4 GEOLOGY

4.1 Introduction

The scope of the work is to produce a desk-study of available bathymetric, geological and sediment data that will highlight key geological and geomorphological features in the offshore area around Guernsey, Herm and Sark within the 3 mile Territorial Zone. The review is based on existing legacy data, published reports, scientific peer-reviewed papers and analyses. The review includes an initial assessment of likely impacts (on sediment movements and bathymetry) from the agreed development scenarios. The analysis also provides a brief commentary on the suitability of the seabed for foundations and moorings.

The Report includes:

a) A written review of sediment and solid rock distribution and sedimentary processes within the designated area,
b) Maps of sediment, sediment bed forms and solid geology distribution
c) Summary characterisation map of the seabed,
d) ARCGIS layers as appropriate (from coordinated work with GREC GIS Technician),
e) Identification of data gaps and assessment of data quality,
f) Commentary on likely impacts of marine renewable energy devices on the geology, sediments and bathymetry, together with recommendations for further analysis,
g) Commentary on suitability of seabed for foundations and moorings.

4.2 Baseline Environment

The data accessed was as follows:

- Published information - charts, maps, reports and peer-reviewed scientific papers.
- Legacy BGS geophysical data, comprising bathymetry, shallow penetration seismic and seabed reflectivity data.
- Legacy BGS rock and sediment sample data.

Geological research of the study area is mainly confined to broad scale maps and reports prepared by the British Geological Survey (BGS) and the Bureau de Recherché Géologiques et Minières (BRGM). There is one major study of the Regional Environment Assessment (REA) area comprising a PhD Thesis on the marine geology of the Normandy-Brittany Gulf by Hommeril (1967). Other peer reviewed papers were also accessed that focussed on more regional descriptions of the sedimentary processes of the English Channel, notably Reynaud et al. (2003). Most of the data used in all of these reports and publications is French.

The BRGM report comprises a map of the surficial sediment distribution of the English Channel at 1:500,000 scale (Vaslet et al., 1979) and a brief report (Auffret et al., 1979) that is in both French and English, on the sediments present and their origin. The BGS maps are of the solid (bedrock geology) and seabed sediment distribution at a scale of 1:250,000. The data base for these is mainly French, with some limited BGS samples and seismic data. There are no specific reports accompanying the maps, , but a description of the area is included in the BGS publication, 'The Geology of the western English Channel and its Western Approaches (Evans, 1990) .

The main resource on the area is the PhD Thesis - Hommeril P. 1967. ETUDE DE GEOLOGIE MARINE CONCERNANT LE LITTORAL BAS-NORMAND ET LA ZONE PRE-LITTORALE DE L'ARCHIPEL ANGLO-NORMAND (STUDY OF THE MARINE GEOLOGY ON THE COAST OF LOWER NORMANDY AND THE OFFSHORE AREA OF THE CHANNEL ISLANDS). This document was identified by Andrew Casebow and ordered by BGS in October 2009. However, it took over five months to arrive (in March 2010), thus there has been only a very short period in which to translate and interpret the contents and results. The Thesis is 305 pages long with over 100 Figures. The translation was undertaken by the author of this report, who is not a native French speaker; additionally there was insufficient time to have this translation checked and verified. Thus there may be errors in understanding.

The above data sources provided most detailed base maps on the geology of the REA area. However, most of these are old (circa 1960's) and although the data is important for identifying the distribution of seabed sediment rock and sediment the knowledge of sedimentary processes in the marine domain has advanced significantly since their publication. Thus other more regional reports and papers have been used to address this gap in understanding. Obviously, whereas these provide a regional context, they may not specifically address the local environment of the REA area.

Additional reports (research theses) were identified (e.g. M'hammdi, 1994; Quesney, 1983; Reynaud, 1996; Walker, 2001) however, these were not available for review. Additionally, they are in French.

4.3 Data availability: sampling and geophysics

Sample data within the area is mainly confined to dredges, acquired by Hommeril (1967) during four surveys carried out in May 1962, May 1963, June 1964 and May 1966. Additional samples are rock cores acquired by BGS in July 1972 (Figures 4.3.1 and 4.3.2).

Some limited seismic data are available from BGS, comprising echo sounder and pinger (Figure 4.3.3). The hard seabed in the REA area results in limited acoustic penetration, thus there is little information on the thicknesses of the seabed

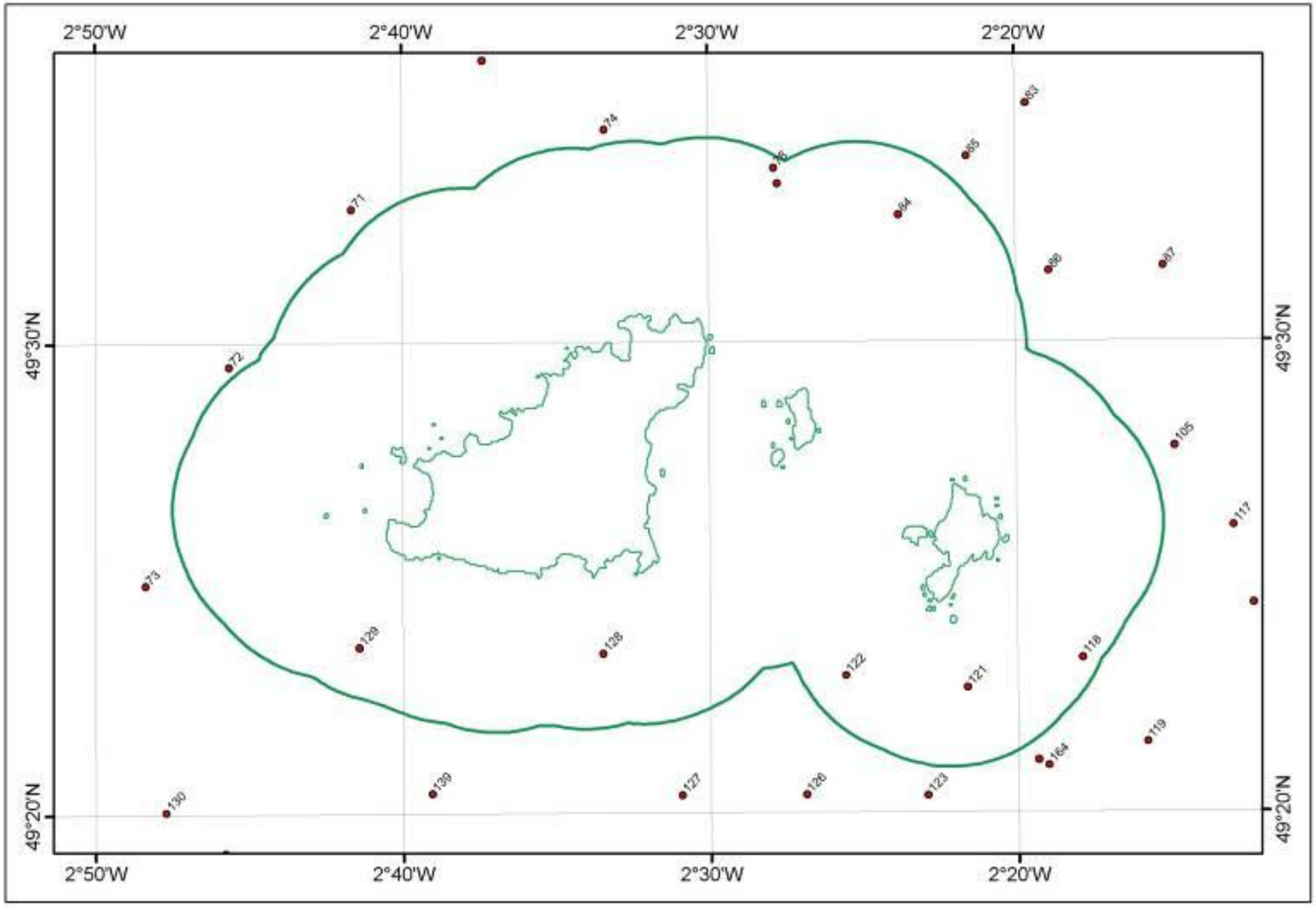

Figure 4.3.1 BGS samples

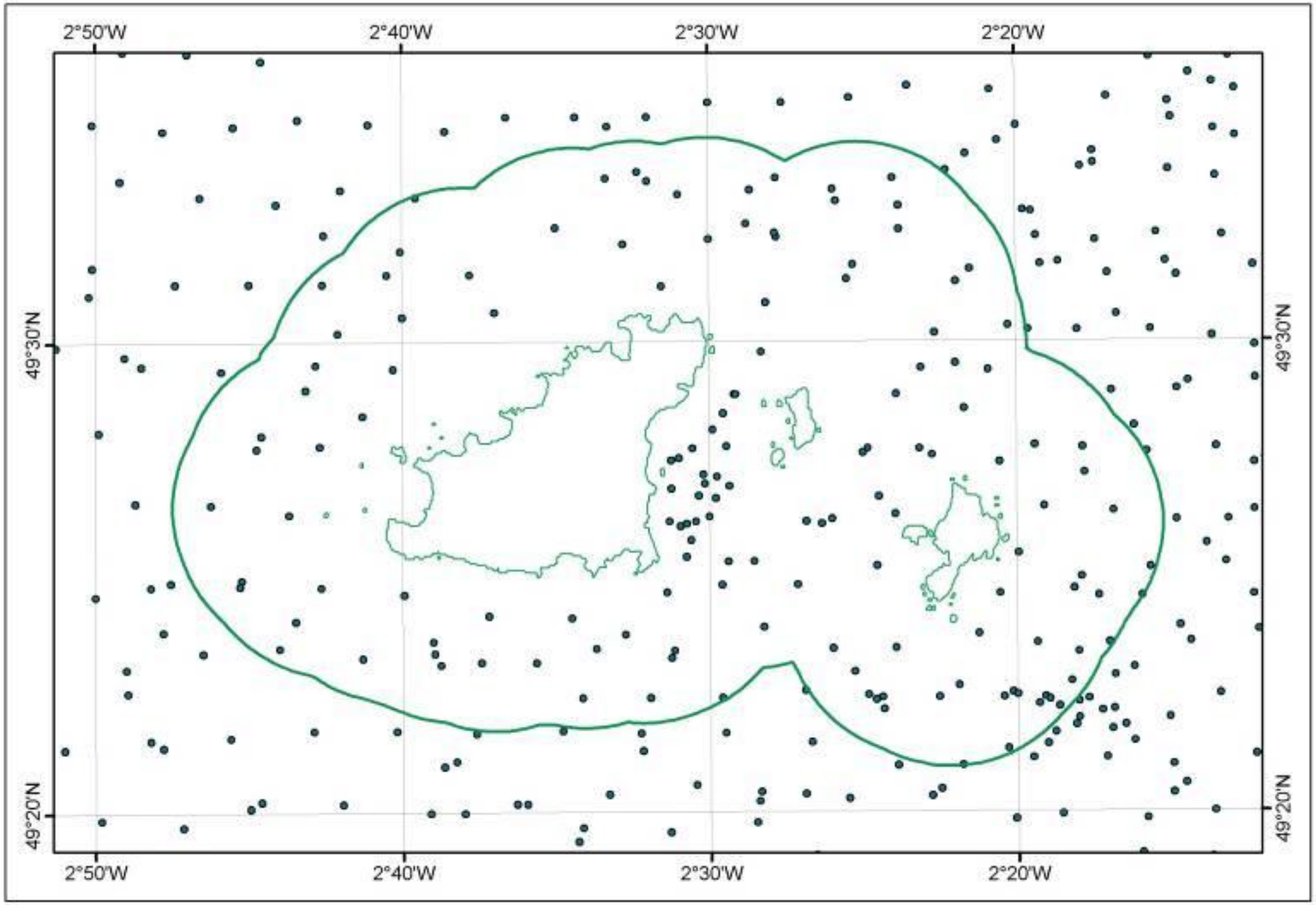

Figure 4.3.2 Non BGS samples

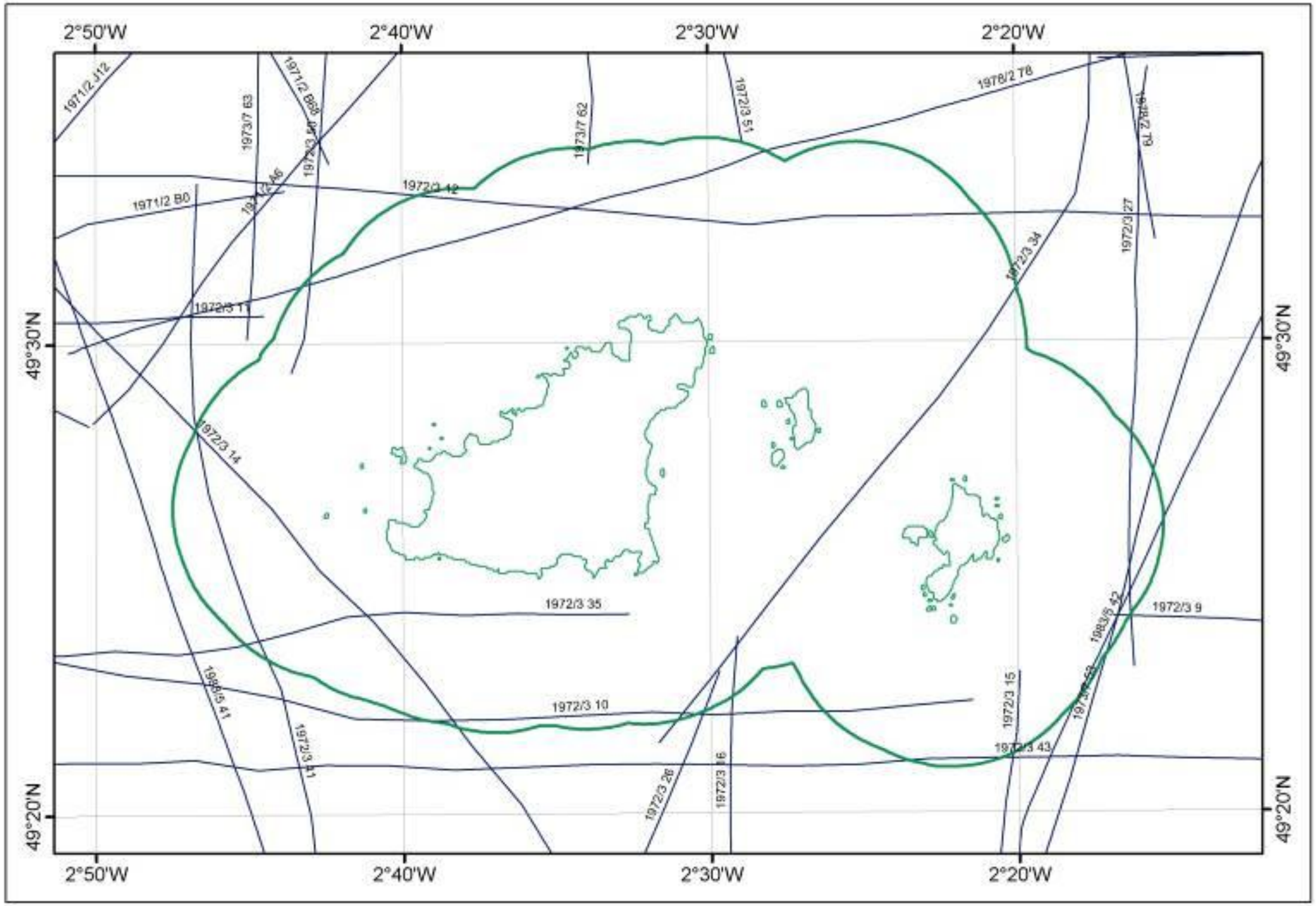

Figure 4.3.3 BGS seismic data (labels indicate year of survey, survey number and line number – e.g. 1972/3 35)

sediment nor of the rock structure of the sub-seabed. Echo sounder profiles over the Great Bank are published by Hommeril (1967) in his thesis.

As the sampling and geophysical acquisition was undertaken before the Global Positioning System (GPS) was available, position fixing is by the hyperbolic radio navigation system DECCA NAVIGATOR. Thus the positional accuracy of the sample locations is of the order of ±100 m. The dredge samples were acquired over seabed distances of 50 to 100 m. The dredge sample sites are between 1 and 5 kilometres apart. With the dredging, where no sample was recovered at the first attempt, a second deployment took place, if this too was unsuccessful, then the site was interpreted as having no sediment present.

4.4 Bathymetry and Current Circulation

The study area comprises 720 km^2 of land and sea. The land areas of Guernsey (78 km^2) Sark (5.5 km^2), Herm (2 km^2) and Jethou (0.2 km^2) total approximately 86 km^2. Thus the sea area is approximately 630 km^2.

Located on the western margin of the Normandy-Brittany Gulf the REA area lies on the boundary with the western English Channel. There is one large island, Guernsey and several small ones to the east, Sark, Herm and Jethou. These islands generally have a low topography, and are bounded by rugged coastlines and shallow offshore shoals. Only Herm has an appreciable accumulation of sand on its southern margin.

Water depths are up to 60-65 m (Figure 4.4.1). Around the islands the water depth increases rapidly to 20 m and then more gradually to 40 m. To the west of Guernsey water depths offshore increase fairly rapidly to 60 m.

There are two major controls on sedimentation: wind driven waves, that mainly affect the shoreline and are dominated by westerly swells, and offshore tidal currents that are dominant.

Figure 4.4.2 shows current circulation in the western English Channel and around the Channel Islands. A description of the tidal processes is provided in Chapter 5.

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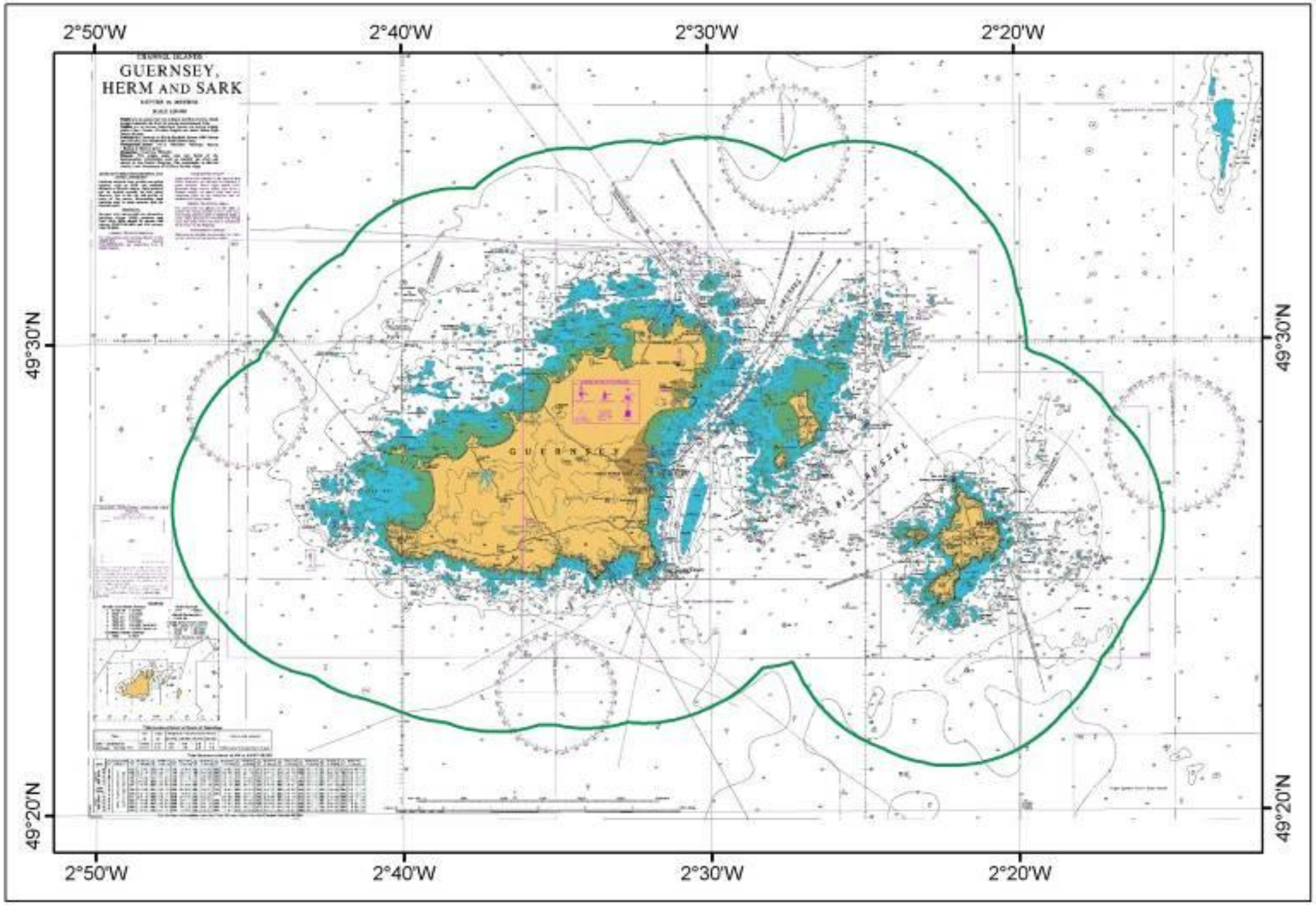

Figure 4.4.1 Admiralty Chart 3654 of the Guernsey REA (Green line is the 3 mile Territorial Boundary)

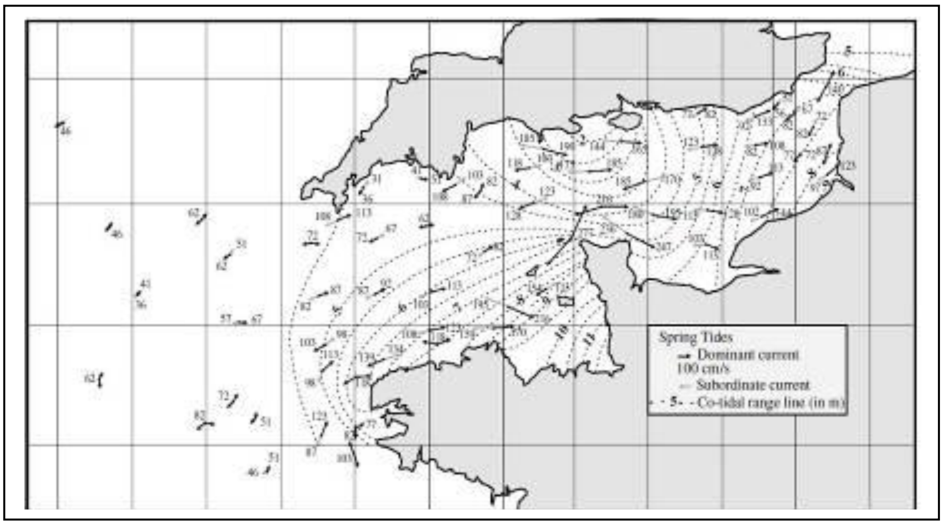

Figure 4.4.2 Present-day surface currents in the English Channel. Spring maximum current vectors using data of the SHOM (1968) (From Renaud et al, 2003)

4.5 Solid (bedrock) Geology

This section refers to both the islands and the offshore (Figure 4.5.1). On Guernsey, Sark and Herm only rocks of Precambrian age are exposed. Thus descriptions of these onshore exposures are readily available.

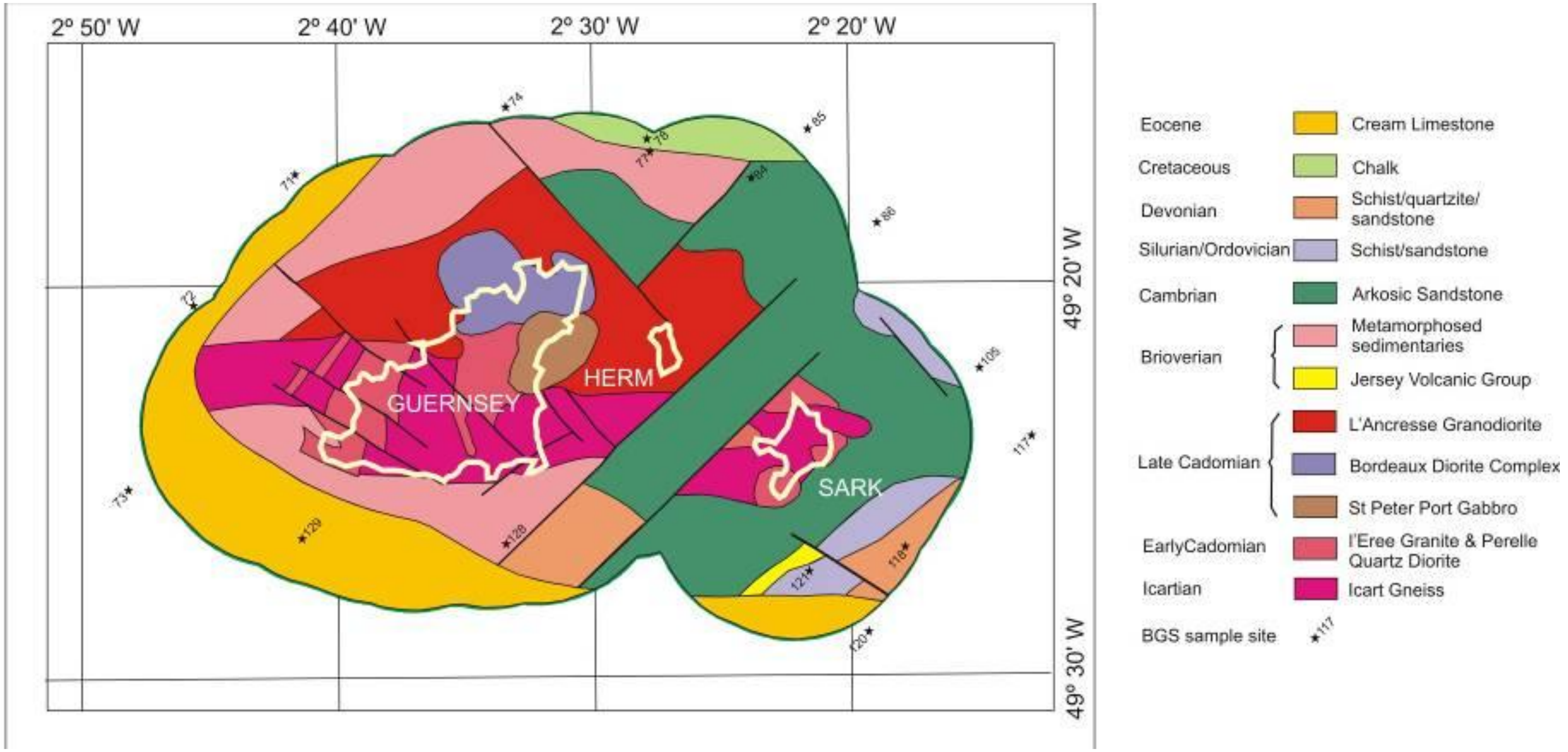

Figure 4.5.1 Guernsey – Solid (bedrock) geology and BGS sample site locations of bedrock (for description of units see text)

Descriptions of other Precambrian rocks, such as those of the Jersey Volcanic Group, may also be obtained from their onshore exposures. Descriptions of younger rocks may be obtained from other adjacent islands, such as Alderney (Alderney Sandstone) and from farther afield in France. For Mesozoic and Tertiary rocks there are some short cores (centimetres long) acquired from the offshore that provide some indication of the likely lithologies present. Thus when reading this section it should be borne in mind that there is a lack of good *in situ* information on the offshore bedrock, and that this compromises our ability to give anything but a 'possible-to-likely' idea of the rock types present. Not only is the data on the rock lithologies limited, but their distribution is too. Lithological boundaries within the Precambrian and Palaeozoic rocks are mainly based on dredge samples. The distribution of the Mesozoic and Tertiary is better constrained, by the seismic data, especially their contact with the older rocks. This is because the internal structure of older formations is poorly imaged using acoustic (seismic) technology. These older rocks have been greatly altered and have undergone lithification that cements them, thereby increasing rock hardness and reducing internal velocity variations upon which the seismic methodology depends.

4.5.1 Basement rocks.

The Armorican massif, bound to the north by the Ouessant-Alderney Fault zone and comprising Northwest France and the Channel Islands is formed of Precambrian rocks with minor Palaeozoic outliers and Variscan intrusions. The Precambrian rocks represent the lower and middle crust and are divisible into two units: the older, Cryogenian-Orosinian, which predominates in the area of southern Guernsey and Sark (Icartian and Early Cadomian) and the younger Neoproterozoic 3 (Late Cadomian Igneous Complex) exposed in the north of Guernsey and Herm, and which rests unconformably on the Cryogenian-Orosinian (Evans, 1990; Gibbons and Harris, 1996; Roach et al., 1991). The Cryogenian-Orosinian rocks comprise: granitic and quartz dioritic orthogneiss and migmatites, schist and amphibolite deformed during orogenic episodes (2000 Ma and ?[1]650 to 700 Ma). The ?Brioverian Supergroup (?Cryogenian) strata comprise sandstone with siltstone and conglomerate, overlain by dark siltstone and mudstone. Evans (1990) describes the sequence as turbidites, deformed between 700 and 650 Ma. The deformation folded the rocks into northeast to east trending structures, including the Ouessant- Alderney fault zone, during a period of crustal growth (Lagarde et al., 2003). Granites, granodiorites, diorites and gabbros were emplaced before and after the main tectonism (Evans, 1990, Gibbons and Harris, 1996; Roach et al., 1991). Lees et al. (1989) describe the occurrence of approximately nineteen dykes of albite-dolerite (Perelle-type albite-dolerites) that trend east northeast and occur only in association with the Cryogenian-Orosinian deposits, suggesting that they were emplaced between the

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[1] Denotes uncertainty in the age of a rock unit or its' affiliation

two orogenic episodes (Cadomian and Hercynian) during a period of crustal stretching. These dykes do not show deformational fabrics. They do, however, exhibit a low temperature metamorphic assemblage of minerals, including chlorite, albite, epidote, prehnite and pumpellyite, which give rise to characteristic pink feldspathic patches. Lees et al. (1989) suggest that these albite dolerites are representative of mildly alkaline basaltic magmatism.

Basement weathering has been observed on Alderney, for example Rathan (1983) reports on the occurrence of weathered and exfoliated granodioritic and felsitic basement. Went (1991) also recognises basement weathering, which takes the form of uniformly decomposed areas in homogeneous diorite host rocks and corestone weathering in jointed porphyry dykes. This weathering has implications for the off-shore deposits, especially on their bearing capacity and excavation potential. However, no data have been identified that establishes how extensive this weathering might be in the marine environment.

Table 4.5.1 BGS offshore Basement samples (for location see Figure 4.5.2)

Sample No	Sediment thickness (m)	Sediment type	Rock thickness (m)	Rock description
74	0.1	Sand	0.1	Grey clay
77	0.1	Fine sand and pebbles	0.2	Grey Quartz sandstone
128	0.1	Sand	0.2	Granite

4.5.2 Cambrian.

The Cambrian, comprises the Alderney Sandstone Formation, a fluviatile sequence present offshore to the east of Guernsey. The Formation has been mapped in detail on the eastern part of Alderney Island, from where this description is taken (Rathan, 1983).

The sediments on Alderney are the remnant of a major series of deltaic sandstones laid down from an eastward- flowing river after the denudation of the Cadomian mountains. At its type section the Formation is nearly 800 m thick and comprises red and yellow arkosic sandstone with rare siltstone. Rathan (1983) subdivided the sequence into four lithofacies, which characterise the different depositional environments. Whereas the extent of each individual facies has not been mapped beyond Alderney, their characteristics are summarised in Table 4.5.2 to provide an indication of the rocks types likely to be present offshore. The presence of thrusts in these deposits indicates a potential for movement upon down-dip excavation.

Table 4.5.2. Characteristics of the Alderney Sandstone.

Facies	Depositional Environment (increasingly distal).	Lithological characteristics
A	Debris flows and localised sheet flows	The only facies with a normal sedimentary contact on the basement. Approximately 15 m thick. 3 m of structureless, matrix supported lithic breccias over sedimentary contact. The subangular, occasionally rounded, clasts of the breccias are mostly of felsites, but also of quartz and granodiorite. The clasts predominantly fine upwards. The matrix is poorly sorted, coarse and angular. Planar cross-bedded and cross laminated, pebbly, fining upward (to medium grained) sandstones overlie the breccias. There is a notable absence of channelling, or scouring in these beds. Occasional thin, red, micaceous siltstones are observed.
B	Multiple or continuous, incised, stream flows	Above a thrust contact and quartzitic sandstones, which show fining upward sequences, planar cross stratification and planar lamination. The thrust is interpreted as being of small movement, along the original sedimentary contact. Stream lain feldspathic sandstones and conglomerates (orthoconglomerate) overlie the quartzitic sandstones. These are partially stratified and comprise rounded, pebble size clasts in a gritty matrix. Large scale, trough cross-bedding is present. Euhedral and rounded feldspar clasts of up to 7 cm diameter are characteristic.
C	Sheet flow dominated intersection zone	Sheet flood sandstones, comprising finding upward sandstone units. Thin (10 to 40 cm) fining upward horizons of oxidised siltstone and fine sandstone interdigitate with the sandstones. Areas of considerable cross-bedding in stratified gravel horizons.
D	Fan sweeping braided streams	Regular interdigitation of coarse-grained stream-lain deposits of up to 1 m in thickness and finer-grained floodplain horizon (~10 cm). These deposits commonly represent scour and fill sequences with large-scale scour features and laminations parallel to the scour base, trough cross-bedding with steeply dipping foresets and laterally impersistent silt drapes. Planar cross bedding is also abundant.

Offshore samples from the offshore area of the Alderney Sandstone comprise schists (Table 4.5.3).

Table 4.5.3. BGS offshore Cambrian samples (for location see Figure 4.5.2).

Sample No	Sediment thickness (m)	Sediment type	Rock thickness (m)	Rock type
84	0.1	Gravel	0.2	Schist
86	No record		0.2	Grey schist

4.5.3 Ordovician to Carboniferous.

Undivided Ordovician-Silurian strata are identified on the BGS/BRGM (2000) 1:250 000 scale Guernsey Solid Geology Map located to the southeast and northeast of Sark. BGS samples comprise mainly schist (Table 4.5.4). From France, Roach et al. (1991) describe the occurrence of limestone and suggest that these deposits were generally laid down in a shallow, marine environment. There is clearly some uncertainty regarding the nature of these strata offshore.

Devonian strata overlie Ordovician-Silurian beds to the southeast of Guernsey and to the southeast of Sark (Figure 4.5.2). Only one sample, a red clay, has been recovered (Table 4.5.4). The BGS/BRGM (2000) Guernsey Solid Geology map also indicates the presence of a fault bounded basin of undivided Devonian to the south of Guernsey. From France, Roach et al. (1991) describe these deposits as a Culm-type sandstone and mudstone sedimentation with occasional limestone, which formed in isolated sedimentary basins.

Table 4.5.4. BGS offshore Ordovician to Carboniferous samples

Sample No	Sediment thickness (m)	Sediment type	Rock thickness	Rock type
105	0.1	Sand	0.2	Grey Schist
117	No record		0.1	Schist
118	No record		0.3	Red clay
121	0.1	Sand and limestone pebbles	0.2	Schist

4 5.4 Permo-Triassic.

Not represented in the area.

4.5.5 Jurassic.

Not represented in the area.

4.5.6 Cretaceous.

To the north of Guernsey, Late Cretaceous Chalk of Maastrichtian age overlies Brioverian strata with marked unconformity (Figure 4.5.2). Short cores of this unit acquired by BGS both within and outside of the REA area are described as soft to hard in character (Table 4.5.5).

Table 4.5.5. BGS offshore Cretaceous samples (for location see Figure 4.5.2).

Sample No	Sediment thickness (m)	Sediment type	Rock thickness	Rock type
78	No record		0.3	White clay
85	0.2	Sand, Gravel & Flint pebbles	0.2	Chalk

4.5.7 Tertiary.

On the BGS/BRGM (2000) 1:250 000 scale Guernsey Solid Geology map, Lutetian and Bartonian (Eocene) limestones are found on the western and southern boundary of the REA area (Figure 4.5.2). BGS samples include white marls, Chalk and limestone. Outside of the REA area Evans (1990) reports that these rocks may comprise biosparite and biomicrite, locally silty, and with glauconitic. The bioclasts largely comprise foraminifera, bryozoan and echinoid fragments with calcareous algae and molluscan debris. The deposits were laid down in warm, shallow seas with local hypersaline basins.

Table 4.5.6. BGS offshore Tertiary samples (for location see Figure 4.5.2).

Sample No	Sediment thickness (m)	Sediment type	Rock thickness	Rock type
71	No record		0.1	?Marl
72	No record		0.1	Chalk with clay and sand

73	No record		0.1	?Limestone
120	No record		0,1	White marl
129	No record		0.1	Chalk

4 5.8 Quaternary.

Keen (1978) reported from Guernsey that terrestrial deposits present are solely the product of periglacial deposition. Loess is the most widespread deposit, occupying plateau surfaces and typically, orange brown, structureless, silt. Loess deposits are around 5 m in thickness in the east of Guernsey, but decrease in thickness to the west. This is indicative of an easterly source for the sediment. Calcareous concretions are found at St Martin's Point, Guernsey, where the loess has yielded non-marine mollusc. Head deposits can be subdivided into coastal and inland types on the basis of the grain size. Deposits at the coast comprise a rubble head, as described by Warren, J.P. and Mourant, A.E. (1937) and Collenette, A., (1916). The maximum thickness of the rubble head is controlled by the height of the former cliffs (a ratio of ~1:4) against which the head is banked (Keen, 1978). The inland deposits comprise loess with weathered fragments of the underlying rock. These deposits have considerable areal extend, but rarely exceed 3 m in thickness. Below the plateau there is a transition from loess to loessic head and the extent of loessic Head is influenced by the ground slope angle. At some locations, which occur at specific elevations (49 – 55 m and 66 m above sea level), e.g. Longue Rocque, Guernsey, the loessic head contains rolled pebbles, which are considered to be derived from former raised beaches (Keen, 1978).

Marine deposits, largely locally-derived, are of varying proportions of well-rounded flint cobbles that originally formed the raised beaches. The tidal range of the Pleistocene was probably comparable with the current range (maximum 12 m Jersey and 10 m Guernsey).

4.5.9 Structural setting.

This area was subject to the Caledonian (Late Silurian to Early Devonian) and the Variscan orogenies (Devonian to Carboniferous), that broadly led to north-south compression and thrusting (east northeast striking thrusts). The east northeast thrusts were subsequently dissected by a series of south southeast trending strike slip faults (Figure 4.5.2) (Evans, 1990). Subsequent tectonic movements were largely accommodated by movement along these pre-existing structures. Of particular note in the REA area is the northeast striking, Leon Thrust to the northwest of Guernsey, which bounds the basement outcrop on its north-western boundary and a further Precambrian thrust close to the southern boundary of the basement outcrop (BGS/BRGM, 2000). By the late Permian to Early Triassic, crustal rifting led to the formation of fault-bounded basins, which accommodated the subsequent phase of sediment deposition during the Triassic and Jurassic, until uplift occurred during the Middle Jurassic. As a consequence of these movements, on the southern side of the Channel, the presence of Mesozoic rocks is much reduced, or they are absent south of the reactivated Cotentin-Ushant line, or the Alderney-Ushant Fault system, which bounds the Mesozoic basin to the south. A deep structure associated with the Hurd Deep, to the northwest of the REA area, is controlled by the Median Channel Fault, limiting a basement block to the north and a half-graben to the south, which could be 7 km deep (Lericolais et al., 1996). The Mesozoic strata dip to the northwest, but are offset by steeply dipping south-facing normal faults. They are overlain by subhorizontal Upper Cretaceous and Tertiary strata (~ 700 m thick). Short, upright folds and faults in the Mesozoic strata indicate that the mid Channel faults were later reactivated (Lericolais et al., 1996). The Median Channel Fault, which is situated over a syncline between two normal faults, has been interpreted as one of tectonic inversion (Lericolais, et al., 1996). During the late Jurassic to Cretaceous crustal stresses associated with the opening of the Atlantic, led to a period of uplift and rifting. English Channel basin development and initial planation of the area is attributed to the mid-Tertiary (Oligocene- Miocene) Alpine uplift (Lagarde et al., 2003). Within the English Channel, a gently westerly dipping planation surface is thought to date to the Neogene (Lagarde et al., 203).

4.5.10 Seismicity.

Lagarde et al. (2003) reported that the main historical earthquakes in the Channel are associated with the Cotentin peninsula; with events in 1853 (Coutances with a magnitude of 5.8), 1889 (Cherbourg, with a magnitude of 5.6) and earthquakes between Jersey and Normandy in 1926 and 1927 (estimated magnitudes of 5.5). The present day seismicity of the English Channel is moderate with an event of 5.2 expected every 100 years (Lagarde et al., 2003). The location of seismicity is due to reactivation along pre-existing northwest and east northeast trending, fault zones (Lagarde et al., 2003).

4.5.11 Hydrogeology.

Robins et al. (2000) and Robins and Rose (2005) established that the groundwater resources of Guernsey are derived from superficial Quaternary deposits, including head, loess and raised beach deposits). Surface water recharge to these deposits flows from the high ground via the fractured rock towards springs on the south and northwest coast. Deeper groundwater flow paths are limited to the depth of dilated fissures (a maximum of about 35 m depth). The upper and lower flow paths form part of a continuum in the weathered bedrock. Robins et al. (2000) did not find any evidence to support suggestions of recharge from the French mainland.

4.5.12 Evidence for recent sea-level change.

Some of the caves of Guernsey appear to provide evidence of sea-level change. Collenette (1916) described the Moulin Huet cave as being formed in three stages: Cave cut at the level of the 25’ beach, which is evident elsewhere along the coast, in ?gouge fill material. Cliff material is washed away by being undercut and the cave becomes an open gully and pebbles were washed in and out. Sea level fell and the cave developed through further rock falls. Subsequently, relative sea level rose to the 52’ level. The cave was filled with beach stones. Then sea level fell again and the upper pebbles became cemented and form the current roof of the cave, which was reactivated by erosion from the base. Whilst there is no dating associated with this work, it indicates sea-level changes of ~17 m. A simpler scenario was presented by Warren and Mourant (1937) for a collapsed cave, nearly filled with stalactites intermixed with snail shells on a carbonate cemented floor. Warren and Mourant postulated the following sequence: erosion of a composite dyke (Hornblende schist) by the sea of the 50’ raised beach, possibly followed by the 25’ raised beach and associated with deposition of beach material; infilling of the cleft with head (clayey rock breccias) and capped by loess; cementation of the head; erosion of less cemented lower material, leaving the void with a roof of firmly cemented breccias; formation of stalactities and stalagmites; collapse of breccias arch of cave roof; denudation, except for heavy blocks, as sea level fell.

Keen (1978) defined the raised beaches as: 30 m, 18 m and 8 m and suggested the chronology tabulated below:

Table 4.5.7: Quaternary events in the Channel Islands (derived from Keen, 1978).

	Stage	Event	Evidence
Upper Pleistocene	Devensian	Head and loess deposition	Overlies 8 m raised beach deposits
	Early Devensian	Sea level fall, suspected to be gradual	Upper cultural complex at La Cotte de St Brelade
	Ipswichian/ Devensian	Marine transgression	Deposition of Fliquet peat and blown sand over 8 m raised beaches
	Ipswichian	Marine deposits of the 8 m beaches	Pollen bearing deposits of La Cotte de St Brelade
	Early Ipswichian	Marine transgression	Trimming of the 8 m rock platform.
Middle Pleistocene	Late Wolstonian	Sea level fall.	Presence of humans (La Cotte de St Brelade) in Jersey, indicates sea-level fall exposing land in the shallow Strait with France. Head underlies the 8 m

			beach deposits of the Ipswichian. Probable deposits of loess
	? Wolstonian	18 m erosional surface	Levels of occurrence indicate a separate event to the 30 m surface. Beach deposits.
	Hoxnian	30 m erosional surface	30 m erosion surfaces and beaches. Dating assumed from estuarine deposits around 30 m above OD at Kirmington, Lincolnshire; Nar Valley Norfolk, and Swanscombe, Kent.
	Pre-Hoxnian	High sea level stands. Possible commencement of the 8 m platform	Erosional surfaces at 49 – 55; 66 and 100 m above mean sea level. Beach pebbles in head at these levels.

As noted above, the tidal range of the Pleistocene was probably comparable with the current range (maximum 12 m Jersey and 10 m Guernsey).

4.5.13 Periglacial Conditions.

Detail with respect to the Pleistocene and periglacial deposits of the English Channel land areas was presented by Bates et al. (2003) and Murton and Lautridou (2003) presented information with respect to the recent advances in understanding periglacial processes in the Channel area. The latter was primarily focused on modelling and demonstrated ice-segregations and consequential permafrost damage in chalk at the boundary between the active and frozen layers. The modelling also showed how permafrost development is likely to have contributed to rapid valley incision. Other aspects of this research examined thaw-related deformation.

4.6 Offshore Sediment Distribution

Because of the different nationalities mapping the seabed there are a number of different sedimentary classification schemes presented in the REA report. Each sediment is a mixture of grains of varying sizes. There have been different definitions of terms used for the different sizes of individual grains and similarly differing definitions for the terms used to describe the relative proportions of different grain sizes. As noted there are three main sources that provide the basis for our present knowledge of the distribution of sediment, two are regional (BGS and BRGM) and one is a local study (Hommeril, 1967).

4.6.1 BRGM Surficial Sediment Map (Auffret et al., 1979; Vaslet et al., 1979) (Figure 4.6.1)

The French map is based on data acquired up to 1977. It is based on a sediment type defined from both its grain size *and* its calcium carbonate content.

Influence of grain size: There are four main categories of sediment: pebbles, gravel, sand and mud. These categories enhance the importance of smaller particles (lutites) on one hand, and coarse material on the other. It is these extremes that predominantly determine the physical and chemical properties of the deposits and hence their environmental characteristics and possible diagenetic processes. If heterogeneous sediment is both coarse and muddy, the muddy characteristics comes first and the sediment is classified as a muddy sediment and designated, for instance, as a muddy lithoclastic gravel if of such nature.

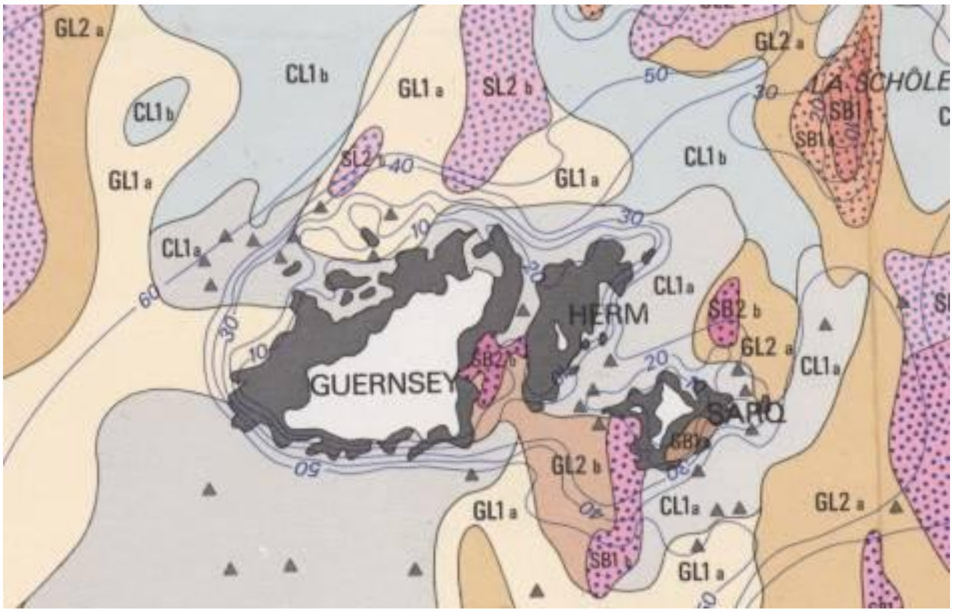

Figure 4.6.1 BRGM map of sediment distribution in the Guernsey region (see text for explanation)

Influence of the calcium carbonate content: In the study area, the calcareous fraction of the sediment is mainly of organic origin, mostly zoogenic (derived from living organisms – animals rather than plans). Fragments of limestone are rare and do not noticeably modify the nature of the sediment. There are no muddy sediments. Three distinctions have been made respectively at 30, 50 and 70 % of the total sediment, including both lutites (clays) and the coarse fraction over 2 cm as well.

Thus the following four categories of deposits have been identified:

lithoclastic sediments (less than 30 % $CaC0_3$);

litho-bioclastic sediments (30 to 50 %);

bio-lithoclastic sediments (50 to 70 %)

bioclastic sediments (more than 70 %).

Each sediment has a specific key symbol that identifies its' major and secondary grain size and carbonate content. The two first letters correspond to the main grain size and to its lithoclastic (L) or bioclastic (B) nature.

e.g. GL lithoclastic or litho-bioclastic gravel.

SB = bio-lithoclastic or bioclastic sand.

The word 'lithoclastic' is used in its very broad sense, meaning all the rock fragments whatever their nature.

The following figure, either 1 or 2, is related to the calcium carbonate content, either low (l) or high (2), in the deposits which are mainly lithoclastic or bioclastic, such as

The small letters a, b, c, d differentiate the sediment types according to their secondary grain size:

a = pebbly
b = gravelly
c = coarse sand
d = medium sand
e = silts

In the study area seven sediment types are present (Figure 4.6.1):

CL1a Lithoclastic Pebbles (Pebbles +Carbonate >70%; Carbonate < 30%; lutites < 5%)

GL1a Lithoclastic-pebbly gravel (Pebbles + Carbonate > 15%; Carbonate <30%; lutites < 5%)

GL2a Litho-bioclastic pebbly gravel (Pebbles + Carbonate >15%; Carbonate 30 - 50%; Lutite <5%)

GL2b Litho-bioclastic gravel (Pebbles + Carbonate <15%; Carbonate 30 - 50%; Lutite <5%)

SL2b Litho-bioclastic gravelly sand (Gravel > Pebbles + Carbonate; Sand and lutites > 50%; Carbonate 30 - 50%; lutites < 5%; 15 to 50% at 2mm)

SB1b Bio-lithoclastic gravelly sand (Gravel > Carbonate + Pebbles; Sand and lutites > 50%; lutites < 5%; 15 to 50% at 2mm; Gravel > Carbonate + Pebbles)

SB2b Bio-clastic gravelly sand (Gravel > Carbonate; Sand and lutites > 50%; lutites < 5%; 15 to 50% at 2mm)

The main sediment areas covered and bedrock at seabed are as follows

Rock = 100 km^2

CL1a = 322 km^2

GL1a = 135 km^2

GL2b = 40 km^2

GL2a = 18 km^2

The area of exposed bedrock is mainly around the islands of Guernsey, Sark and Herm. The lithoclastic pebbles of sediment type CL1a cover over 50% of the seabed. They found mainly to the south of Guernsey and occupying an arc from the NW of Guernsey to the SE of Sark. These sediments occupy 50% of the seabed area. Sediments of Lithoclastic pebbly gravel – GL1a – occupies 25% of the seabed and lies in patches to the N, W and S of Guernsey. An area of GL2b - Litho-bioclastic gravel - lies to the south of Guernsey and GL2a - Litho-bioclastic pebbly gravel - to the NE of Sark. Areas of SB2b - Litho-bioclastic gravelly sand – are located to the east of Guernsey and the to the NE of Sark, where they form sand banks; notably the Great Bank off Guernsey. South of Sark there is an area of SB1b - Bio-lithoclastic gravelly sand. Small areas of SL2b -Litho-bioclastic gravelly sand – are located on the northern margin of the REA. A small patch of SB1b -Bio-lithoclastic gravelly sand is found just offshore to the SE of Sark. Thus the large majority of the area is covered with pebbles and gravel, with bioclastic sands forming shoal areas and other, more restricted areas of seabed.

4.6.2 BGS sediment distribution map (Figure 4.6.2)

The BGS map is basically an interpretation of the French sediment map of Auffret et al (1979). The areas of seabed with bedrock exposed are similar, but the other areas with sediment are somewhat different because BGS use a different classification of sediment based on a modification of Folk (1954).

Folk (1954) is a common sediment classification. It groups grains into mud, sand and gravel on the basis of their diameter, with the boundary between mud and sand size grains at 63µm (0.063mm) and the boundary between sand and gravel size grains at 2mm. The relative proportion of the grains in the three categories is then used to

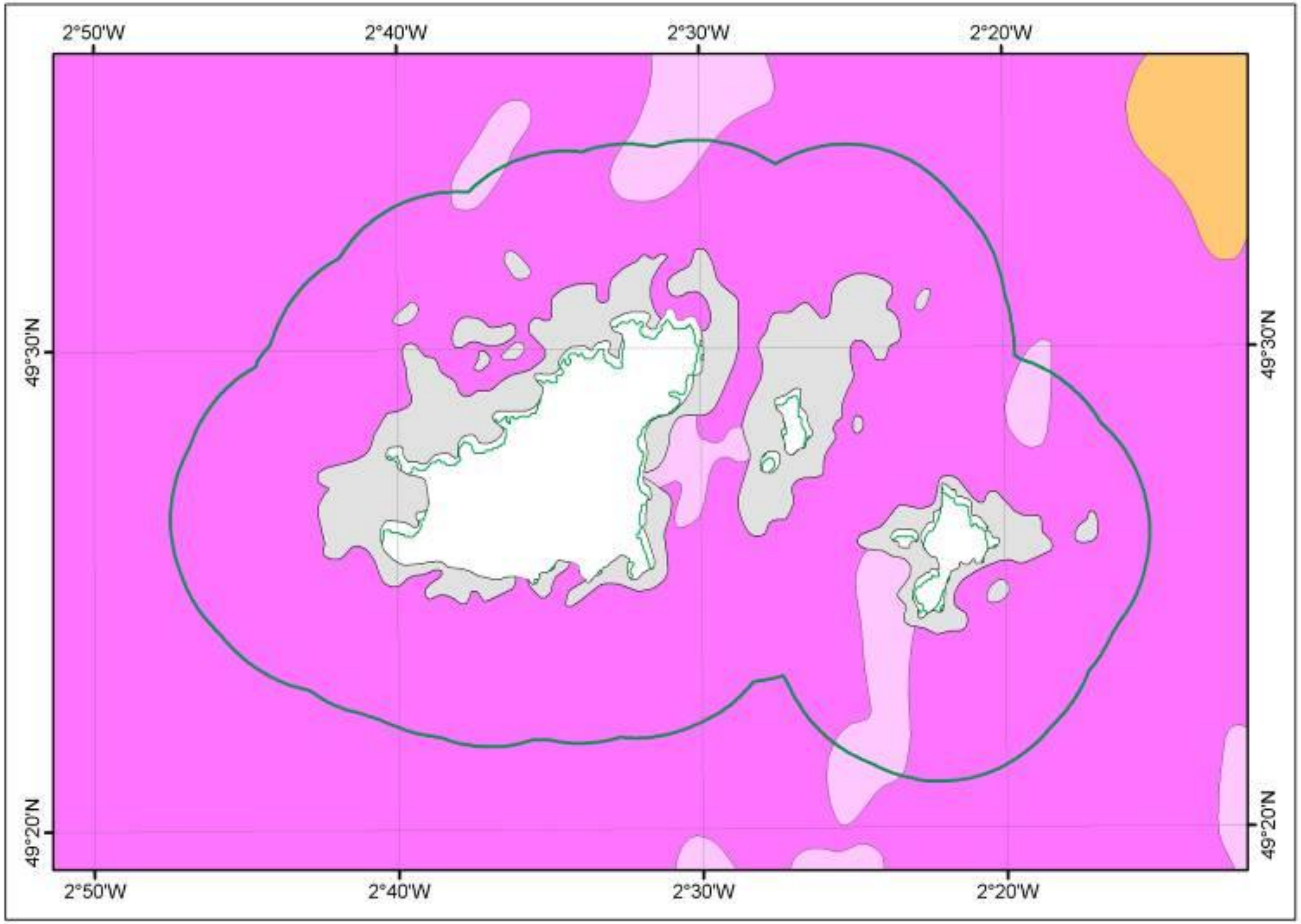

Figure 4.6.2 Guernsey –BGS sediment distribution map (grey is bedrock, dark pink is gravel and pale pink is sandy gravel.

describe the sediment and is displayed in a diagram commonly called a “Folk triangle” (Figure 4.6.3). This classification with 15 terms to describe the seabed sediments is used by BGS for all of its 1:250,000 offshore sediment distribution map series.

For the classification, it is important to realise that the “Folk triangle” diagram is not to scale rather, it is a topological representation of the subdivisions. If the modified classification was drawn to scale the areas of each seabed sediment class change dramatically. It shows clearly that the addition of only a small amount of mud to a coarse-grained sediment will result in reclassification to “mixed sediment”. This grouping of classes reflects the natural environment, because most seabed sediment samples occur along the Mud to Sand axis or along the Sand to Gravel axis and, therefore, plot in the middle of the triangle.

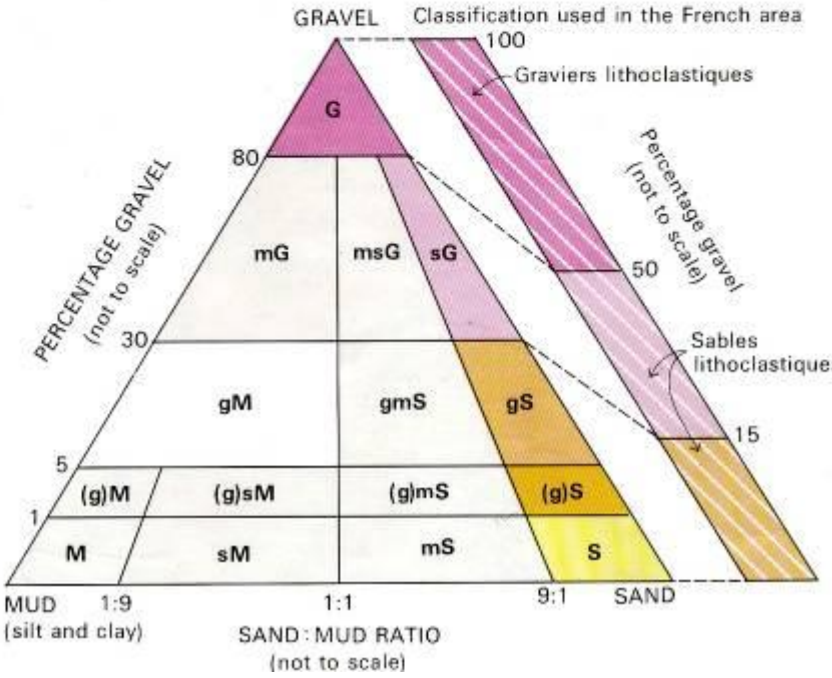

Figure 4.6.3 Folk sediment classification with comparison of French classification used on the BRGM map.

On the BGS sediment maps the main map only displays the sediment grain size (Figure 4.6.1). The Total carbonate content of the sediment is included as a 1:1,000,000 scale inset (Figure 4.6.4). On the map of the Guernsey REA the majority of the study area is composed of gravel (more than 50% of sediment). There are very small patches of sandy gravel to the south of Sark, north of Guernsey and between Guernsey and Herm. Two of these correspond to sand banks as in with the French map. The seabed surrounding the islands is predominantly sediment free with bedrock at the seabed or beneath a very thin sediment veneer.

Referring to the total carbonate content of the sediment it can be seen that sediment over the most of the offshore area has a content of between 0 to 30%. There are small areas with carbonate contents between 30 and 50% and even more limited areas between 50 and 70%. As with the French map the sediments with the highest carbonate concentrations are associated with sand banks, the east of Guernsey and NE of Sark. These areas correspond to the SB2b - Litho-bioclastic gravelly sand – of the French. The sediment with 30 to 50 % total carbonate correspond to the GL2b - Litho-bioclastic gravel – of the French.

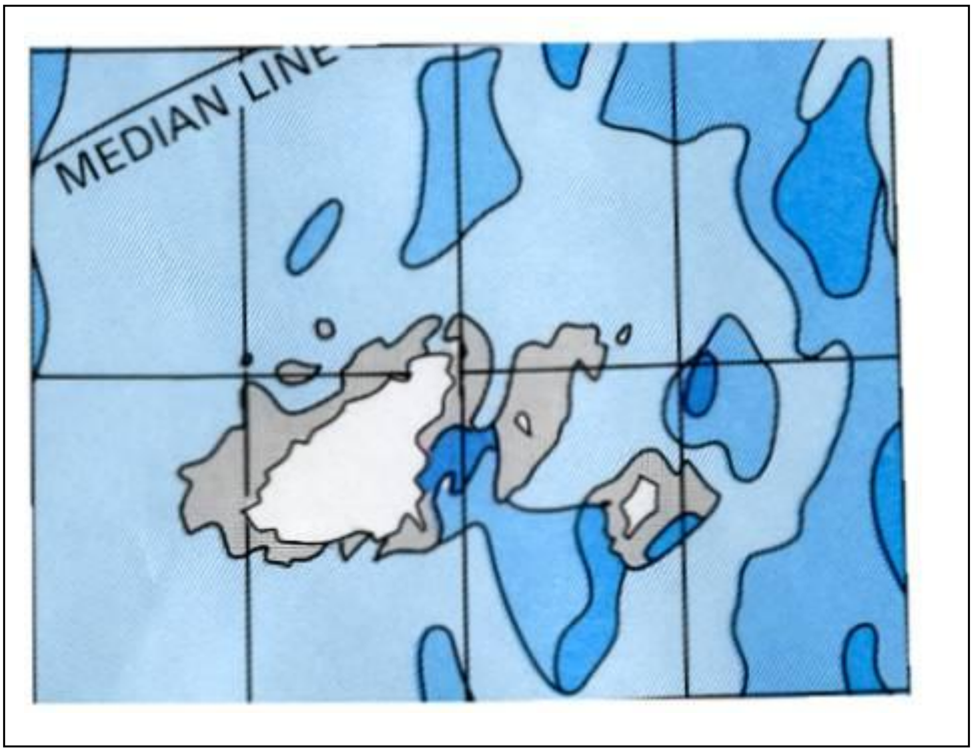

Figure 4.6.4 Guernsey – BGS total carbonate content (Darkest Blue 50-75%; Mid-Blue 30-50%; pale Blue 0-30%)

4.6.3 HOMMERIL (1967) Sediment distribution

The study by Hommeril (1967) is a *magnum opus* on the physical environment of the Normandy-Brittany Gulf. It covers both coastal areas of the Cotentin and the Channel Islands, as well as the offshore area extending to the west of Guernsey and south of Alderney. It is comprehensive in that it includes both sedimentation and the biology of the region. The objective of the thesis was not solely to map the sediment distribution of the region (although this was achieved) but to address the 'total' marine environment and its influence on the coast over the long term, thereby to apply modern day active sedimentation processes to those environments 'ancienne'. The research was conducted over (probably) 6 to 7 years. Much of the material and results remain unpublished in the scientific peer reviewed literature.

For the offshore area Hommeril made maps of the:

1. sedimentary zones,
2. global distribution of shell debris,
3. carbonate content of the sediment fraction less than 2 cm,
4. distribution of different pebble types,
5. distribution of living seabed organisms in the sand fraction , and
6. distribution of Sabelleria,

All of these maps have been scanned and redrafted for the present report. They form a fundamental basis for the understanding of the geology of REA area. Putting together a coherent data set of maps was problematic because of the different projections used. That used by Hommeril is not known, but the GIS projection used here is ED 1950 UTM Zone 30. All scanned figures imported into the geological GIS were georeferenced (as far as possible) to this zone. Where the figures were exported into graphics packages used in drafting the figures the UTM projection was used for the base map and those figures not in this projection were 'reprojected' by hand. Thus it will be noted that different coastlines do not always match. Hommeril's sample locations were taken from the BGS database (Non-BGS samples). The actual locations of these samples were not included in the Thesis.

Based on analysis of the dredge samples Hommeril produced three types of sediment distribution maps:

1. sedimentary zones,
2. global distribution of shell debris,
3. carbonate content of the sediment fraction less than 2 cm,

4.6.3.1 Sedimentary zones (Figure 4.6.5)

In the study area, four main zones are identified:

ZONE I - PEBBLES

A deposit containing more than 50 % of pebbles (whether they are rounded or not, whether they are siliceous or limestone), subdivided into:

Sub-zone Ia: PURE PEBBLES with more than 70 % of pebbles.

Sub-area Ib: SANDY-GRAVELLY PEBBLES: containing between 50 and 70 % of pebbles. The rest is made up of gravel or sand, most often by the two phases in variable proportions.

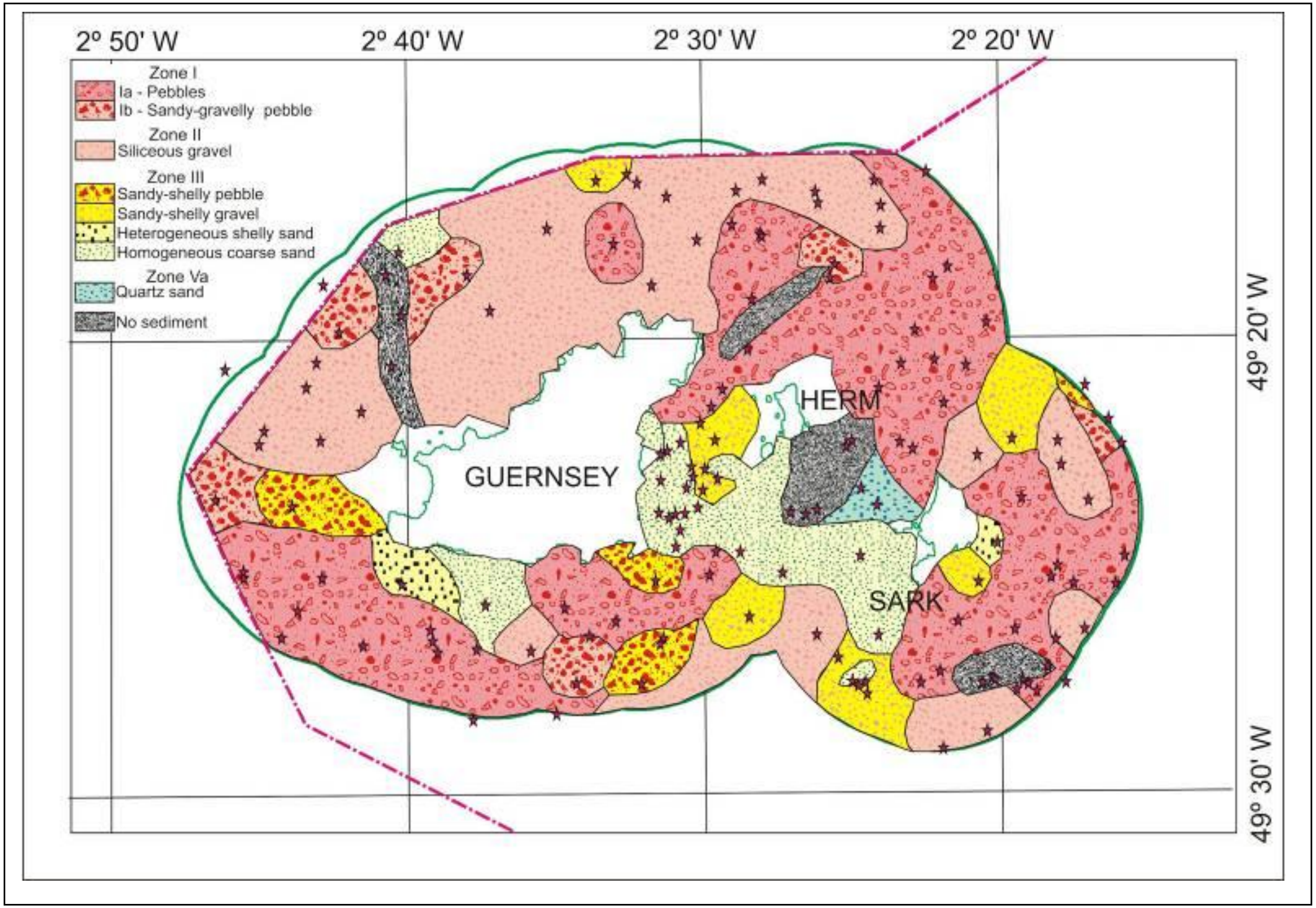

Figure 4.6.5 Hommeril - Sediment Zones (red stars are dredge stations; red dashed line is the limit of Hommeril's sample area)

ZONE II: SILICEOUS GRAVEL:

Deposit containing at least 25% of siliceous gravel (particles between 2 and 20 mm) the content of pebble, as with content of the sands, must be less than 50 %; the overall proportion of limestone is very generally less than 50 %.

ZONE III THE SHELLY SEDIMENTS.

Deposit containing less than 50 % of pebbles, less than 25 % of siliceous gravel, more than 50 % of carbonate (essentially shell debris) in the gravel-sand fraction. Subdivided into five subzones:

Subzone IIIa: SANDY SHELLY PEBBLE: containing 15 to 50% of pebbles.

Subzone IIIb: SANDY SHELLY GRAVEL: deposit containing less than 15% of pebbles and 5 to 25% of siliceous gravel.

Subzones IIIc, and IIId: Deposits containing less than 15% pebble and less than 5 % of siliceous gravel are differentiated by their grain size into:

Subzone IIIc: HETEROGENEOUS SHELLY SAND: Sands where one of the indices of dispersion 6^{68} and 6^{86} (see Ch. III) is less than 1.

Subzone IIId: HOMOGENEOUS COARSE SAND: sands where neither dispersion indices 6^{68} and 6^{86} exceeds 1, where the median is within the class of coarse sand (median greater than 0.65 mm) and whose fraction greater than 1.3 mm exceeds 10%.

ZONE V: TERRIGENOUS COASTAL SEDIMENTS:

Deposits containing more than 50 % of sands and less than 50 % of limestone in the sandy-gravelly fraction are located a short distance from the coast and can be subdivided into two sub-areas

Sub-area Va: QUARTZ SANDS having less than 20 % of GRAINS below 0.065 mm.

4.6.3.1.2 Sediment Distribution - Interpretation

The REA study area is characterized by great diversity of sediments which have an irregular distribution. Most sediment is coarse-grained and represented by the pebble and gravel of Zones I and II. Zone 1 sediments are located mainly to the southeast of the NE-SW oriented NW coastline of Guernsey projected to the northeast and southwest, where they form approximately 60% of the seabed. The siliceous gravels of Zone II are mainly complimentary to the Zone I sediments with the largest extent to the northwest of Guernsey, where they represent the dominant sediment lithology. Shelly sediments of Zone III are not so extensive, occupying approximately 20% of the seabed. An extensive area of Zone III sediment lies between Guernsey and Sark (Homogeneous coarse sands) with smaller areas to the south of Guernsey and Sark and to the east of Sark. At two locations these shelly sediments form sand banks. The most significant, the Great Bank, lies to the east of Guernsey and is formed of Homogeneous coarse sand. The bank to the northeast of Sark is formed of Sandy, shelly gravel. The quartz sands of Zone V form a very limited area between Herm and Sark. There are a few areas where the sediment cover is either very thin or indeed absent, these lie to northwest of Guernsey, to the north of Guernsey and Herm and to the southwest of Sark.

4.6.3.2 TOTAL CARBONATE CONTENT (Figure 4.6.6)

The distribution of total carbonate content is presented on Figure 4.6.6. The areas rich in carbonate, with levels of 70-90% include the Great Bank and the bank to the northeast of Sark. Other areas are between Guernsey and Sark and south of Sark. Outward from these regions of high carbonate content, levels decrease gradually until the seabed is exclusively siliceous.

4.6.3.3 Total Carbonate - Interpretation

In the REA area the main control on the carbonate is the presence of shell debris which causes carbonate levels of above 50%. Hommeril (1967) also produced a map of the carbonate content in the gravel-sand fraction to identify carbonate sources apart from shells (and from maerl in areas to the east of the REA area where this is common) (Figure 4.6.7). There is significant correlation between this map and the total carbonate map, with high carbonate contents in the same areas, for example east of Guernsey and west of Sark. Other areas are south of Guernsey and south of Sark. The bank to the NE of Sark has high carbonate content, but not as high as the Great Bank east of Guernsey.

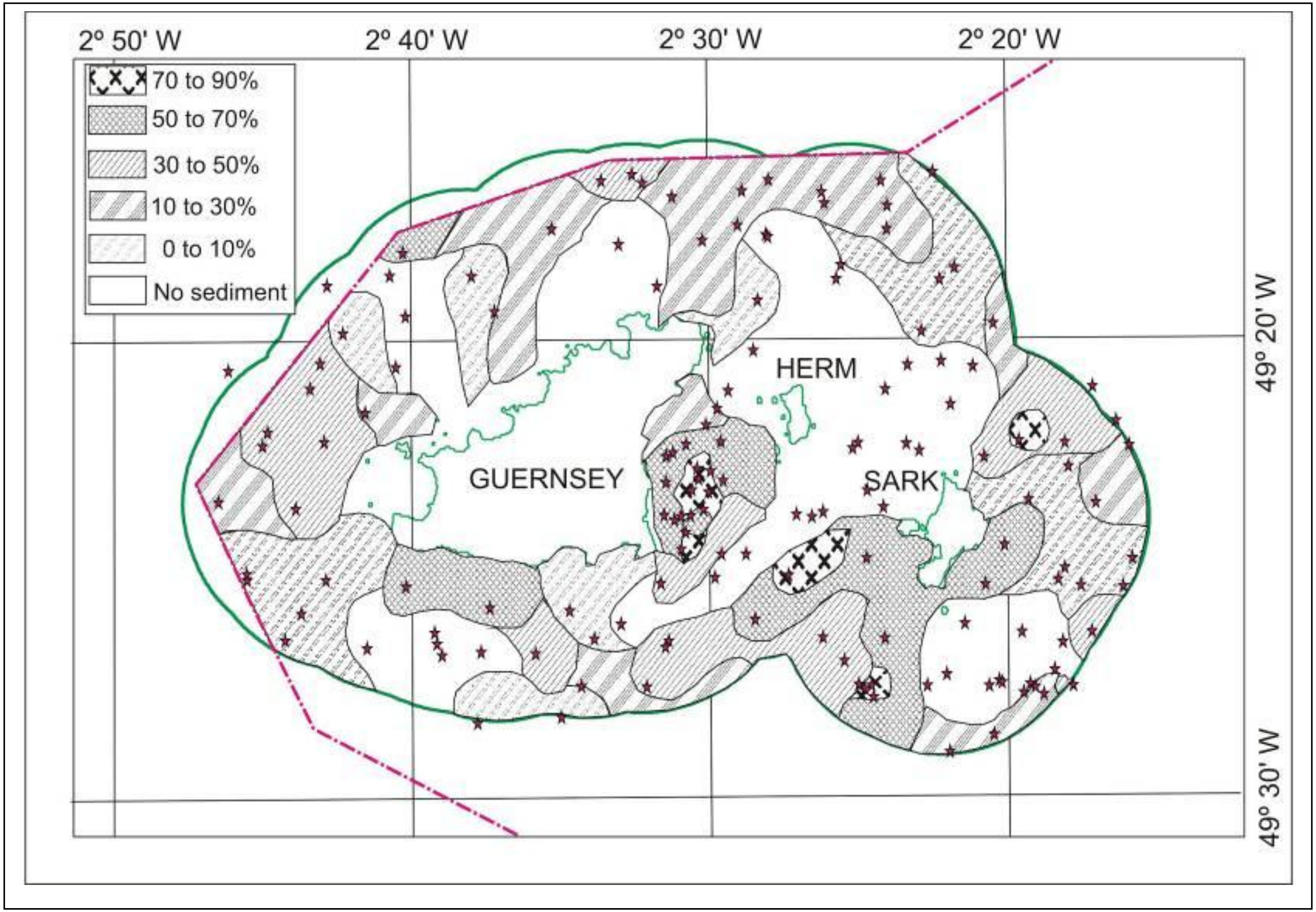

Figure 4.6.6 Hommeril – Total carbonate content (red stars are dredge stations; red dashed line is the limit of Hommeril's sample area)

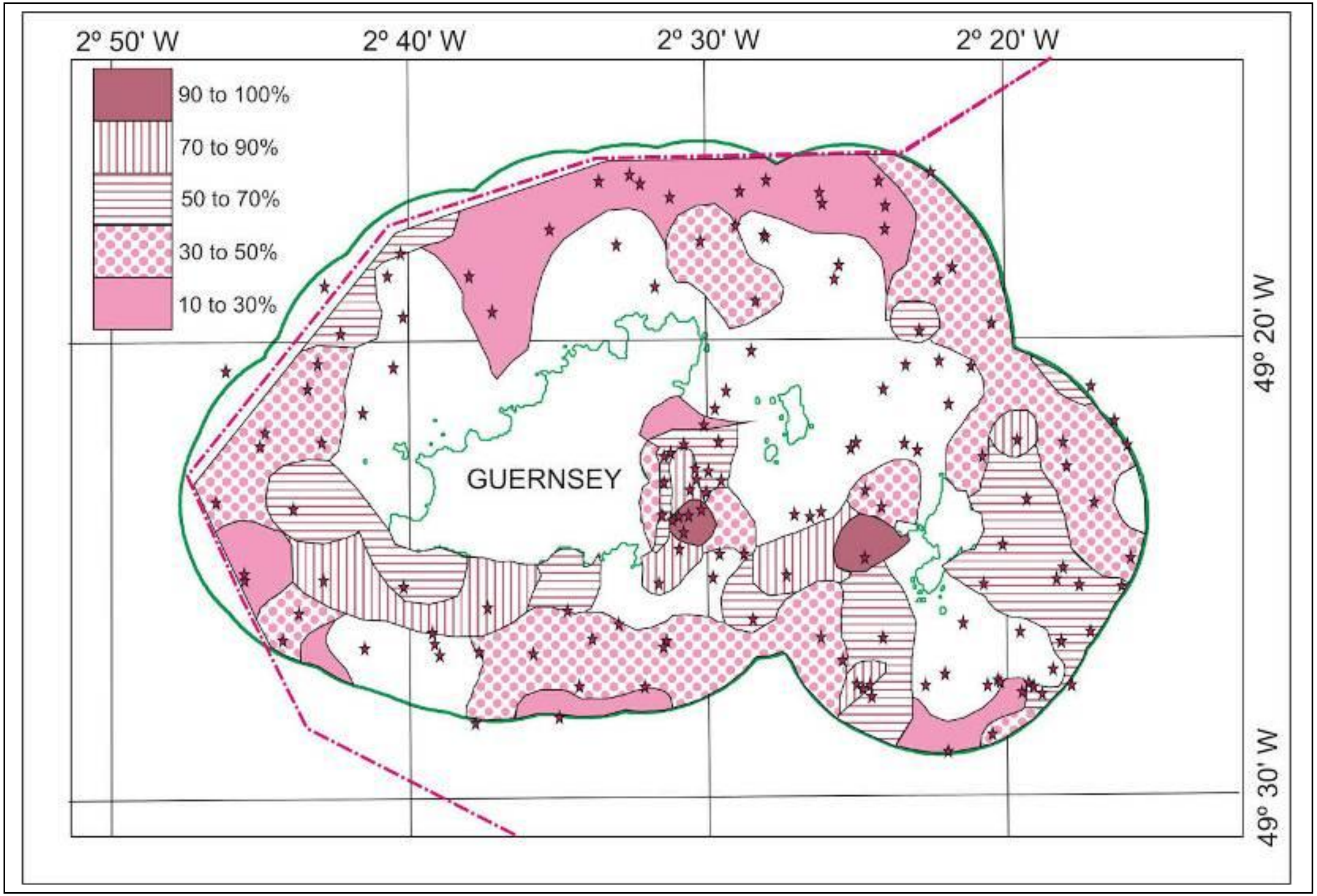

Figure 4.6.7 Hommeril – Carbonate in the sand-gravel fraction (red stars are dredge stations; red dashed line is the limit of Hommeril's sample area)

4.6.3.3 Analysis of the Pebble Fraction

To identify sediment movement patterns in the Normandy Gulf, and their timing, Hommeril studied in detail the coarsest sediment fraction of the dredge samples – the pebbles (Figure 4.6.8). He investigated their petrography, their grain size and their roundness.

4.6.3.3.1 Petrographic composition:

Over the area of the Gulf studied, there are a number of common pebble lithologies found in dredges. On the basis of petrography, Hommeril identified the three most frequently occurring types: granite (plus gneiss), schist and sandstone. In the REA area the distribution of these lithologies is as follows:

1. Granite: dominant to the north of Guernsey, and between Guernsey and Herm,
2. Gneiss: Hommeril included with the granites because they were less numerous and little different in appearance, these rocks are particularly concentrated to the NE of Sark.
3. Schist (with some phyllite): representing mainly the Cambrian series of coastal Carteret: these are located in the east of the REA area where represent about 1 / 3 of the dredged pebbles to the east of Sark,
4. Sandstone, arkose and especially pink quartzite of the Palaeozoic: common to the S and W of Guernsey and a significant importance east of Sark.

Other rocks, less common over all the area studied by Hommeril, but common in the REA area include:

1. Rhyolite lavas to the east of Sark and west of Jersey, that are derived from Jersey,
2. Chalk flints, numerous south of Guernsey, but less so to the west and north,
3. Pebbles of the red series, to the SE of Sark, and
4. Eocene limestone pebbles close to their seabed exposure, e.g. south of Guernsey and Sark.

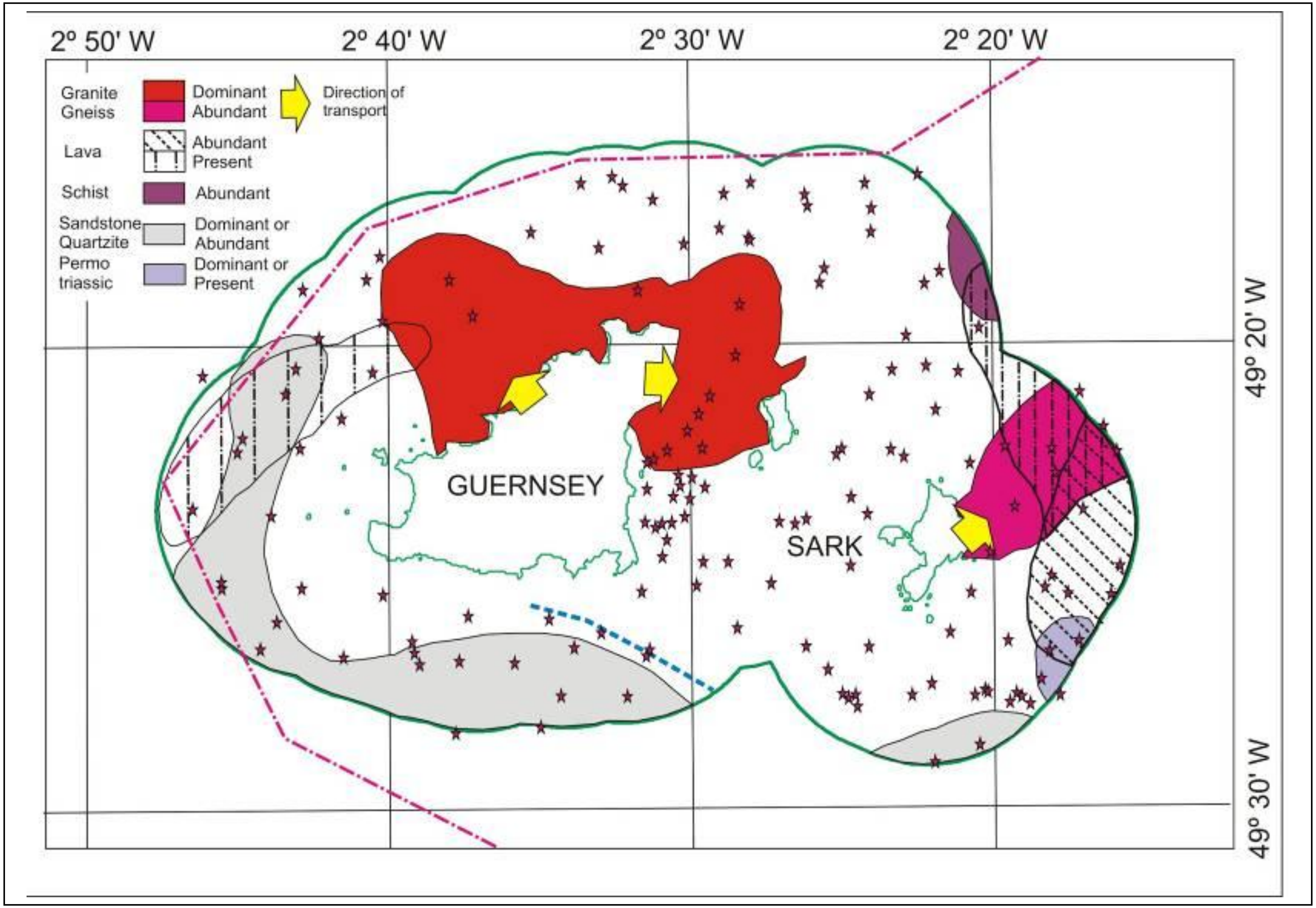

Figure 4.6.8 Hommeril – Locations of pebble lithologies and their direction of movement (red stars are dredge stations; red dashed line is the limit of Hommeril's sample area, blue dashed line is the 52-55 m ancient strand line)

4.6.3.3.2 Rounding and Grain Size

Hommeril measured the roundness of over 2,000 pebbles. Comparing the analyses with his work on the beaches of Guernsey and Jersey, he found that the pebbles from the offshore were very similar to the barrier beaches on these islands. His interpretation was that the rounding of the offshore pebbles took place in similar environments, but at a different time when sea levels were lower. More specifically, he found that there were concentrations, in fact strands of pebbles at a certain depth, at 52 to 55 m. His interpretation was that this depth represented a sea level still stand during which a barrier beach was formed. One such ancient barrier beach is located to the south of Guernsey and trends in a west northwest to east northeast direction (Figure 4.6.8). The beach was laid down during transgression, because during a regression, any deposit laid down would have been eroded under subsequent subaerial environments. Thus the feature must have been laid down within the past 8,000 years

With regard to grain size, Hommeril found that the smaller pebbles were more rounded than the larger. The smaller pebbles were also more worn than their present-day beach counterparts.

4.6.3.3.3 Biological cover

Hommeril also noted that most of the pebbles, independent of their rounding, were almost completely covered with a biological encrustation, including:

- Lithothamnium lenormandi (even to depths of50 m).
- various algae
- Bryozoa crusts,
- arenaceous tubes of Sabellaria spinulosa (cf.),
- fixed lamellibranches such as ephippium L. Anomia,
- fauna that the pebble could support on an extremely restricted surface area (Bryozoaires "plumescents" for example).

He also noted that pebbles dredged from restricted passages or tidal channels, such as the Petit and Grand Russel, were generally without an encrusting biological cover.

4.6.3.3.4 Pebbles - Interpretation

The interpretation by Hommeril for the Normandy-Brittany Gulf, of the pebble distribution and pebble morphology was that, except for Cretaceous flint and Palaeozoic quartzite, the pebbles had not been transported very far from their source rock (compare Figures 4.5.1 and 4.6.8). Hommeril suggested that the most pebbles had travelled distances of less than 10 km from their source exposures. Hardness of the rock types obviously influences their 'erodability' and hence their size; thus rock type is a major control on transport potential (larger pebbles need more energetic mechanisms to be transported). The pebbles were laid down during in strands that represent pre-existing barrier beaches formed during lower sea levels; most probably those later than the last glaciation, although Hommeril postulated that very rounded and much worn pebbles might have been created during older glaciations, and thus reworked.

However, the extent of the pink quartzite and flint, outside of present source areas, is due to these source rocks having a previous extensive areal extent in the region. The quartzite is relatively more important in the locations lacking other rocks. The rock substrate is formed of many exposures of sandstone or quartzite, (for example Brioverian metamorphosed sedimentaries) that underlie the current seabed sediment. Additionally, these pebbles are often a little more rounded, especially the small sizes, than other types of pebbles. Thus they are older and have suffered more numerous phases of reworking. The Cretaceous flint is common because of erosion from the large areas of Chalk substrate present today in the area, as well as the previous greater extent. It is probable that Chalk covered all of the area at one time, including the islands themselves.

It is fairly obvious, comparing the geology map (Figure 4.5.1) of the REA figured here with the distribution map of pebbles produced by Hommeril (Figure 4.6.8) that his conclusions on pebble sourcing have a great deal of validity. Granite and gneiss pebbles are found offshore of similar lithologies on Guernsey and Sark. These are generally hard rocks, resistant to erosion and thus, because of their size have not moved too far. However, the gneisses may not be quite as hard, and in fact quite fragile when weathered (see Coastal Section), that probably explains their more widespread distribution to the northeast of Sark. The sandstone and quartzite to the south of Guernsey relates to the Brioverian metamorphosed sedimentary rocks offshore in this region. The presence, to the east of Sark and west of Guernsey, of rhyolitic lavas of the Jersey Volcanic Group, is intriguing. Hommeril attributes their presence in this area to lengthy transport from their source. However, the small (presently) mapped exposure of this Group to the south of Sark may indicate that their extent perhaps maybe greater than presently identified.

One of Hommeril's most significant interpretations is that the pebbles accumulated as ancient beach strands that formed during the lower sea levels of glacial periods and during marine transgression.

Not covered here, but significant, Hommeril also analysed the petrography of the gravel component of 14 dredge samples to determine its origin. He identified eight rock types similar to those from the analysis of the pebbles:

- granular rocks (primarily granites or gneiss),
- lavas,

- quartz,
- schist and phyllite (of the Precambrian or the Cambrian),
- pink or white sandstone and quartzite (of the Palaeozoic),
- red calcareous pelites,
- flint, and
- Eocene limestone.

With some provisos, the results of his analysis confirm the study of the pebbles. The petrographic composition of the gravel reflects the very local rock substrate; as with the pebbles, the gravel has not moved very far. However, also like the pebbles, the sandstones and pink quartzite together with the flints are more common, and have probably a more variable source. Their content is higher in the dredge samples more distant from the shore and thus the sandstones and quartzite form the bulk of the gravels lying to the west of Schôle Bank. One further aspect of both pebbles and gravel is that in dredges close to each other there may be marked differences in content; confirming that sources are, indeed, mainly local.

4.7. Seabed Morphology

The only available data of the seabed morphology of the area of the REA area is from the Admiralty Charts, maps and descriptions from Hommeril (1967) and the BGS geophysical legacy data.

4.7.1 Sand Banks

Two sand banks are identified in the area:

The Great Bank – off eastern Guernsey, and

The Sark Bank, eponymously named from the island to the southwest.

4.7.1 .1 The Great Bank

Oriented N 20°E, the Bank is between 1 and 3 km from the southern part of the east coast of Guernsey (Figure 4.4.1). It is located at the southern end of the Little Russel, southwest of Herm and Jethou. It is 5 km long, 1200 m wide in the middle, tapering towards the south at the 10 m isobath, but, at greater depths, tapering to both ends. It is shallowest at around 4-5 m, rising above the surrounding seabed that is 35 m depth on its west and 25 m on its east side.

The Great Bank is virtually devoid of sand waves, it is a simple sand bank; unbranched. There are a few simple sand waves, more or less parallel to its long axis, 200 m wavelength and 3 m in height at its termination in the south-east and of

100 m to 1 m high of the crest in the middle of the bank. A few other sand waves are perpendicular to the long axis.

The morphology of the Great Bank merges to the north with the Little Russel. It also gradually merges to east, toward the rocky 'Lower Heads'. It is isolated from the east coast of Guernsey by a narrow channel 500m wide and 40 m deep, and almost continuous with Point St Martin and St Peter Port, then gradually diminishing away from the coast.

Hommeril (1967) acquired a number of dredge samples over the Great Bank. Grain size analysis reveals that the sediment is characterized by a wide dispersion of its components including granules, coarse- and medium-grained sand, and, locally, gravel , that comprises large shells but also siliceous debris.

The channel between the Bank and the coastline is occupied by very fine, partly muddy, sand. The carbonate content is very unevenly distributed, but is still very high (often 60 -80%). The shell debris is much worn, but does not appear to be strongly moved by currents. On the other hand, Cellaria fragments, that characterize the Bank, are very unevenly distributed. They are most common on the crest of the Bank. The Bank is formed of sediment of Zone IIIc (shelly heterogeneous sand).

4.7.1 .2 The Sark Bank

The Sark Bank lies 2 km to the northeast of Sark and is oriented in the same direction. It is 3 km long and tapers to the northeast, being 700 m wide in the south. At its crest, water depths are ~10 m. The seabed on each side is ~40 m deep. It is formed of Zone II sediment (siliceous gravel) in the south and Zone IIIa sediment (Sandy shelly pebbles) in the north. There is no detailed description of the morphology or the sedimentology that was available for this study although a research thesis on the Bank has been published in French (M'hammdi, 1994).

4.7.1 .3 Origin of the banks

The most recent study of the sediment bodies English Channel area is by Reynaud et al (2003) who review the present state of knowledge and summarise their origin based on sea-floor imaging, very high-resolution seismic surveys and a few piston cores. The regional approach is appropriate because the sediment deposition within the Gulf of Normandy (in which the REA is located) is part the larger sedimentary distribution system that encompasses the English Channel and Western Approaches. The sedimentation has taken place under a number of environments that are determined by global climate change over the past 400,000 years, during which the area has been subject to both marine and subaerial conditions.

The English Channel is a typical funnel-shaped tidal shelf that is presently starved of terrigenous sediments. Most of mobile sediments at the sea-floor are autochthonous (formed in place) and either skeletal carbonates or siliciclastic sands reworked from older littoral (coastal) barrier deposits or incised valley fills. Three zones are recognised:

1. the Central (and western Central) Channel, which is a bed load parting zone characterised by a pebbly lag making up the Quaternary sediments throughout the shelf area;

2. the Eastern Channel, a flood-dominated area characterised by medium to fine siliciclastic sands, mainly of aeolian periglacial origin;

3. the Western Approaches, an ebb-dominated area with a polygenic sediment cover characterised by coarse, carbonate-rich, gravelly to muddy sands of marine to glaciomarine origin, with a diachronous faunal content.

There is a predominant control on sedimentation by the tidal dynamics, together with a general interplay between the Channel morphology and sea-level change. The thickest deposits in the Eastern Channel and Western Approaches are built up into bank systems during the last, post-glacial, sea-level rise. In the west, the Celtic Banks represent the tidal transgressive systems whereas the Eastern Channel banks are highstand systems.

The Gulf of Normandy is part of the Central Zone. Here the sediment cover is thin, comprising (as we have seen) mainly coarse-grained sediment (Vaslet et al., 1979). This is mainly a result of high ebb-dominated current velocities (>1 m s^1), that transport any size of sand. Some large sand banks, however, have been formed in this area during the last postglacial sea-level rise, mostly by trapping of sediment within tidal eddies generated by headlands or flow convergence (Walker, 2001). This is the case for the Great Bank of Guernsey and the Bank of Sark (Figure 4.7.1).

Most sand bodies in the Gulf have been mapped and described extensively by means of side-scan imagery, high-resolution seismic surveys, swath or narrow-beam bathymetry and, to a lesser extent, coring (e.g. Quesney, 1979; M'hammdi, 1994; Walker, 2001). All these studies demonstrate the high mobility of the sand and gravel fraction, with bed form migration rates reaching several tens of metres per year. For instance, off of Cotentin, large three-dimensional asymmetric dunes in the Surtainville area, 8 m in height, have been monitored on a 4 year basis and shown to have an average migration of 20 m yr^1 in the direction of the dominant (flood) tidal current (to the north).

Sand banks, lying over a planar substrate, have heights of 20 to 30 m above the sea-floor. The morphology and orientation of superimposed bed forms (large dunes, sand ribbons etc.) demonstrate a circulatory sediment transport with net convergence toward the top of the banks (Walker, 2001). These banks are stable on a long time-scale (tens of years) and are in equilibrium with local hydrodynamic conditions. The effect of storm waves mainly results in erosion of shallowest superimposed sand dunes on the top of the banks.

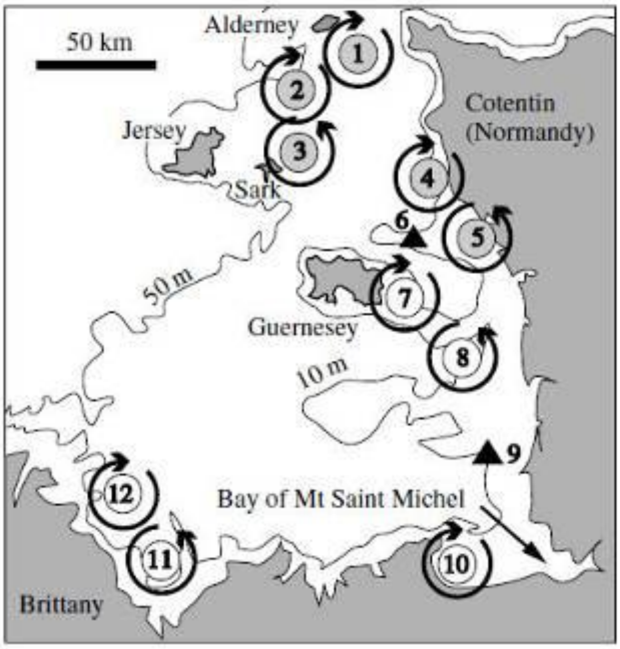

Figure 4.7.1 Banks in the Normandy–Brittany Gulf. Bank of: 1, Alderney; 2, La Schôle; 3, Sark; 4, Surtainville; 5, Basses de Portbail; 6, Ecrevières; 7, Le Château; 8, Le Marié; 9, La Haute Foraine; 10, Corbières; 11, Le Goëlo; 12, La Horaine; full circles, offshore banks; empty circles, banner banks; triangles, leeward banks (at the back of islands). Rotary arrows represent tidal eddies. Modified from Walker (2001), after Reynaud et al (2003)

Although there is no modern detailed study (post-Hommeril, 1967) the evidence by Hommeril indicates that over short (decadal) time scales the Great Bank is not mobile. There are no fields of sand waves indicating rapid sediment movement and the colonisation by the biota suggest a stable substrate. However, there is no modern study available for this feature. There is no neither multibeam nor side scan sonar. The study by M’hammadi (1994) of the Sark Bank was not available for this report. Reynaud et al. (2003) cautioned that not all is understood on the dynamics of these features, it is obvious that the controls on their evolution are local, and thus need individual study .

4.7.1.4 Other areas

Examination of bathymetry records has identified a small number of sedimentary features as detailed in Table 4.7.1 and Figures 4.7.2 and 4.7.3.

Table 4.7.1 Seabed features mapped from BGS legacy seismic data

Line	**~ Reference**	**Feature**	**Description**
72/3/10 Pinger	E to W. Fix 3.	Sand Wave – east facing	~ 20 m high trough to peak. Migrating east. From ~ 55 m. Depth increasing to west.
72/3/34 Pinger	Fixes 5 – 13 from NE to SW		
72/3/34 Pinger	Stations 7 – 8	Rises in bed	Platforms, possibly joint or fault-bound. Rises of ~ 2 to 2.5 m. Water depth in this zone decreases from 47 m to 44.5 m and 42 m then increasing to 45 m to the southwest.
72/3/34 Pinger	Stations 9.5 to 10	Rock pinnacles	Shoals at 20 m.
1983/5/42 Echo-sounder	Stations 27 to 31 within the REA.	?Planation surface at 52m.	Sea bed rising to north north east. Zones of planation at 52 and 40 m depth separated by zones with bed fluctuation of up to 2 m. Indicated to be gravel.
1978/2/78	Fixes 6 to 9.	Rugged seabed - ?rock outcrop	Sea depth decreases from 68 m to 41 m then increases to 54/55 m to east north east (Figure). Rise coincides with moving from Palaeocene bedrock to the Brioverian Supergroup.

The BGS seismic data is limited and comprise Pinger and Echo-sounder lines that provide a limited perspective of seabed morphology. These seismic sources are high-frequency, thus there is minimal sub-seabed penetration, especially in the pebbly, gravelly and sandy sediments that are present in the REA.

From the data the only evidence of mobile seabed is on Line 1972/3/10, where sand waves are present. Elsewhere the seabed in mainly planar, with some areas of irregular morphology that are interpreted as rocky regions.

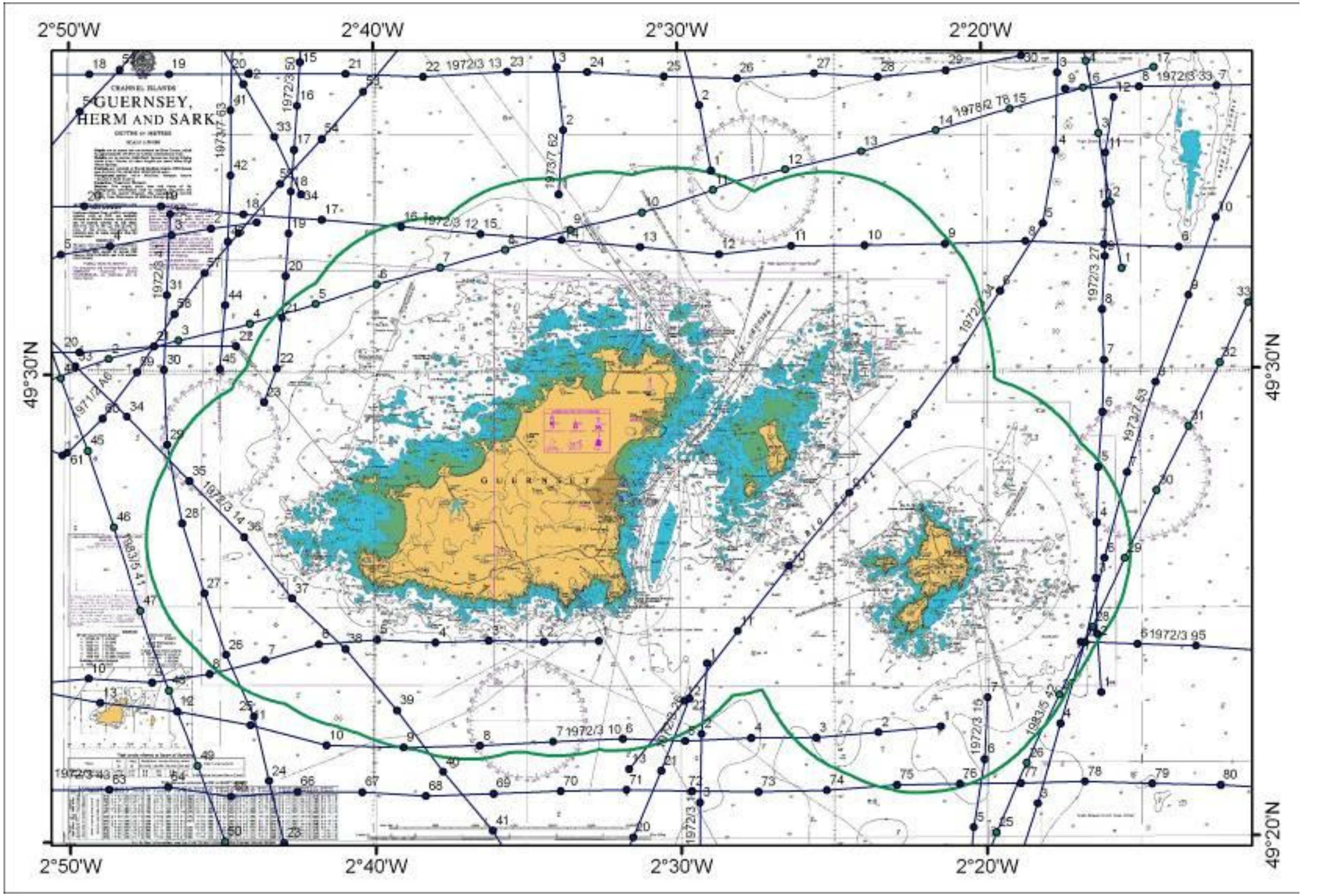

Figure 4.7.2 Admiralty Chart 3654 with overlay of BGS Pinger and Echo-sounder lines

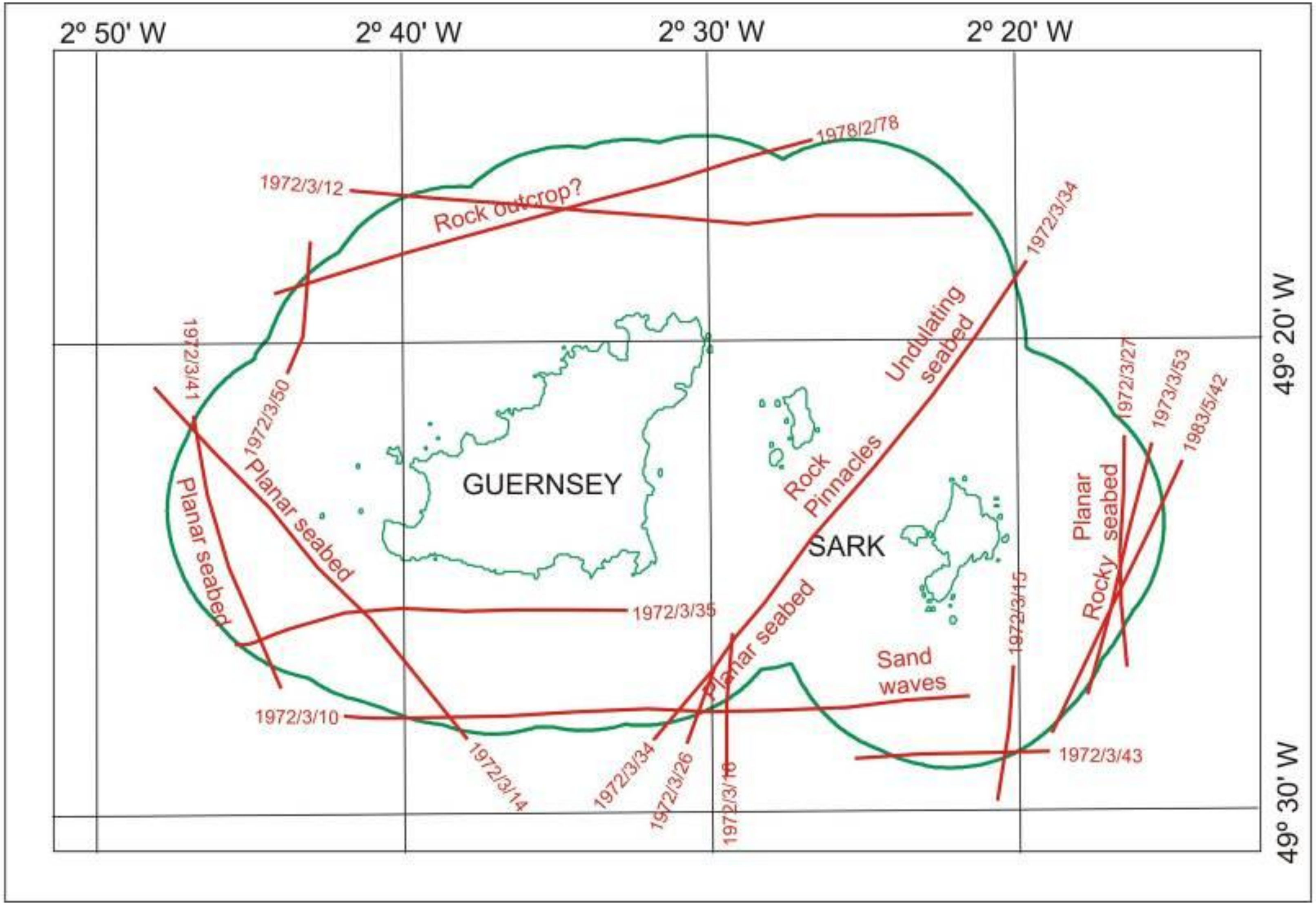

Figure 4.7.3 Interpretation of BGS Pinger and Echo-sounder data

4.8 Brief Resume Of The Sediment Distribution And Seabed Morphology

The sediment in the REA offshore area is dominantly coarse-grained, comprising pebbles and gravel with a subsidiary carbonate component, mainly derived from shell debris. There are subsidiary deposits of sand, mainly located to the south of Guernsey and between Guernsey and Sark. Apart from two sand/gravel banks, the sediment cover is thin (decimetres). Around the islands the coastal zone is probably sediment free or with very thin sediment cover. Areas with no sediment were identified by Hommeril (1967).

Two major sand/gravel banks are present that are formed of thicker and finer-grained sediment accumulations. Of these, only the study of the Great Bank was available for review.

The present sediment distribution is the result of sea level change over the long term together with present day (recent) biological activity. The coarse-grained gravels are the lag deposits derived from low sea level stands and reworked during the last marine transgression. The shelly sands are multisourced biolithoclastic deposits aggraded into tidal bed forms, again during the last marine transgression.

From the limited database, the seabed morphology of the REA area is mainly planar, with low gradients, except in coastal areas where there are shoals. Two sand banks are known to be present, the Great Bank off Guernsey and Sark Bank off of Sark. Based on the limited data available a general seabed morphology map with main sediment grain size classes is presented as Figure 4.8.1.

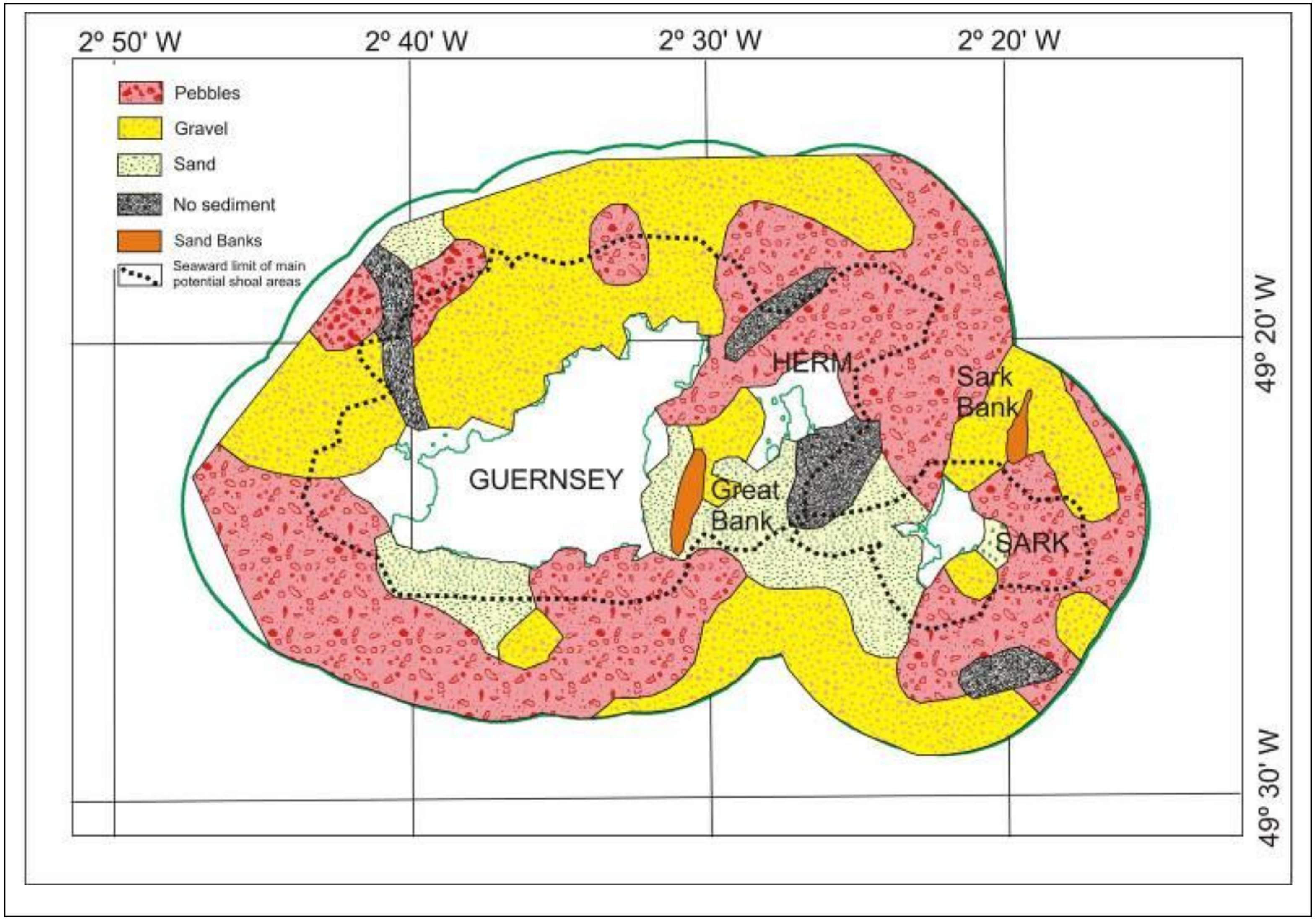

Figure 4.8.1 General seabed morphology of the REA area, with main sediment grain size classes

4.9 Biology

4.9 .1 Distribution of living Seabed organisms in the sand fraction (Figure 4.9.5)

In the Normandy Gulf Hommeril noted that the shell debris in the dredges mainly comprised the shells of molluscs (Lamellibranchs, Scaphopoda and Gastropoda). Between the islands, encrusting bryozoans are very frequent and are fixed on the gravel without being entrained in the sand fraction where their presence is quite low. Generally, the shells of lamellibranchs are more abundant than gastropods: they are in fact almost all remnants and usually found very near the coast. Small echinocyamus pusillus are not an important constituent of the samples role SW of Sark at the edge of the area of ophiuroids.

As for arborescent Bryozoa such as Cellaria (Figure 4.9.1), living forms were dredged to the west of Guernsey. However disarticulated remains were found in some sediments. To the west of Guernsey, dredge counts reveal a significant presence, often abundant (more than 50 parts per cm^3 for 6 samples), to the east, between Guernsey and Sark and to the east of Sark. Based on the change in frequency in the dredges Hommeril considered that there was a decrease in umbers to the east, thus the source was to west. There are areas of particular concentrations notably to the west of Guernsey and between Guernsey and Sark, where they are common on the Great Bank.

Figure 4.9.1 The bryozoa Cellaria

An important area of living Ophiuroids (Figure 4.9.2) were found to the east of Sark on rocky or gravelly seabed. The surface distribution of these seabed Ophiuroids (Ophiotrix fragilis) extends in the direction SW - NE mirroring the direction of flow of the tidal currents. However, these Ophiuroids do not seem to be an important part of the organic component of deposition.

Figure 4.9.2 Ophiotrix fragilis

The gastropod Bittium reticulatum (Figure 4.9.3) lives mainly in seagrass meadows and in the REA is found to the west of Guernsey across an extensive area and to the west of Sark.

Figure 4.9.3 Gastropod – Bitium reticulatum

Figure 4.9.4 Modiola barbata

Finally, Modiola barbata (Figure 4.9.4) was found to the west of Guernsey, and east of Sark.

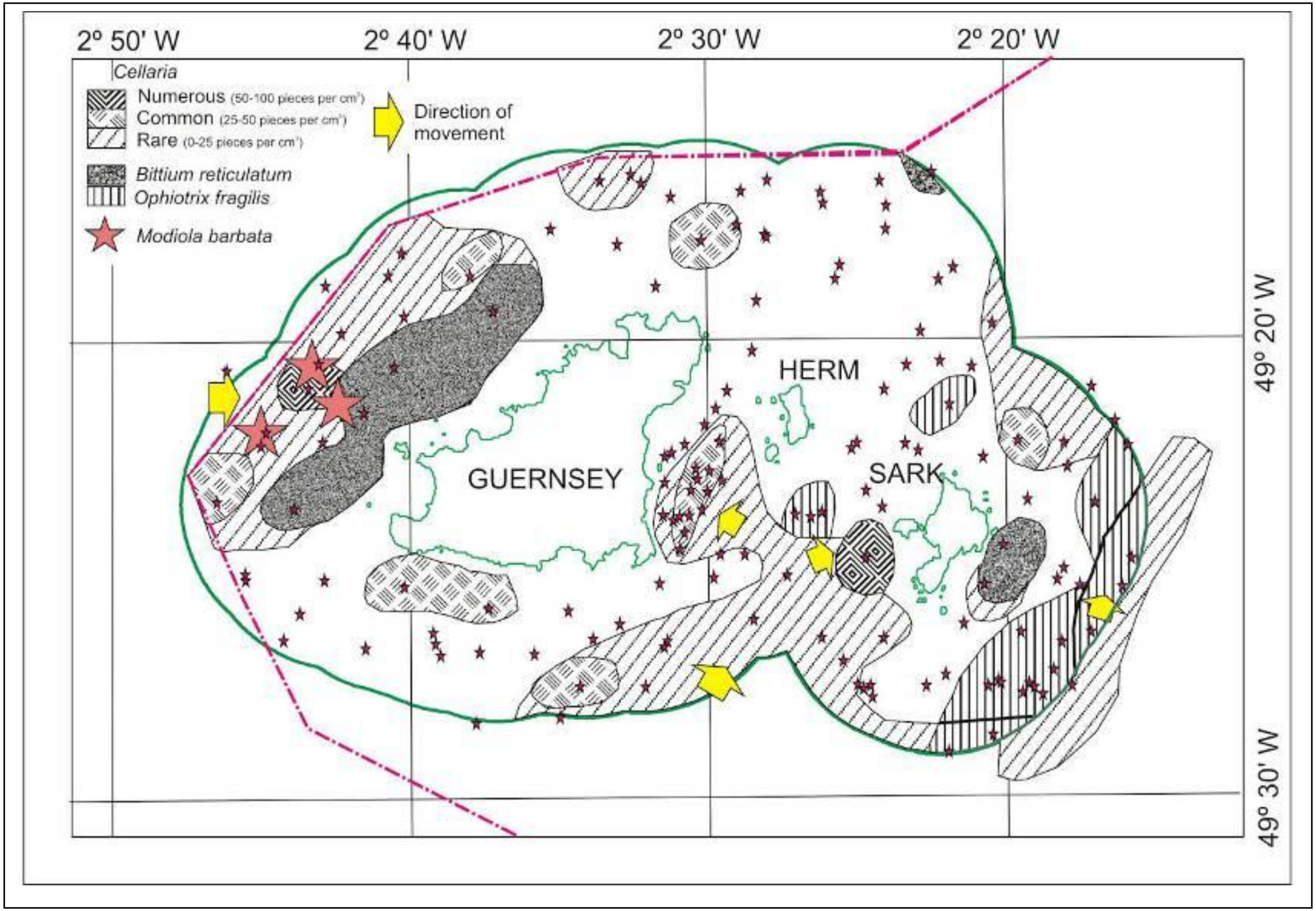

Figure 4.9.5 Hommeril – Distribution of living seabed organisms in the sand fraction (Red dashed line – the limit of Hommeril's sampling area; red stars are Hommeril's dredge locations).

4.9.2 Distribution of sabelleria spinulosa (Figure 4.9.6)

Hommeril commonly sampled Sabelleria spinulosa (Figures 4.9.6) and they were found in 46% of his dredges. They were rare in depths less than 10 m and found down to 60 m. The map he produced is not quantitative; the content of Sabelleria debris was assessed visually, and is quite subjective. Sabelleria spinulosa were dredged in the area of the Channel Islands there they form the small bioherms that Hommeril terms "nano-bioherms". Mostly they are located on a substrate of pebbles or on coarse shells. Constructions may exceed 5 cm in height, and their size depends strictly on the surface of the substrate. Sponges, bryozoans and serpulids participate actively in the construction and consolidation of the nano-bioherms.

Figure 4.9.6 Sabelleria spinulosa

Thus, their presence is in response to a favourable biotope (stones and large shells).

Thus, their presence is in response to a favourable biotope (stones and large shells) . Their absence on the shallow bottoms is due to the fine-grained sediment at these depths often silica sands. Also, Sabelleria was not dredged on the sand waves formed of fine shell sand. In addition, pure pebble, without a sandy matrix, is not favourable, because, of a lack of sand for construction of the tubes. This explains the absence of tubes of S. spinulosa SW of Guernsey. In the REA there is a close association of Sabelleria with coarse substrates.

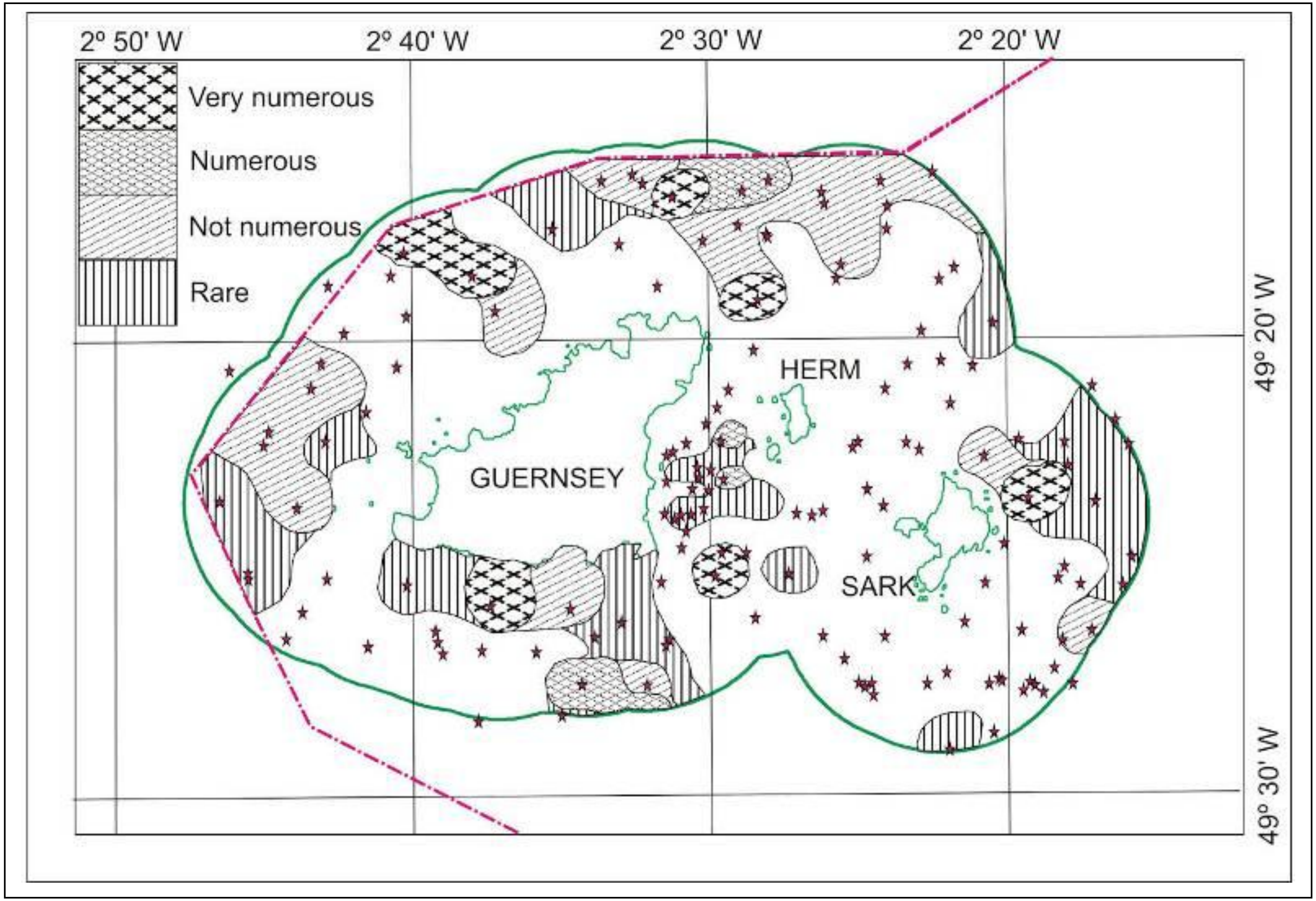

Figure 4.9.7 Distribution of Sabelleria spinulosa (Red dashed line – the limit of Hommeril's sampling area; red stars are Hommeril's dredge locations)

4.10 Engineering Geology

4.10.1 Precambriam

From the onshore exposures in the Channel Islands, we know that the Precambrian rocks comprise granites, quartz dioritic orthogneiss and migmatites, schist and amphibolites. All of these are extensively altered and deformed. Sampling suggests that similar lithologies are present offshore and that these too are likely to have been subject to similar degrees of alteration and weathering. Because of their age, they would have experienced long term evolution under many different climates and environments. They would have been altered under changing sea levels and bottom currents (and therefore sediment loading). The main weathering product would be clay, which can have significant control on the stability of excavations and also on the potential for settlement and, therefore, the bearing capacity of the strata. Offshore, where these rocks are present, they are mostly covered by a thin sediment veneer comprising mainly pebbles, gravel, with some sand. The weathering of theses rocks is likely to be mainly controlled by foliation and jointing.

Schist and gneiss tend to have mineral concentrations which give their characteristic banded appearance. Accumulations of minerals such as biotite, muscovite and hornblende will tend to weather preferentially before quartz and feldspar rich bands. The presence of rebound fractures, caused by cycles of loading and unloading, subparallel to the rock surface, provides another mechanism for preferential weathering. The main rock weakness to weathering is likely to be through jointing. Dominant, fault-preferential, weathering along joints can result in the classic ‘core-stone’ weathering (Went, 1991) that forms rounded boulders (see the above section on Hommeril). These occur individually or in piles at the ground surface, or in exposed sections. They result from an initial phase of subsurface chemical weathering of a joint-bounded block, followed or accompanied by surface erosion that exposes the ‘corestone’. This process results in weathering to variable depths, that depends on the nature of the jointing, and also on variations in the characteristics of the bedrock (Price, 1995). Rathan (1983) reported on the weathering of exfoliated granodioritic and felsitic basement on Alderney. We can surmise that the depth of weathering is likely to be influenced by the depth of open joints and by changes in flow base levels. However, at this time we have no data available to quantify the depth or extent of weathering in the rocks in the REA area. Additionally, there is no information on the effects of halmyrolysis[2].

To the north of Guernsey the offshore Brioverian strata are believed to comprise sandstone with siltstone and conglomerate, overlain by dark siltstone and mudstone, laid down as turbidites. The weathering product of these deposits is expected to be primarily clay (Price, 1995). As noted above, the presence of clay has implications on slope stability and settlement, thereby limiting bearing capacity.

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[2] Early diagenesis, modification, or decomposition of sediments on the sea floor

In the Cadomain granites, granodiorites, diorites and gabbros, differences in grain size and mineralogy will result in varying resistance to weathering. Price (1995) proposed that coarser-grained rocks tend to weather more readily. Exfoliation and the zonation of granite weathering have been described for other regions, e.g. (Lee and de Freitas, 1989). Hill (1884) presented a figure (p. 409) to illustrate the grooved weathering of diorite to the south of Fort Doyle on Guernsey, which he attributed to differences in rock structure, or rock banding. South of Fort Le Marchant, Hill (1884) distinguished between blue diorite that weathers to bluish-white, and granite that weathers to pinkish-white. The petrological variability of these rocks suggests that there is a potential for significant variation in the depth of weathering. Roach et al. (1991) commented on the highly weathered, crumbly, condition of the L' Eree Granite, in the southwest corner of Guernsey. The weathering product associated with the decomposition of granite is more likely to be granular or sandy, although the variability of the materials is such that more cohesive banks are also likely to be encountered. On Sark, Hommeril (1967) noted the 'granular' condition of the exposed surfaces of the Icartian gneisses that rendered them extremely vulnerable to subaerial erosion. On Sark caves commonly form in these rocks.

Cadomian Granite and Icartian gneiss underlies the floor of the Little Russel; so the possible alteration identified here should be considered in any marine development in this area.

4.10.1.2 Cambrian

Offshore, to the east of Guernsey and enclosing Sark, fault bounded areas of the Cambrian are probably formed of arkosic sandstone with siltstones similar to those on Alderney. There are few offshore samples. The rock strata appear to be faulted and thrusted during the Caledonian Orogeny. Hence they are likely to be deformed. This possibility should be considered in the context of proposed seabed development, especially in the Great Russel. No information on the engineering properties of these rocks is available.

4.10.1.3 Ordovician to Carboniferous

The undivided Silurian to early Devonian strata, fault bounded to the south east of Guernsey, underlie the marine area on the south-eastern boundary of the REA area. They are described as schist and sandstone overlain by shale and schist. Younger than the Precambrian and Cambrian, they have undergone less deformation, and are only affected by the Variscan Orogeny, with milder deformation during the Tertiary. Nevertheless they will be weathered during subaerial exposure as well as during submergence and marine transgression. There is a significant interval between the early Palaeozoic and the Cretaceous, during which the older rocks will have been repeatedly exhumed and buried, suffering alteration and deformation in the process. No information on the engineering properties of these rocks is available.

4.10.1.4 Cretaceous

The Chalk of the Maastrichtian occupies a limited area of seabed to the northeast of Guernsey on the northern margin of the REA area. There are extensive onland exposures in France and offshore samples suggest that the rocks present may be similar to these, mainly Chalk and Marl. The calcium carbonate that forms Chalk is susceptible to dissolution, particularly in zones of ground and surface water mixing. The evidence for fluctuating sea levels suggests that, potentially, there will be present a number of zones of former active dissolution within the Chalk. Additionally, sedimentary grading in the Chalk renders it susceptible to freeze-thaw weathering and breakdown, especially during glacial episodes, Thus it would have been intensively weathered during the lowered sea levels of the Pleistocene, when the Chalk was periodically subaerially exposed. Weathering would be concentrated along zones of more intense fracturing, and at the surface of the Chalk.

4.10.1.5 Palaeocene

These strata primarily comprise limestone and are subject to similar erosional processes, including dissolution, to those described for the Cretaceous strata. Offshore samples are mainly carbonates.

4.10.1.6 Quaternary

Quaternary sediments are less indurated and consequently potentially more mobile. It is within these sediments that marine sedimentary features are formed by the ocean currents as a consequence of winnowing and deposition. The currents and wave activity fluctuate considerably in response to the tides and changing atmospheric conditions. Over much of the channel bed surface the superficial deposits comprise coarse flint gravels derived from the chalk and weathering of the bedrock, which are the remnant of current winnowing of the finer-grained material (in particular the loess deposits that are evident on the islands and the river deposits associated with the former Channel river). This is indicative of high velocity zones with maximum surface currents exceeding 1.5 m/s (Jago in Fookes and Vaughan, 1986). In lower velocity environments of 1.3 – 1.5 m/s sand ribbons are deposited. These can be up to 15 km long and 200 m wide, but are usually less than 1 m in height (Jago in Fookes and Vaughan, 1986). Sand waves occur where maximum surface water maximum surface velocities are 0.5 – 1.0 m/s (Jago in Fookes and Vaughan, 1986).

4.11 Potential Marine Hazards

A range of possible marine hazards can be surmised from the desk study, as detailed below in Table 4.11.1.

Table 4.11.1: Range of possible marine hazards and their likelihood in the REA area.

Hazard	Description	Reference/ Known occurrences
Continental slope/ slope failure	None identified	None identified
Sediment banks/ slope failure	None identified	None identified
Faults – reactivation?	None identified – although the Gulf of Normandy region experiences earthquakes	None identified
Rift zones	None identified	None identified
Buried valleys	None identified, but may be present.	None identified
Periglacial features	Older shorelines – thick pebble accumulations leading to potential seabed instability (e.g. off southern Guernsey)	South of Guernsey
Seismic	Historic earthquakes known in the general region	Historic
Scour	Potentially	Evident from the seabed sediment mapping
Rocky protrusions	Numerous	Nautical charts
Cables/ Cable trenches	Numerous No information probably not because of thin sediment cover	Nautical charts
Wrecks	Numerous	Nautical charts
Fishing materials	Numerous	See Fishing Chapter

4.12 Potential Effects

According the REA Scoping Document (GuernseyRenewableEnergyCommission, 2009), two main technologies are proposed as the main marine energy sources in the REA area:

- Wave energy devices such as overtopping, hydraulic and air driven devices – sited on the shoreline, nearshore or offshore, and

- Tidal Stream energy such as turbine technology and oscillating devices – sited at locations of strong tidal flows.

Both types of devices may be moored, attached to r fixed by piles into the seabed. For tidal devices the various methods of attachment include:

- Seabed Mounted – attached to the seabed around its base,
- Gravity Base – fixed by a massive weight, but may have additional fixing,
- Pile Mounted – attached to a pile penetrating the sea floor,
- Floating –
    - Flexible Mooring – tethered to the seabed allowing freedom of movement,
    - Rigid Mooring – secured using a fixed system;
    - Floating Structure – mounted to a platform that can move in relation to changes in sea level,
- Hydrofoil Inducing Downward Force – using a number of hydrofoils mounted on a frame to induce downward force from the tidal flow.

These are taken here to represent the various methodologies (both wave and tide) that will impact on the geology of the REA area. All devices named have a connection to the seabed, but each differs in the level of seabed excavation required for mooring the device and that will impact on the seabed sediment and subseabed rock both during construction and afterward There may also be a secondary impact of construction on the coast too. The impacts will vary according to the nature of the construction and the sediment type and thickness and the subseabed rock type. Additionally, there will be impacts resulting from initial construction (short term) and the longer term impact of the established structure on the general environment, as well as at decommissioning.

Potential Impacts already identified in the Scoping Report include:

- Impacts on tidal current regimes and attenuation of wave energy, leading to,
    - Impact of sediment scour
    - Impact of sediment dynamics
- Impacts on the seabed from installation of export cables,
- Impacts on sub surface geology from devices and foundations,
- Impacts on seabed morphology,

- Impacts on sediment composition,
- Localised effect on bathymetry,
- Secondary impact on sediment movement,

Accordingly, the main environmental geological aspects are considered to be:

- Tidal currents,
- Water depth,
- Sediment type,
- Sediment boundaries,
- Rock types:
    - lithology, and
    - alteration,
- Sedimentary relationships between the coast and the offshore.

Of these the most important geological controls/relationships to consider are the:

- variation in the strength of the tidal currents notably between the channels and in the open sea areas that affect sediment dispersal,
- probable significant local variation in tidal currents that affects sediment dispersal,
- dominant coarse-grained nature of the majority of sediment in the REC area,
- thin sediment cover over most of the REC area,
- significant areas of exposed bedrock at seabed,
- large areas of shallow water shoals (affect currents and hence sediment dispersal),
- large areas of rugged seabed,
- dominance of fine-grained sediment (sand and gravel) in the channels with high tidal velocities,
- variability of the rock type at the seabed,
- dominant source of present day sediment from biogenic processes,
- relationships between seabed sediment and morphology and active biological activity

All of these may be impacted during construction, operation and decommissioning. However, it is clear that the size and nature of potential impacts are very project specific. The nature and magnitude of impact will depend on the type of sea bed engineering, with end members perceived as i) simple mooring devices and ii) pile driven foundations. Both may impact on the superficial seabed sediment but with increasing depth below the seabed the rock type present will become increasingly important. One major constraint on assessment of impact is the present limited data base and the lack of knowledge of construction on the bedrock; both of its geographical distribution and engineering properties. Thus, although the geological controls may be in principle established from the offshore database this database is limited and old. However, some general statements may be made. In addition, we will describe here the further studies and analyses that could be undertaken in the assessment of project and device specific impacts.

Key receptors to seabed construction and the mechanisms by which they are affected as follows:

1. Impact on seabed scour

The presence of high velocity seabed currents in some areas (such as the channels) indicates a potential for active sediment winnowing over some areas. This scour will depend on the current velocity and the sediment grain size. Thus there is a potential for seabed scour to occur in the vicinity of engineered structures, whether tethered or piled, and increasing with the scale of construction. The potential for scour will be greatest in areas of highest tidal currents in channels, and where the sediment is fine-grained (also in the tidal channels).

The impact could be from the generating device or the transmission cable to shore.

It is anticipated that there will be an initial impact during construction, and in areas of fine-grained sediment this will be greatest. The operational period will have the greatest long term impact.

Mitigating scour will be of paramount importance in the engineering design. The strongest seabed currents are in the Russel channels. As these are the prime areas for development of tidal power generation, these channels will be particularly vulnerable to this effect.

Although the Great Bank is understood to be formed under a different sedimentary/climatic regime, sediment activity on the Bank is unknown. Hommeril's research indicates that it is stable, but there is no modern high resolution swath type data, such as sonar nor, multibeam bathymetry to confirm this interpretation. The mobility of the fine-grained sediment in the Russels is also unknown.

New research is available on sediment movement in the REA area (notably the specific study on Sark Bank by M'hammdi 1994), (in French), and should be accessed and reviewed. The relationship between the offshore banks and the onshore coastal sand accumulations (such as on Herm) need to be established.

2. Impact on bedrock

There is a great variety of bedrock in the REA area, ranging from relatively soft rock (the limestone and marl of the Cretaceous and Tertiary) to the hard and indurated Precambrian igneous and metamorphic rocks. The weathering and alteration of these may mitigate their hardness, but this may result in other problems, because if the rocks are friable (as in the case for example of the gneiss on Sark) establishing deeper foundations for piled structures may result in other problems, such as increase in sea water pollution.

3. Impact on local coastal sediment systems

The potential impact of seabed structures on the wave energy climate is regarded as minimal as the sedimentary regime is dominated by tidal currents. However, the effects of seabed construction on tidal currents should be considered, particularly on potential impact on the overall sedimentary system – offshore to coast.

Not covered by this report (that is marine) is a possible impact on marine sediment delivery to the coast leading to increased coastal erosion of the adjacent islands. Two recent reports have investigated the erosion on the coasts Guernsey and Herm (GuernseyRenewableEnergyCommission, 2009; PosfordDuvivier, 1999). Both are comprehensive, in that they have identified problems and recommend solutions. However, they do not specifically identify the underlying cause(s) of erosion and no in-depth consideration of sediment sources and sinks. There is no overall sediment budget constructed for either Guernsey or Herm.

On Guernsey, the cause of erosion is most likely over use of beach sand for construction. Downstream impacts are expected to be from rising levels associated with global warming. It is likely, because most of the beaches are ‘pocket’ types, established in isolated bays, the sediment sources are local and regional mechanisms of natural replenishment do not have major influence.

On Herm, however, the beaches are different to those on Guernsey, especially the large area of ‘fossil’ sand in the north of the island. In northern area, on the north coast, there is rapid erosion taking place, reported (in a local newspaper) as ‘metres’ of recession per year. The causes of this erosion are not known. Hommeril (1967) identified an offshore source for the sand on Herm, from pre-existing sand banks, apparently there is an active one offshore to the east. Thus, if the erosion is as reported, any man-made interference in the vicinity of Herm, such as seabed infrastructure, might have an impact on the northern beach of Herm.

4. Impact on bio-sedimentary processes - biotopes

It is established that there are two main sediment sources: i) relict (mainly lithic and coarse-grained) and, ii) modern (biogenic). The biogenic sources are concentrated on sand banks. The degradation of marine shell provides the carbonate component of the modern sediment. The impact of seabed construction on the marine benthos will need consideration because of a potential impact on sediment productivity. This aspect needs to be reviewed in both a geological and biological context because of impacts on the biotopes in the REA. It should be noted that the biotopes are the result of a number of interrelationships and physical processes, including; water depth, the prevailing hydrodynamic regime, the seabed sediment type (grain size and lithology) and seabed morphology (itself dependent on sediment type, grain size and hydrodynamics).

5. Impact on biotopes

As discussed in 4. the biotopes of the REA are the result of a number of interrelationships and physical processes, including; water depth, the prevailing hydrodynamic regime, the seabed sediment type (grain size and lithology) and seabed morphology (itself dependent on sediment type, grain size and hydrodynamics). From Hommeril's mapping we know that there are a number of extant organisms in the area (see Figure 4.9.5 and 4.9.7) that could be impacted by seabed constructions.

4.13 Sensitivity of receptors

1. Seabed seabed scour - sediment mobility

   On the basis of present knowledge the main impacts of seabed construction on the geological marine environment would be expected to be confined to those areas of fine-grained sediment. If the fine sediment is not mobile under the current day regime, the seabed infrastructure would have little impact. However, as noted, the data base for the area is old and there is little information available for this report on the sand banks: the Great Bank and the Sark Bank. Present data available indicates stability, but this data is 40 years old.

   The coarse-grained sediment is regarded as stable.

2. Impact on substrate

   The present understanding of the bedrock geology, its engineering properties and geographical distribution is limited if not poor. In areas of rock older than the Mesozoic, it is difficult to image the detailed structure of the substrate by seismic methods, especially in a region of hard seabed, covered with pebbles and gravel. How the substrate around the Channel Islands was mapped on the BGS Guernsey 1:250.000 sheet is unknown, as it was provided by the French. However, it is likely that its distribution is based on the pebble content of the dredges acquired by Hommeril (1967). Thus the reliability of the mapped units is considered poor. This of course impacts of the knowledge of the engineering properties of the offshore rocks.

3. Impact on local coastal sediment systems

   The relationship of the sedimentary system (marine to coastal) is poorly known. The impact is considered low, but it is possible that there is a connection between the on and offshore that needs investigation.

4. Impact on bio-sedimentary processes – biotopes

   As with 3, the impact on biosedimentary processes is considered low, but needs investigation.

5. Impact on biotopes

   Very little research is available, and for this report there was no time to combine the geological and biological reviews. During seabed construction, there could be raised levels of water turbidity that could impact of benthic biotas. Similarly during decommissioning. This would particularly occur in areas of fine sediment.

4.14 Potential Significance of Effects

1. Impact on seabed scour - sediment mobility

Of local effect, with low magnitude of impact, except in areas of thick fine sediment, where it will be High. However, the response of tidal currents and wave climate to obstructions in the sea are unknown. Therefore, significance of seabed scour is also ‘unknown’.

2. Impact on substrate

Of local effect, with low magnitude of impact

3. Impact on local coastal sediment systems

Of local effect, with low magnitude of impact

4. Impact on bio-sedimentary processes – biotopes

Of local effect, with low magnitude of impact – although the database here is poor.

5. Impact on biotopes

Of local effect, with low magnitude of impact, except during commissioning and decommissioning. Main effect would be expected in areas of fine to medium grained sediment.

4.15 Likelihood of Occurrence

For all the potential effects of seabed construction, the likelihood of occurrence is considered low, however, there is insufficient data to establish this conclusively; this particularly in the instance of the biotopes, where no research has been undertaken. The exception is during construction and decommissioning in areas of fine sediment, when the likelihood of impact on biota is anticipated to be higher.

Table 4.15.1: Table outlining the probability of effect on receptors

Receptor	Effect	Likelihood of Occurrence
Fish/Cetaceans	Increase Water column turbidity during construction and decommissioning	Moderate during construction and decommissioning
Sediment transport	Increase scour in locations of seabed construction	High
Coast beaches	Erosion	Low
Seabed biotopes	Decrease in biodiversty	Unknown
Tourism	Increased coastal erosion of popular beaches	Low
	Decrease in Tourism due to loss of amenity	Low

4.16 Mitigation Measures

Whereas five individual impacts/effects have been identified, these may be broadly subdivided into two main themes:

1. Effects/impacts on substrate and,
2. Effects/impacts on sediment mobility (increased scour) and biotopes.

To address these impacts more information is required on present conditions, and long term programmes of monitoring need to be established. Firstly, environmental baselines need to be established before construction. Secondly, monitoring programmes need to be formulated, initially for conditions during and immediately after construction (high frequency) and, secondly, during operation. A final phase of high frequency monitoring could be set up to identify changes during decommissioning.

1. Effects/impacts on substrate

Here there needs to be identified and obtained data from onshore construction projects in rocks and lithologies similar to those offshore.

Potential sources of information include:

- the soil nailing project in St Peter's Port that Keller Foundations had an involvement with.
- site investigation data obtained by RSA Geotechnics Limited in the area of Guernsey airport:

http://www.rsa-geotechnics.co.uk/newsDetail.asp?NewsID=24

It is important to consider the engineering solution and approach prior to investigatory work in the preferred locations for construction. At the time of the preparation of the first draft of this report there was no design information available for the proposed development. Some of the technical issues relating to foundations and geotechnics for offshore installations in the UKCS can be found in Jardine (2009). This document includes a review of piling (driven) in a variety of ground conditions, including sands, clays and soft rock and Chalk. It also reviews jack up foundations and gravity base structure foundations. It identifies a number of geo-hazards that should be mitigated for, including the potential problem associated with 'running sands' and group effects of piling. Additionally, it provides a useful set of references.

Tomlinson (1995) recommends that foundations on rock should take account of jointing and weathering in the assessment of settlement of foundations. The influence of scale renders assessment of the deformation modulus of weak rock difficult. One approach is to conduct plate bearing tests within the zone of the potential stress bulb associated with the proposed structure. An alternative approach is to use the empirical relationship:

$E_m = jM_rq_{uc}$

Where,

E_m is the deformation modulus of the rock mass;

J is a mass factor related to the discontinuity spacing in the rock mass and broadly ranges between 0.2 in very poor rock and 1.0 in excellent rock;

Mr is the ratio between the deformation modulus and the unconfined compression strength (quc) of the intact rock.

Hobbs (1974) in Tomlinson (1995) indicates the modulus ratios presented in Table 4.16.1

Table 4.16.1: Characteristic modulus ratios (Hobbs, 1974, in Tomlinson, 1995)

Group	Characterised by:	Modulus ratio
1	Pure limestones and dolomites Carbonate sandstones of low porosity	600
2	Igneous Oolite and marly limestones Well-cemented sandstones Indurated carbonate mudstones Metamorphic rocks, including slates and schists (flat cleavage/ foliation)	300
3	Very marly limestones Poorly cemented sandstones Cemented mudstones and shales Slates and schists (steep cleavage/ foliation)	150
4	Uncemented mudstones and shales	75

This information has been used to establish broad ranges of allowable bearing values for a range of discontinuity spacings (Tomlinson, 1995).

As noted above, further sources of site investigation data have been identified and it is recommended that where possible these sources are utilised. Notwithstanding the above, there is only limited data available and the results of site investigation will be required to facilitate the engineering design. The nature of the investigation will need to be adapted to suit the anticipated ground conditions in the preferred location. This is likely to include a combination of intrusive investigation (boreholes) and geophysics to establish detailed bathymetry and material properties. Cone penetration testing (CPT) could be used to supplement the investigation in areas where there known sequences of Quaternary deposits. The use of CPT is potentially useful in areas that might be prone to liquefaction.

2. Effects/impacts on sediment mobility and biotopes.

As noted, the data on the sediment mobility of the REA is comprehensive, but 40 years old. The overall understanding of sediment mobility in the Normandy-Brittany Gulf is good on the regional scale, but there is uncertainty locally in the REA area. Four main issues have been identified:

1. potential impacts on seabed sediment mobility – impact of increased scour,
2. relationships between the seabed sediment and the coastlines (sediment budgets),
3. the potential impact on seabed biology and
4. the potential impact on biotopes.

All these are inter-related and require research to establish current baselines on which to base downstream monitoring programmes.

A starting point for this aspect of mitigation is the existing research held in French research theses (Hommeril, 1967; M'hammdi, 1994; Quesney, 1983). Hommeril (1967) has already been translated, and used in this report, but the translation was by a non-French speaker and needs review. The other reports need full translation and assimilation with this report. This will provide a good basis for evaluating the validity of this report in a modern context. It will provide data on the likely mobility of sediment movement in the REA. Any existing marine geophysical/geological data within the REA, but not accessed for evaluation of potential impacts here, should be reviewed and incorporated.

Secondly, a review of the coastal reports carried out in 1999 and 2007 (Haskoning, 2007; PosfordDuvivier, 1999) is required to establish the sediment budgets of the coastal areas of the REA islands. This review may require additional fieldwork to establish where the sediment 'sources, transport paths and sinks' are located. This report would also form the basis of a review of monitoring established from the previous reporting. Additionally, it would recommend future monitoring programmes in the context of potential new seabed infrastructure.

Thirdly, the results of the marine and coastal reviews should be integrated to establish relationships (if any) between the on and offshore; thereby to determine any potential impact from offshore construction.

Fourthly, all the biological and geological data should be integrated to establish the biotopes of the REA, their type and distribution. This would form a powerful tool for identifying any protected species and/or species of economic or cultural importance so as to ensure appropriate husbandry and securement of biodiversity. The result of this report would feed into the better understanding of the active sedimentary processes, noting that seabed biology is the most active contributor to present day sediment production.

Finally, any remedial action resultant on the above reporting should be carried out, followed by the establishment of appropriate monitoring programmes over both short and long timescales.

4.17 Confidence and Knowledge Gaps

To date it has been established that although there is considerable information pertaining to the tectonic setting, geology and geological history, which is integral to understanding the engineering geology, there is very little published information that details the engineering geology of this area. Potential sources of ground investigation data are known to occur from onshore work in Guernsey; thus it might be possible to access additional information through site investigation reports held by the States of Guernsey Building Control Department.

Additionally, there are significant gaps in knowledge on the activity of the present seabed environment in the REA area that has a negative impact on the confidence of predictions. Clearly, there is a lack of knowledge on modern seabed sediment mobility in the REA area and its relationship to the coasts of Guernsey, Sark and Herm.

Finally, there is a lack of knowledge on the biotopes of the REA area.

4.18 Residual Effects

Conducting the additional work identified in 4.16 would increase the confidence of predictions made in this report. It would establish better supported baselines on which to develop more appropriate and cost effective monitoring programmes on the impact of any potential seabed engineering development.

4.19 Recommendations for Survey and Monitoring

1. Access new French research reports,
2. Acquire additional data to update understanding of sediment movement in the REA area and sedimentary relationships between the on and offshore. Carry out additional surveys as identified and required.
3. Survey Herm coastline and establish a sediment budget and potential cause(s) of coastal erosion.
4. Access geotechnical reports from onshore construction projects to provide data on potential engineering geology of similar lithologies offshore.

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