaries of the FLA is the most favourable area for installation of the turbines, where the optimum water depth interval for turbine installation is 5-30 m. This area is characterised by granitic substrata, maximum proximity to land, and low maximum 50 year wave heights. That area shrinks to the Kelly Rock Plateau, Fools Shoal and possibly northeastern Mile Rocks areas, where the optimum water depth interval for turbine installation is 5-20 m.

12. It is inferred that bedrock exposure in the FLA is 75% or greater. Accumulation of unconsolidated seafloor sediment is minimal above at least 20 m water depth in the FLA. Seafloor sediment accumulating in 20-30 m water depths is most likely in areas with reduced wave base and water velocities. The shallow trough that runs along the southern two thirds of the northeastern boundary of the FLA, east of the Kelly Rock Plateau occurs within the wave shadow of the Skerds, and may exhibit elevated seafloor sediment accumulation. Assuming the sediment accumulations in this area do not impede the installation of turbine foundation piers, this area is otherwise favoured for siting turbines where the optimum water depth interval for turbine foundation piers is 5-30 m.

13. Future geological work in the FLA should focus on the distribution of faults and joints within the granite types, as well as the distribution, depth and character of unconsolidated seafloor sediments. These features are presently poorly defined, yet are expected to have a significant influence over the design and siting of turbine foundation piers. Thus, these areas of uncertainty are earmarked as requiring detailed study.

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APPENDIX 1. Brief Description of Samples for Geotechnical Testing

Sample No.	Description
GST-02-01	GaEb. Hollow in centre of Doolick Island. Weight: 6 Kg. Pinkish grey with rusty pinkish-brown weathered surface. Inequigranular, porphyritic adamellite with prominent coarse (i.e., ≤2 cm) pink K-feldspar megacrysts set in a finer granular matrix of whitish (not greenish) weakly saussuritised plagioclase, quartz, black biotite and hornblende.
GST-02-02	GaCu. Shoreline at Carna quay. Weight: 2 Kg. Faint pinkish grey sample with pale pinkish grey weathered surface. Granular, medium-grained monzogranite with some coarse, irregular K-feldspar megacrysts set in a finer matrix of greenish white, saussuritised plagioclase, quartz, black biotite and lesser hornblende.
GST-02-03	GaCn. 30 m north of road, 1.5 km west of Carna (opposite Cuilleen Hill). Weight: 1.5 Kg. Rust-brown stained friable sample with pinkish medium grey in colour and grey heavily weathered surface. Granular, fine- to medium-grained granodiorite with some coarse, irregular K-feldspar megacrysts set in a finer matrix of greenish white, weakly saussuritised plagioclase, quartz, black biotite and lesser hornblende.
GST-02-04	GaCn. Moyruss crossroads. Weight: 1.5 Kg. Pinkish medium grey fresh sample with a mottled grey weathered surface. Fine- to medium-grained granodiorite with no apparent K-feldspar megacrysts. Granular matrix of prominent, pale greenish white, weakly saussuritised plagioclase, pink K-feldspar, quartz, black biotite and lesser hornblende.
GST-02-05	GaCu. Moyruss jetty. Weight: 2 Kg. Faint pinkish grey fresh sample with pale pinkish grey weathered surface. Granular medium-grained monzogranite with some coarse, irregular K-feldspar megacrysts set in a matrix of pale greenish white, weakly saussuritised plagioclase, quartz, black biotite and lesser hornblende.
GST-02-06	GaCu. Moyruss well. Weight: 7.5 Kg. Pinkish medium grey fresh sample with faintly pinkish grey weathered surface. Granular medium-grained, porphyritic monzogranite with distinct phenocrystic pale greenish white, weakly saussuritised plagioclase megacrysts (i.e., ≤1 cm), and some coarse, irregular K-feldspar megacrysts, set in a granular matrix of feldspars, quartz, black biotite and lesser hornblende.
GST-02-07	Mg. 40 m south of road at Leitirard, adjacent to contact with granite and invaded by granite apophyses and insipient stoping. Weight: 2 Kg. Mottled to streaky/banded medium translucent green, fine-grained, massive, non-schistose sample with rusty brownish green weathered surface.

Sample No.	Description
GST-02-08	Mg. 10 m south of road at Cregduff Lake. Weight: 1.5 Kg. Dark green, massive, schistose sample with rusty brownish green weathered surface. Sample contains fine, irregular, patches and boudinaged trails of light green mineral.
GST-02-09	Mg. 150 m north of Cregduff crossroads. Weight: 1.5 Kg. Dark green, fine-grained, massive, non-schistose sample with greenish grey weathered surface. Several shear planes are apparent on the weathered surface.
GST-02-10	GaEb. 300 m west of Cregduff crossroads. Weight: 1.5 Kg. Pink to pale grey with rusty pinkish-brown weathered surface. Inequigranular, porphyritic adamellite with prominent coarse (i.e., ≤2 cm) pink K-feldspar megacrysts set in a finer granular matrix of whitish (slightly greenish) weakly saussuritised plagioclase, quartz, black biotite and hornblende.
GST-02-11	GaEb. Bend in road 50 m east of Gurteen crossroads. Weight: 3 Kg. Brownish grey to pale pink with heavily developed rusty brown weathered surface, and possible slickensides indicating shearing or faulting. Inequigranular, porphyritic adamellite with prominent coarse (i.e., ≤1.5 cm) pink K-feldspar megacrysts set in a finer granular matrix of brown rust stained, greenish white saussuritised plagioclase, quartz, black biotite and hornblende.
GST-02-12	GaEb. Shoreline at Gurteen beach. Weight: 2.5 Kg. Pinkish brown to pale grey with rusty brownish grey mottled weathered surface. Inequigranular, porphyritic adamellite with prominent coarse (i.e., ≤2 cm) pink K-feldspar megacrysts set in a finer granular matrix of greenish white, weakly saussuritised plagioclase, quartz, black biotite and hornblende. Some of the plagioclase appears phenocrystic.
GST-02-13	GaEb. Dogs Bay crossroads. Weight: 1.5 Kg. Pinkish brown to pale grey with heavily developed rusty brown weathered surface. Inequigranular, porphyritic adamellite with prominent coarse (i.e., ≤2 cm) pink K-feldspar megacrysts set in a finer granular matrix of brown rust stained, greenish white saussuritised plagioclase, quartz, black biotite and hornblende.
GST-02-14	GaEb. 300 m west of Dogs Bay crossroads. Weight: 2.5 Kg. Pink to pale grey with weak brownish-pink grey weathered surface (i.e., very fresh, largely unweathered sample). Inequigranular, porphyritic adamellite with prominent coarse (i.e., ≤1.5 cm) pink K-feldspar megacrysts set in a finer granular matrix of rarely phenocrystic, slightly greenish white, weakly saussuritised plagioclase, quartz, and abundant black biotite and hornblende.

APPENDIX 2. Simplified Sequence of Deformation Events in Connemara

Event	Description
D6	Variscan/Hercynian orogeny. c. 300-260 Ma. (Late Carboniferous to Early Permian) • Thermal overprinting of Devonian granites and Carboniferous dykes. • Folding of Carboniferous sediments. • Late Carboniferous sub-alkaline dolerite dykes relating to abortive early rifting of North Atlantic • Deposition of lower Carboniferous basal clastics and limestones in eastern Connemara c. 355 Ma.
D5	Caledonian and Acadian orogeny. c. 420-375 Ma. Late Silurian to Mid Devonian • D5a main folding of Silurian rocks during Caledonian/Acadian orogeny at end of lower Devonian c. 387 Ma. Probable timing of folding (local D3) of South Connemara Group. Late upright open N-S folds in Delaney Dome area. • Galway Granite intruded c. 405Ma. Timing with respect to D5 is unclear, though late shearing has affected granite locally. Associated igneous bodies include Caledonian dykes and appinite suite now largely engulfed by Galway Granite. Hydrothermal fluid circulation and late metamorphic retrogression. • Base of Silurian overstep c. 430 Ma.
D4	Late Grampian orogeny. c. 465-462 Ma (i.e., Mid Ordovician). • Intrusion of Oughterard Granite in 462 Ma post D4. • Probable timing of folding (local D2) of South Connemara Group. Sub-greenschist facies metamorphism. • Development of Connemara Antiform broadly and other more northern parallel folds, associated with Manin Thrust which is folded by D4. • Manin Thrust mylonitic fabric (including Ballyconneely Amphibolite) developed with N-S flat lying tight to close folds of fabric broadly synchronous. Inverted metagabbro in hanging wall. • Major uplift, possibly associate with development of Manin Thrust.
D3	Grampian orogeny. c. 475-465 Ma (i.e., Mid Ordovician). • Delaney Dome Meta-rhyolite Formation probably volcanically erupted in late Arenig - evolved separate from Connemara before development of D4 Manin Thrust. • Latest K-feldspar gneisses post-date D3. • M3 main thermal peak of regional metamorphism in Connemara. Upper amphibolite facies with new garnet and breakdown of D2 garnet. Hornblende formed in upper sillimanite zone. • Folding and development of a stack of tight to close F3 folds, with a spaced S3. • Intrusion synorogenic quartz diorite and granitic rocks that were deformed and metamorphosed into orthogneiss as they cooled, with formation of paragneiss and migmatite in the broad contact zone (c. 467 Ma). Metamorphism of gabbroic suite into metagabbro, and regional scale thermal metamorphism of Dalradian schists with growth of sillimanite (pre- to syn-D3). • Intrusion gabbroic suite probably between D2-D3. c. 475 Ma. • Deposition of South Connemara Group from Arenig to Caradoc or later. • Separation of Connemara from southern margin of Grampian Terrane, probably following D2.
D2	Early Grampian orogeny. c. 475 Ma (i.e., Lower Ordovician). • Peak Barrovian-type regional metamorphism D2 and M2 in low amphibolite facies, related to crustal thickening. • Development of regional scale, isoclinal Derryclare Anticline, with penetrative S2 schistosity - dominant schistosity in Connemara.
D1	Brazilide orogeny. c. 600 Ma (i.e., Late NeoProterozoic). • Only S1 schistosity preserved.

Notes:

1. D1 to D6 is a unified numbering scheme for events over the whole area of Map Sheet 10, with D1 to D4 relating mainly to the Dalradian schists and the rocks that intruded them during the Ordovician. The events are listed in general chronological order.
2. D refers to deformation, F refers to fold, M refers to metamorphic, and S refers to fabric or schistosity.
3. Modified from Table 3 of *Long et al.* (1995) with data from *Friedrich et al.* (1999b).