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The Magellan mound province in the Porcupine Basin

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Abstract:

The Magellan mound province is one of the three known provinces of carbonate mounds or cold-water coral banks in the Porcupine Seabight, west of Ireland. It has been studied in detail using a large and varied data set: 2D and 3D seismic data, sidescan sonar imagery and video data collected during ROV deployment have been used to describe the mounds in terms of origin, growth processes and burial. The aim of this paper is to present the Magellan mounds and their setting in an integrated, holistic way.
More than 1,000 densely spaced and mainly buried mounds have been identified in the area. They all seem to be rooted on one seismic reflection, suggesting a sudden mound start-up. Their size and spatial distribution characteristics are presented, together with the present-day appearance of the few mounds that reach the seabed. The underlying geology has been studied by means of fault analysis and numerical basin modelling in an attempt to identify possible hydrocarbon migration pathways below or in the surroundings of the Magellan mounds.
Although conclusive evidence concerning the processes of mound initiation proves to be elusive, the results of both fault analysis and 2D numerical modelling failed to identify, with confidence, any direct pathways for focused hydrocarbon flow to the Magellan province. Diffuse seepage however may have taken place, as drainage area modelling suggests a possible link between mound position and structural features in the Hovland-Magellan area. During mound development and growth, the interplay of currents and sedimentation seems to have been the most important control. Mounds which could not keep pace with the sedimentation rates were buried, and on the few mounds which maintained growth, only a few corals survive at present.

Keywords Carbonate mounds - Cold-water corals - Porcupine Basin - Spatial distribution - Mound morphology - Fault analysis - Numerical basin modelling

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Keywords. *Carbonate mounds, cold-water corals, Porcupine Basin, spatial distribution, mound morphology, fault analysis, numerical basin modelling*

1. Introduction

The Magellan mound province is one of three provinces of carbonate mounds or coral banks in the Porcupine Seabight, west of Ireland (Fig. 1; Kenyon et al. 1998; De Mol et al. 2002). The mounds were first discovered in 1996 during a site survey with the MV Svitzer Magellan (Britsurvey 1997): the shallow structures recognised on seismic data were described in the survey report as ‘dome shaped knolls or mounds’, and were thought to have the same origin as the carbonate knolls reported by Hovland et al. (1994) just to the south and centre of the basin (‘Hovland mound province’, Fig. 1). Several research cruises with the RV Belgica, in 1997, ’98 ’99 and 2001, and the results of a 3D seismic survey shot for Statoil Exploration (Ireland) and its partners in 1998, provided further detailed information. Many more mound structures were discovered by examination of the seismic profiles. Comparison with previously sampled mounds elsewhere in the basin, together with the description of a limited number of samples from the Magellan mounds themselves (Kenyon et al. 1998), suggested that the Magellan mounds were associated with the growth of cold-water coral species such as *Lophelia pertusa* and *Madrepora oculata* (Britsurvey 1997, Henriet et al. 1998). The presence of deep-water corals and debris on the Magellan mounds was further confirmed during a recent ROV cruise (CARACOLE cruise, Olu-Le Roy et al. 2002).

The Magellan mounds differ considerably from other mound provinces in the Porcupine Seabight, described in detail by De Mol et al. (2002) and De Mol

(2002). The Magellan mounds are typically buried, although a few do reach the seabed. They are generally smaller, and the province covers a larger area and has a higher mound density than the other mound provinces. This setting, with both recently buried and surface mounds, provides a unique opportunity to constrain the overall geometry and the mechanisms that are responsible for mound initiation, growth and decay. Furthermore, they are excellent analogues for older, deeply buried mounds, often seen on seismic data.

Several hypotheses have been proposed to explain the origin, development and burial of mounds in general, and of the Magellan mounds in particular. Hovland et al. (1994) linked the occurrence of mounds to the presence of underlying faults, which were considered as pathways for hydrocarbon or fluid migration from depth to the seabed. Via a microbial link, the nutrient enhanced waters then would be the ideal location for corals to live. Henriet et al. (2001) suggested that the Magellan mounds may be influenced by pulses of seeping gas, released from gas hydrate layers which repeatedly waxed and waned during glacial/interglacial cycles. De Mol (2002) stressed the importance of the local current regime and the sedimentation rates during the mound development.

In order to study mound dynamics in terms of origin, growth processes and burial, a holistic, multidisciplinary approach is necessary. Hence the overall objective of this paper is to present the Magellan mound province and its surroundings from different aspects. The mounds are described, comprising an assessment of their morphology, their spatial distribution and their present-day appearance. In addition, the results from fault analysis and fluid migration modelling are used to evaluate the spatial relationship between mounds and underlying structures and to constrain likely fluid pathways in the region.

2. Regional Setting

The Magellan mound province is located in the north of the Porcupine Seabight, a bathymetric embayment in the North Atlantic Margin west of Ireland (Fig. 1). Water depths range from 250 m in the north to more than 3000 m at the mouth of the Seabight. The water mass structure in the area has been revised by Hargreaves (1984) and Rice et al. (1991). The upper layer (< 750 m) is formed by Eastern North Atlantic Water (ENAW), advected from the Bay of Biscay. Between ca. 750 and 1200 m a core of Mediterranean Outflow Water (MOW) can be found, followed by Labrador Sea Water down to 1700 m. Current measurements indicate an annual mean northward current of 3-10 cm/s at the seafloor, although seasonal variations may severely change these values. Tidal currents are enhanced in the area (e.g. Pingree and Le Cann 1989) and locally internal waves can be found (Rice et al. 1990). The detailed hydrography of the Seabight is described by White (this volume).

The Porcupine Seabight is underlain by the Porcupine Basin (Croker and Shannon 1987; Naylor et al. 2002). This underfilled sedimentary basin, of Upper Palaeozoic to Recent age, formed through a series of multi-directional rifts of Permo-Triassic, Upper Jurassic to Early Cretaceous and mid-Cretaceous age (e.g. Sinclair et al. 1994), interspersed with periods of pronounced thermal subsidence, sedimentation and igneous activity. Locally more than 9 km of Mesozoic and Tertiary sediments are present, which gradually onlap the basin margins (Moore and Shannon 1992). The syn-rift sequences are mainly characterised by clastic facies deposited in fluvial to deep marine environments. Post-rift deposition was dominated by fine-grained clastics and carbonates sedimented under deep-marine conditions. However, occasional tectonically-driven regressions took place, which resulted in a return to deltaic and shallow marine conditions (Croker and Klemperer 1989, Moore and Shannon 1992).

At the onset of the Oligocene, a major change in the oceanographic circulation pattern of the North Atlantic caused strong erosion in the Porcupine Basin. This event is marked by a Late Eocene - Early Oligocene unconformity (the ‘C30’ of Stoker et al. 2001 and McDonnell and Shannon 2001; Fig. 2a). Afterwards, sedimentation was dominated by shales and deep-marine deposits. A second, localised, Mid-Oligocene unconformity in the basin was followed by the onset of contourite drifts. Several other unconformities were recognised on seismic data, of which the Mid-Miocene (‘C20’) and Early Pliocene (‘C10’) are the most pronounced (McDonnell 2001, McDonnell and Shannon 2001).

A more comprehensive description and discussion of the geology of the Porcupine Basin and the Irish margin is given in Shannon et al. (this volume).

3. Methodology

3.1. Data

This study is largely based on an extensive seismic data set containing data from the following surveys (Fig. 1):

- A 3D seismic volume of about 1040 km2 acquired in 1998 by Statoil Exploration (Ireland) and its partners. The high quality data set extends down to 6 s TWT (two-way time) with inline and crossline spacings of 12.5 m and a vertical resolution of ca. 4 ms TWT. The survey covers only part of the Magellan province, but provides very valuable information.
- A set of high-resolution 2D seismic profiles, collected over several years by the RCMG (Renard Centre of Marine Geology; RV Belgica cruises). The data were mainly shot with a sparker or watergun source of 500 J or 140 bar, respectively, and were recorded using a single channel streamer. The vertical resolution of the data is about 1 ms TWT, and the penetration depth is ca 300 to 450 ms TWT, depending on the source used.
- A set of high-resolution 2D seismic profiles, obtained during a site survey for Total Marine Ireland Ltd. by the MV Svitzer Magellan in 1996. These data were shot with an airgun cluster and recorded with a multichannel streamer. The processed and migrated data have a vertical resolution of ca. 2 ms TWT and a penetration depth of 2 s TWT.
- Selected high quality 2D seismic profiles were used for the basin modelling, together with a set of maps of the main unconformities in the Tertiary (C10-40), derived from the interpretation of several industry 2D seismic surveys.

The seismic records were complemented with the following data that document the appearance of the present-day seabed over the Magellan province:

- Part of a recent TOBI (Towed Ocean Bottom Instrument) survey covering the Magellan province (RV Pelagia cruise M2002). The main instrument on the TOBI vehicle is a 30 kHz sidescan sonar. It has a swath width of 2 x 3 km, and the processed imagery has a typical pixel size of 6 x 6 m.
- One dive of the CARACOLE cruise (RV l’Atalante, 2001, deploying Ifremer’s ROV Victor 6000; Olu-Le Roy et al. 2002) was targeted towards 2 Magellan

mounds which reach the present-day seabed. About 14.30 h of video surveying data were collected along an 8 km track.

3.2. Study of the Magellan mounds

As a first step, the Magellan mounds, together with significant reflectors and seismic packages, were mapped in both the 2D and 3D data sets in order to identify the geometry and structural setting of the mounds and their embedding sediments. A complete description of the seismic facies is provided in Huvenne et al. (2003). The key reflections mapped are the following (Fig. 2b):

- TS (top slide unconformity): a high-amplitude continuous reflection forming the top of a chaotic seismic facies.
- MB (moundbase reflection): a regionally continuous reflection on which the Magellan mounds appear to be seated.
- MS (moundshape reflection): the first continuous reflection that can be traced over the mounds, interpreted as the surface indicating the beginning of their gradual burial. This reflection is used to characterise the shapes of mounds and moats (depressions in the reflections adjacent to the mounds).
- SF (seafloor reflection): mapped as an indication of the present-day expression of the mounds at the seabed.

The horizons were imported into a GIS and the mounds (and adjacent moats) were mapped semi-automatically from the MB-MS isochore map. A range of characteristics describing their morphology, such as their height above MB, width in N/S and E/W direction, cross-sectional area, and spatial distributions were extracted (see also Huvenne et al. 2003). The spatial distribution of the mounds was studied by means of Ripley's K-function (Ripley 1976, Cressie 1993).

The TOBI imagery was interpreted in terms of backscatter strength. In particular the difference in backscatter between mounds was noted, as this could indicate a difference in mound dynamics and burial stage. Core descriptions from previous cruises (Kenyon et al. 1998, De Mol 2002) and seabed images (Caracole cruise) were used as ground-truthing. In addition, video images from the Caracole dive were analysed for different types of seabed facies, which were mapped along the dive track.

3.3. Study of the underlying structure

The deeper parts of (mainly) the 3D seismic data were analysed in order to constrain the structural setting of the mound province. A series of fault systems, which characterise specific levels of the stratigraphy, were mapped and analysed at UCD (University College Dublin), and their spatial correlation with the mound locations was investigated. Special attention was also paid to a layer with a chaotic seismic character positioned at a shallow level beneath the mounds (Fig. 2b,d).

Numerical basin modelling, using the simulation program PetroMod3d® (version 7.1) from IES GmbH Jülich was carried out in order to predict the occurrence and composition of petroleum in time and space, focussing especially on identifying hydrocarbon migration pathways and directions, i.e. potential sites of gas leakage to the surface. Details are presented in Naeth et al. (this volume).

4. Results

4.1. The Magellan mounds

Seismic characteristics

The mounds are seen on 2D profiles as zones with a transparent acoustic facies (Fig. 2c,d), while in the 3D data they form small centres with chaotic reflections (Fig. 2b). All mounds in the province appear to be rooted on one reflection, mapped as MB. The reflections in the horizons directly below the mounds are generally continuous and not affected by any type of amplitude reduction or frequency change. Velocity pull-ups only occur beneath the larger mounds that reach the present-day seabed. Disturbances due to diffraction cones, resulting from the steep and sharp flanks of the mounds on the other hand are common. The mounds are embedded in a package of semi-parallel stratified reflections, about 100-120 ms TWT thick. Sometimes these abut abruptly against the mound flanks, and in other cases bend downwards creating a depression or moat surrounding the mound. Several of these abrupt ends or depressions create sharp diffraction patterns in the 2D seismic profiles. Moats that are crossed by seismic lines running besides the mounds, appear as single V-shaped depressions in the 2D data, often resembling the typical seismic pattern of pockmarks. Towards the tops of the mounds the reflections gradually onlap the transparent facies bodies, until they finally cover them and can be traced continuously over the mounds (see also De Mol et al. 2002). Most of the mounds are buried, although not all to the same depth, with only a few protruding to the present day seabed (see below).

Mound numbers and geometries

The mounds mapped from the 2D and 3D seismic data are shown in Fig. 3. Mapping results from the 3D data give a more complete representation of the actual mound density and shape, and therefore analysis of mound morphology and spatial distribution has been limited to this segment of the Magellan province. While the 3D volume only covers approximately one third of the entire province, it nonetheless provides a representative subset of the mound population. In addition, the 2D profiles allow the extrapolation – at least qualitatively – of the conclusions drawn from the 3D area.

In total 326 mounds have been mapped from the MS-MB isochron of the 3D volume, located in a sharply bounded, approximately NE-SW trending area of ca. 300 km^2. This results in an average mound density of approximately 1 mound per km^2. As the mound density seems to be constant over this block (Huvenne 2003), and over the whole province (ca. 0.45 mounds/km on high-resolution 2D data), more than 1000 mounds are estimated to be present in the Magellan province in the north of the Porcupine Basin.

The maps in Fig. 3 also show that many mounds are elongated in a N/S direction. This observation is even more striking for the moats, which in many cases joined up into large structures encircling several mounds.

Mound sizes and shapes have been characterised using the MS-MB isochron map from the 3D seismic data volume. The mounds are on average 72 m tall above the MB. This mean value is constant over the whole 3D area, with mound sizes, at the moment of deposition of MS, ranging from 50 to 157 m. Mound widths vary from 25 to 1450 m, with mean values in N-S direction of ca. 290 m and in E-W direction of ca. 200 m, illustrating the significant N-S elongation. The corresponding mean cross-sectional area is 0.051 km^2. The moats are on average

24 m deep, although there is considerable variation in depths, and the corresponding mean moat cross-sectional area is ca. 0.5 km^2. Most of these mound and moat characteristics have a skewed distribution, with many small and only few large structures (Fig. 4). A similar result was found by O'Reilly et al. (2003) in the Rockall Trough. A more extensive description of the morphological characteristics of mounds and moats in the Magellan province, together with an assessment of their size distributions, is given in Huvenne et al. (2003), and especially in Huvenne (2003).

Depth and isochore maps of some underlying horizons and sequences are presented in Fig. 5. The different horizons have a similar slope and dip direction, but the isochore maps show that different depocentres existed for the different sequences. The Magellan mounds are located along the southern margin of a large lens-shaped deposit between the TS and MB reflections, interpreted as a mounded sediment drift. The majority is embedded in/covered by locally thick deposits in the sequence between MB and SF.

The biggest mounds are mainly located along the WNW edge of the mound cluster in the 3D volume. They are the widest structures, and display the largest variation in mound morphology. Significantly, these mounds are located where the sediment cover is thinnest, on the edge of the deposit between MB and SF (Fig. 5). It is suggested that mounds in these circumstances experienced less stress from the continuous hemipelagic sedimentation, and therefore could develop better.

Spatial distribution of mounds

For the study of the spatial distribution of the mounds, Ripley's K-function was used (Ripley 1976, Cressie 1993). This function is defined as: *K(h)* = $1/\lambda$**(average number of extra mounds in a circle of radius h around an arbitrary mound);* in which λ represents the mound density (number of mounds per area). In case of completely spatially random processes, $K(h) = \pi h^2$. In case of clustering the estimated *K(h)* will be higher, in case of regular spacing between the mounds, *K(h)* will be lower.

For the calculation of the K-function, the locations of the mound tops were digitised from the MB-MS isochore map, in order to eliminate possible errors of

the automatic mapping algorithms in the GIS. The analysis was limited to the main area, leaving out the two separated mounds to the north (Fig. 3). The resulting K-values are presented in Fig. 6. At the MS level, the Magellan province has a triple structure. Over distances of less than 400 m the mounds appear to be regularly spaced, they are repulsive towards each other. This result was expected: as the average mound width is 250 m, mounds located close to each other probably will have merged together, and be counted as one mound. The regularity effect is quickly accommodated for, and for medium distances mounds seem completely randomly distributed, with a slight hint of clustering between 750 and 1250 m, however only significant at a range of about 800 m. Over distances larger than 2000 m the mounds appear to be clustered. This is due to the large-scale structure in the mound pattern: a few zones with higher and lower mound density can be distinguished in the mound set. The highest densities seem to occur mainly in the western part, while in the eastern part locally mounds are wider spaced.
To validate the results obtained from this one observed K-function, a Monte-Carlo test was performed, based on 50 simulations of spatially random processes with the same density, in the same province area as the original mounds (Fig. 6). It is obvious that for small ranges the mound process has lower K-values than the simulations. Hence the observed mounds are different from a completely spatially random process on a 1 % confidence level. The conclusions about clustering are only significant at ca. 800 m, and from a distance of 2600 m onwards, and only at the 5 % confidence level, as 1 or 2 of the simulations exhibit higher K-values than the observed ones.

Present-day appearance at the seabed: results from TOBI and VICTOR 6000

In general, the Magellan province appears on the TOBI sidescan imagery as an area with a homogeneous acoustic facies of medium, although rather ‘grainy’ backscatter strength (Fig. 7). Boxcores and seabed photographs/video fragments identify this facies as bioturbated muddy or silty hemipelagic sediments (Kenyon et al. 1998). The seafloor seems to be more or less featureless, apart from the obvious mounds that reached the seabed. Evidence of present-day erosion or sedimentation patterns, such as bedforms, are absent. Against this background, the mounds are clear features, even if they are much smaller than the giant structures

found in the Hovland province. Most of them have a strong backscatter on the flank facing the instrument, both due to their slope and to their composition (see below). Some mounds are rather smooth and do not create a strong shadow. These structures are buried under a sediment drape, as can be interpreted from the seismic data.
The moats are only vaguely discernible from slight variations in backscatter strength as the seafloor slopes away or towards the sidescan sonar. Also further to the centre and the north of the Magellan province, comparable vague variations in grey levels can be interpreted, with the help of the bathymetric information, as depressions, representing traces of filled moats located deeper in the sedimentary succession. Again, the general orientation of these patterns is N/S.

Two mounds were studied during the Caracole cruise in 2001, using the ROV Victor 6000 (Fig. 8). The seabed mound feature to the SW is often referred to as 'Mound Perseverance', is elevated about 50 m above the present-day seabed, and is elongated in a NNE/SSW direction. The total height of this mound above the moundbase is ca. 160 m, hence its seabed expression is only one third of the complete mound structure. The second mound studied is located slightly more to the NE. This structure is a double mound with two summits, elongated in ENE/WSW direction. The peaks reach 33 and 55 m, respectively, above the surrounding seabed.
Seven sedimentary facies were recognised on the video data: (1) heavily bioturbated sediment (high concentration of burrows), (2) lightly bioturbated sediment (low concentration of burrows), (3) non-bioturbated (sandy?) sediments, (4) scattered coral debris, (5) abundant coral debris, (6) dead coral (containing an open framework structure, devoid of sediment), and (7) live coral. The facies map (Fig. 8) shows that the largest part of the area is covered by bioturbated muddy sediments. Coral debris, dead and live coral are only found on the mounds, causing part of the high backscatter response in the TOBI data. On most of the mound flanks, there appears to be a neat transition from more to less bioturbated sediments, over non-bioturbated sediments up to limited, or more extensive, amounts of coral debris. The occurrence of dead coral seems to be rather patchy. Live corals are only encountered on the highest mound tops, or on a shoulder of Mound Perseverance. The most abundant species are *Lophelia pertusa* and

Desmophyllum sp. They occur as bushes or 'thickets', built of a framework of older coral material (*Lophelia*) with live polyps at the outer shell, mostly facing the downslope direction (especially the *Lophelia*). The 'thickets' occur in groups of 5 to 10, are about 1 to 1.5 m across and 0.75 to 1 m high, and give the impression of shrubs on a hilltop. Their internal framework does not appear to be filled by sediments. They are not necessarily placed amongst or on top of large amounts of dead coral (as is the case in e.g. the Haltenbanken-Frøyabanken area and on the Sula Ridge off Norway (Mortensen et al. 1995, resp. Freiwald et al. 2002)), and are often situated in areas of coral debris and patches of plain sediment. On most of the mound flanks, the transition from bioturbated sediments to the debris facies occurs at a depth of ca. 635 m.

4.2. Pre-mound structure and stratigraphy

Fault analysis results

Three stacked fault systems were found within the 3D seismic data (Bailey et al. 2003; Fig. 2a) :

- The lowest fault system comprises large (up to km-scale displacement) Jurassic to Early Cretaceous syn-rift growth faults. Throughout the basin these faults strike predominantly N-S and locally NE-SW, and they define the present-day structural configuration of the Porcupine Basin. The majority of these faults are buried by up to 3 s TWT of sediment, but a few show post-Cretaceous reactivation and extend up to the Miocene or Pliocene succession.
- Systems of N-S trending intraformational faults (max. displacement < ca. 250 m) have been found, mainly constrained between the Base Tertiary and Base Oligocene (C30) reflections. These faults are organised in well-defined systems, located above the Jurassic-Cretaceous syn-rift basin margins, largely within packages of submarine fan deposits. Their location along the basin margins and their time of formation suggest that they are the product of significant differential subsidence (and compaction) of the basin in the Eocene (Bailey et al. 2003).
- Polygonal faults are present as localised packages throughout the basin and are confined to Paleogene and Neogene layers. One of these packages is present in

the 3D seismic data set, in a mudstone-dominated Eocene sequence. It is also truncated by the C30 unconformity.

The various fault systems have been mapped, and their spatial distribution has been compared with the locations of the mounds (Fig. 9a and b). However, no convincing spatial relationship is found between mounds and fault systems. Additionally, also very small (< 5 ms TWT throw) compaction-related faults are present at relatively shallow stratigraphic levels (Fig. 9c), but again, there is no clear relationship between the spatial distribution of the faults and of the Magellan mounds (see also Bailey et al. 2003.).

A buried slide

Within the seismic data, at shallow depth, an intensely faulted interval with chaotic reflector configuration has been identified and interpreted as a buried slab slide (Huvenne et al. 2002, Bailey et al. 2003). The slide contains a set of relatively undisturbed polygonal blocks of 100 to 500 m in diameter, and has a sharp downdip termination to the SE (Fig. 2d and 10). Reverse offsets are characteristic of the faults along this part of the slide and the intervening blocks form distinct arcuate compressional ridges, which collectively form a ‘toe’ region. The main body of the slide is characterised by conjugate sets of faults, which, at the limit of resolution, display evidence of both extensional and reverse offsets, with indications of sediment mobilisation in the form of small ‘diapiric’ ridges at the base of the slide (Bailey et al. 2003, Huvenne et al. 2002). Most of these features are similar to those in polygonal fault systems and by analogy are interpreted as the result of the build-up and release of overpressure in a shale-rich layer, which also induced sliding. However, the amount of lateral movement of the blocks is very limited.

Within the 3D seismic data block, most of the mounds are underlain by this slide interval, which could suggest a causal link. However, the extent of the slide facies and the sharp toe edge could be mapped from the 2D seismic data beyond the limits of the 3D data set. This mapping clearly shows that a large part of the Magellan province is not underlain by this slide (Fig. 10) and hence it is unlikely that there is an obvious or direct link between the slide and the mounds.

4.3. Modelling results

Preliminary 2D migration modelling has been undertaken using regional seismic lines to determine whether or not hydrocarbon migration is expected in the region of mound provinces (Naeth 2003, Naeth et al. this volume). Modelling in the Magellan province is based on the interpretation of a N-S oriented regional seismic line MS81RE-94 (Fig. 11) and on maps of several Tertiary horizons, based on the MS81 seismic survey and which were mapped and provided by the EU Fifth Framework STRATAGEM project. The results suggest a dominant migration pattern involving lateral focussed hydrocarbon flow along Aptian and Miocene sandstones. In addition, a general pervasive vertical component of migration is present, which is due to the low seal capacity of the sedimentary sequences overlying the sandstones. The 2D line modelled showed no obvious focussing of hydrocarbon leakage towards the sites of mound occurrence, even when the spatial variation and lithologic contrasts of Early Tertiary deltaic sequences, slump structures and Late Tertiary contourites (McDonnell 2001) were taken into account. This lack of focussing in the models could be due to an actual absence of focussed hydrocarbon flow, to insufficient resolution of the model, or could be simply attributed to difficulties in modelling a 3D process such as hydrocarbon migration using only a 2D seismic line. In order to address this latter assumption a map-based migration modelling approach was chosen.

As the structure and topography of horizons can direct flow laterally and can influence the fluid migration, drainage area calculations were used, based on the present-day topography of the horizons, in order to analyse possible flow patterns in the study area (Naeth 2003). The horizons included were the near Base Oligocene (C30), Base Miocene, Mid-Miocene (C20) and Pliocene (C10). The drainage area calculations show a remarkable coincidence of most Hovland mounds with closures in the underlying horizons. This is especially obvious when the drainage area boundaries and closures from all maps are considered together (Naeth 2003). The coincidence is, however, limited by the rough resolution of the maps and their limited spatial extent. The Magellan mounds are not so much coinciding with these closures, but they seem to follow roughly a northeast-southwest trend, parallel to some of the calculated drainage area boundaries. These boundaries could indicate a possible link to a deeper structure, for example a structural or stratigraphic feature such as observed beneath the Belgica mound province (Naeth 2003, Naeth et al. this volume).

5. Interpretation and discussion

5.1. Mound initiation

One of the most intriguing questions concerning the Magellan province, and concerning all mound provinces in the area, is why and how the mounds were initiated, and why they developed at these locations and not in other places. The seismic data show that the Magellan mounds are located in a sharply bound province, and that they are all (within the time resolution of the seismic data) rooted on one reflection, the moundbase. Britsurvey (1997) referred to this horizon as ‘near base Quaternary’, an interpretation followed by De Mol et al. (2002), who date the moundbase as (Late) Pliocene. Mapping of the reflection throughout the basin by McDonnell (2001) suggested that it may be correlated with the regional, Pliocene C10 unconformity of Stoker et al. (2001) and McDonnell and Shannon (2001).

The fact that all mounds are rooted on the same moundbase, an unconformity indicating a period of erosion or non-deposition, strongly suggests a geologically instantaneous event that was responsible for the nucleation of this mound field. A similar situation is found in the other mound provinces in the Porcupine Seabight (De Mol et al. 2002). Also within the Rockall Trough several provinces of mounds have been found, rooted on an erosional unconformity (Kenyon et al. 2003), although van Weering et al. (2003) locally recognised at least 2 phases of mound initiation.

However, mounds could only start growing if the conditions for the growth of their main constituents, deep-water corals, were met. This presumes, however, that the mounds consist entirely of the same type of material as found at the present-day seafloor. While there is only geophysical information about the base of the mounds, the fact that the seismic mound facies is so homogeneous from top to bottom suggests that coral debris and bioturbated sediments probably occur throughout the mounds. Kenyon et al. (1998) and De Mol et al. (2002) described shallow gravity cores from Magellan mounds. They consist of packages of dead coral framework interbedded with foraminiferal mud and coral fragments. Coral occurrence in the mounds appears to be patchy, both in vertical and horizontal directions, which probably causes the homogeneous, acoustically transparent facies.

The environmental factors that govern deep-water coral growth are described in detail by, for example, Frederiksen et al. (1992), Freiwald (1998) and Rogers (1999). Particularly important are the presence of a hard substratum, the correct temperature and salinity conditions, a nutrient supply and sufficiently strong currents in order to keep the corals free from sedimentation and to bring enough nutrients to the filter-feeders. The corals often prefer topographic elevations as settling grounds, where streamlines are condensed and currents are enhanced. Evidence of localised elevations are absent on the MB reflector in the Magellan province, but the seafloor, at/after this period of erosion or non-deposition, may have been scattered with coarse materials and patches of compacted sediments, creating sufficient hard substratum for the *Lophelia* corals to settle and initiate a new mound structure.

The presence of hardgrounds has often also been related to hydrocarbon seepage, resulting in microbial chemosynthesis and the formation of so-called 'chemoherms' (Roberts and Aharon 1994). They form a stable substrate that can also be used by corals to settle and grow (Wilson 1979), initiating carbonate mound growth. From the present geophysical data sets it is not possible to identify the origin of any potential hardgrounds at the moundbase, but it seems that the corals have not had great difficulties in finding a hard substrate to settle on.

The abrupt start of mound growth has been related by Hovland et al. (1994) to sudden, localised and direct seepage along deep-seated faults to the surface. However, no convincing spatial correlation between the different fault packages and the mounds was found in this study. Furthermore, 2D basin modelling did not reveal obvious focussed hydrocarbon or fluid flow pathways towards the Magellan province. Hence the Hovland et al. (1994) model does not seem to be valid for this area. It is possible that diffuse seepage may have played a role, occurring along a system of small faults below the resolution of the 3D seismic data, although this remains speculative. From this point of view the faulted slide interval may have been important, although it only underlies half of the Magellan mounds, while the mound density is constant over the whole province. Therefore it probably was not a major factor in the mound initiation. The results of the drainage area modelling suggest that there may be a link between the mound province location and deep-seated tectono-stratigraphic controls such as a shelf break or the pinch-out of a sandstone layer similar to the one observed beneath the Belgica mound province (Naeth et al. this volume). Mound location and hydrocarbon drainage could then be linked by vertical, diffusive (at the scale of the seismic data) migration, although also this point needs further investigation. Nevertheless, if there has been a process of seepage at some point, it has ceased nowadays, as no evidence could be found for it in shallow seabed cores (De Mol 2002). In addition, ample evidence has been found for fluid flow along faults, tilted blocks and gas chimneys in the Connemara oil field, in the northern part of the Porcupine Basin (Games 2001, Rabaute et al., this volume), while no carbonate mounds or corals have been recorded in this area.

As an alternative, the sudden onset of mound growth has been explained by De Mol et al. (2002) as a consequence of the sudden change of oceanographic patterns in the Late Pliocene. Together with the reintroduction of the Mediterranean Outflow Water in the North Atlantic (as far as the Porcupine Seabight (New et al. 2001)), larvae of *Lophelia* and *Madrepora* species may have been spread along the European margin, from Gibraltar to Norway. The density contrast between the MOW and the ENAW may have induced locally enhanced bottom currents, due to the development of internal waves and tides in areas where the seabed slope exceeded the critical slope (Huthnance 1986, Pingree and LeCann 1990). These would have been beneficial for the initial coral build-ups. However, even if this may have been the case in the Belgica mound province, the slope of the moundbase under the Magellan mounds is too shallow to create such an effect.

The present-day available data set of the Magellan province, as it is studied here, does not give sufficient evidence to support one or another hypothesis concerning models of mound initiation in the area. One can even wonder whether or not both geological and oceanographic processes played a role. For example, hardgrounds formed preferentially at sites of paleo-hydrocarbon leakage could have provided the incentive for coral growth, but subsequent mound development did not need to be dependent on active seepage. In any case, analysis (e.g. fluid inclusion) of deeper cores is a prerequisite to testing whether or not hydrocarbons were ever present in this area.

5.2. Mound development

While the actual causes for the mound start-up are still unclear, the important factors during the mound development are better understood. The morphologies and spatial distributions of the Magellan mounds are completely different compared to the other mound provinces in the area (De Mol et al. 2002, Huvenne et al. 2003). Magellan mounds are smaller, mainly narrower, much more numerous, and clustered to a certain degree. Mounds that managed to survive until the present day are generally located on the WNW edge of the province, the area where the embedding sediment cover is the thinnest. The other mounds are covered by the thicker sequences of the deposit. Therefore, the sedimentation rate and pattern seems to be a very important factor in the mound development as suggested by De Mol (2002) and Huvenne et al. (2003). The depositional environment in the Magellan province was quieter than in the other Porcupine provinces, and sediments were draped continuously over the area. This severely limited the mounds in their vertical and horizontal development, and caused their early burial.

The N/S elongation of mounds and moats indicates the influence of a N/S directed current system. The characteristic shape of the Magellan moats even suggests that currents were periodically reversing, and part of an oscillating current pattern (Huvenne et al. 2003). Their frequency and amplitude are unknown, but present-day current patterns in this part of the Porcupine Seabight still consist of a weak residual current, and a stronger tidal component, also due to the intensification of the diurnal tides in the area (White 2001, Mohn et al. 2002).

The apparent clustering of the Magellan mounds at an inter-mound distance of ca. 800 m, may be related to the combination of these 2 important factors: current regime and sedimentation. The presence of the mounds on the seafloor, once they had reached a certain height, caused locally enhanced currents and turbulence in the water column. Especially in the beginning of the mound development, moats were scoured out in a locally erosive process. These enhanced currents could have been slightly favourable for other mounds close-by, keeping them free of sedimentation. This way, mounds, located at the right distance, could influence each other, and it caused moats of adjacent mounds to join into extensive scouring structures. In instances where mounds initiated very close to each other (<400 m), two scenarios were possible. On those locations where the sedimentation was a little less, mounds could start from several patches of corals, expanding in the horizontal direction, until they eventually reached each other and formed multiple structures (e.g. along the WNW edge of the province). In those areas where competition was stronger (ESE side of the province), possibly only the fastest growing of the different coral patches could gather enough nutrients, while the other close-by initial mounds did not survive. The large-scale spatial pattern, with patches of denser and less dense spaced mounds might also be related to positive influence of mounds upon each other, or may simply indicate a patchyness in the distribution of favourable conditions for mound development. Although the overall mound density of ca. 1 mound/km^2 is approximately constant over the province, there seems to be a slight difference in density between the eastern and western part of the mound set in the 3D seismic data. This is probably comparable to the variability in mound 'volume' or horizontal expansion, which differs considerably between the WNW edge of the province, where sedimentation was less and currents were stronger, and the ESE side, where a thicker package of sediments was deposited, hampering the mounds in their development.

5.3. Burial and present-day state

Due to a possible reduction in current strength, sedimentation slowly took over in the Magellan province. Moats were no longer eroded, and after a period of non-deposition, they were even gradually filled with sediments. Higher up in the sequence, sediments start to onlap the mounds, until they eventually drape across the mound structures. Present-day moat depressions on the seafloor are not active any more, and are covered with the same bioturbated fine-grained sediments as can be found elsewhere in the province. This illustrates the importance of the effect of sedimentation on mound development. The Magellan mounds were clearly no longer situated in a good location of the Porcupine Seabight for mound development. Only a few mounds survive today, and even they seem nearly dead. Most of the material found is debris or dead coral, often covered already with a thin veneer of sediments. Live coral can only be found at the mound tops or on a spur, and consists of a few meagre thickets. However, it is striking that these thickets are placed on a surface of coral debris, and not amidst bunches of dead coral. Are they the last few bits of coral surviving on the mound, or have they just recolonised a mound of coral debris, on which they could find a hard substrate to start growing? In any case, it is not a very good environment for coral growth, looking at their limited abundance and their tendency to face the downslope side of the mounds, in order to catch as many nutrients as possible, brought by the currents.

5.4. Further questions

The investigations of the Magellan province to date have revealed a large amount of information on the phenomenon of mounds and their surroundings in the area. However, many questions are still unanswered. Deep drilling would be the only way to find conclusive evidence for one or more of the hypotheses concerning mound initiation and development. Especially sampling of the MB would be necessary, in order to obtain more information about the lithology and the sedimentology of the succession. Dating of this horizon would allow to set the mound initiation in a regional time frame, and to link it to possible environmental changes or events.

There are other important sampling targets in addition to the MB. The complete mound facies, from top to bottom, could reveal information about the mound development. Also the sediments, in which the mounds are embedded, are worth studying, as are the sequences directly below the MB. The story of the Magellan mound province is not yet completed.

6. Summary and conclusions

This paper provides an overview of the Magellan mound province and its surroundings in the Porcupine Seabight, west of Ireland. An integrated approach was used, based on an extensive data set, including 3D seismics, high-resolution 2D seismic data, 2D seismic profiles for basin modelling, sidescan sonar imagery and video images collected during an ROV dive.

- In total more than 1000 mounds are expected in the Magellan province, occurring with a spatial density of ca. 1 mound/km^2. They are influenced and shaped by N/S oscillating currents. Most of them are buried, the few mounds that reach the present-day seabed are generally located on the WNW edge of the province, where the sediment cover is the thinnest. Some of them still exhibit live coral, although in general they seem to be loosing their struggle against the sedimentation.

- Seismic evidence shows that all the mounds are rooted on one reflection, indicating a sudden start-up event.
- Mounds seem to be clustered at an inter-mound distance of ca. 800 m and from a distance of 2000 m onwards (significant at >2600 m). It is possible they could benefit from turbulence and locally enhanced currents, caused by the other mounds in the cluster. Within very short distances (< 400 m), mounds seem to be regularly spaced or repulsive. Mounds that initiated so close to each other may have merged.
- Under the Magellan province, 3 stacked fault layers have been identified, but none of them has an obvious spatial correlation with the mound locations. A chaotic interval in the seismic records has been interpreted as a buried slab slide with the characteristics of polygonal faulting. It underlies the western half of the Magellan mound province.
- 2D basin modelling did not reveal obvious focused hydrocarbon flow towards the Magellan province. However, a deeper, tectono-stratigraphic control may have influenced their setting.

Based on the present study, no conclusive evidence could be found for any of the hypotheses concerning the mound initiation. There is no evidence to support the model of Hovland et al. (1994), involving fluid seepage along faults directly underneath the mounds, in the Magellan province. A more diffuse type of seepage was suggested by drainage area modelling, linked to a deeper tectono-stratigraphic control. However, more investigations are necessary before this can be proven. Especially sampling of the mound base is one of the prerequisites before conclusions can be drawn on the origin of mound growth in the Magellan province.

The main factors of influence during the mound development and burial appear to have been the current speed and sedimentation rate/pattern. These are very important for the coral growth: corals in the Magellan province had, and still have, to struggle against the sedimentation rates. Hence it can be concluded that even if seepage maybe influenced the mound start-up phase, during the later development of the structures the currents and sedimentation were the most important factors.

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Figures

Fig. 1 Overview map of the Porcupine Basin and its mound provinces. PB: Porcupine Bank, MMP: Magellan mound province, HMP: Hovland mound province, BMP: Belgica mound province. Bathymetry derived from GEBCO (1997) database, contour interval: 100 m. Mapping software used : GMT (Wessel and Smith 1991).
Inset : location map of the seismic data set used in this study. Dot-dashed lines: high-resolution sparker and watergun seismic data, full lines: industrial seismic data (high-resolution site survey and seismic line MS81RE-94 used for basin modelling).

Fig. 2. (a) Profile through the 3D seismic volume, showing the underlying geology in the Magellan mound province, containing 3 stacked fault systems. It illustrates the spatial relationships between Jurassic faults, intraformational Tertiary faults and polygonal faults, and mounds (after Bailey et al. 2003).
(b) Representative arbitrary profile through the upper 400 ms TWT of the 3D seismic volume, showing the mapped key reflections and the appearance of the mounds, moats and slide interval in the 3D data. This profile is located along the same track as the high-resolution 2D profile shown in Fig. 2c (see also Fig. 1 and 3 for location).
(c) High-resolution 2D sparker profile illustrating mounds, moats and the slide interval. The mounds appear as acoustically transparent zones, however, no amplitude reductions are visible below them. The key reflections, chosen from the 3D seismic data, have been mapped as well. Due to the difference in vertical resolution and nature of the data, the MS reflection is not continuous over all mounds in this profile.
(d) High-resolution seismic profile from the Britsurvey site-survey (Britsurvey 1997), again showing mounds, moats and slide interval, together with the key reflections. The profile clearly illustrates the sharply bound slide toe.

Fig. 3 Mapping results:
(a) Isochore map of the sediment thickness between the MB and MS horizon within the 3D seismic data volume, showing the mound and moat locations. Triangles indicate the mounds mapped from 2D seismic data. Coordinates in m UTM.
(b) Mound locations and shapes in the 3D seismic data volume, extracted by means of mathematical morphology (Huvenne et al. 2003). Background: time depth contours of the MB horizon, contour interval: 10 ms TWT.
(c) Moat locations and shapes in the 3D seismic data volume. Background: time depth contours of the MB horizon, contour interval: 10 ms TWT.

Fig. 4 Examples of histograms of mound characteristics, illustrating their skewed frequency distribution (after Huvenne et al. 2003):
(a) mound height at the MS level
(b) mound width at the MS level, in E/W direction

Fig. 5 Mapped key horizons (coordinates in metres UTM):
(a) Time depth map of the TS horizon, with the mound positions
(b) Time depth map of the MB horizon, with mound positions
(c) Time depth map of the seafloor, as approximation of the local bathymetry. Some mounds are still visible.
(d) Isochore map of the sequence between TS and MB, with mound positions. A lens-shaped sediment drift can be seen NW of the mounds.
(e) Isochore map of the sequence between MB and SF. Again several mounds and moats can be seen. Deposition mainly occurred over the (SE half of the) mounds, and in the very northern corner of the data volume.

Fig. 6 Ripley's K-function, calculated for the mounds in the 3D seismic volume (thick grey line), for the theoretical case of complete spatial randomness (broken grey line) and for 50 simulations of a completely spatially random process with the same average spatial density as the mounds in the Magellan province. $\sqrt{K(h)/\pi}$ is plotted versus the radius h. Units on both axes are in meters. For inter-mound distances <400 m the mounds are regularly spaced (curve below the cases of complete spatial randomness), for distances >2600 m mounds are significantly clustered (curve towards the maximum of the simulations of complete spatial randomness). For distances between these two values, mounds are randomly spaced, with a hint of clustering being strongest at a range of about 800 m.

Fig. 7 Detail of TOBI sidescan sonar mosaic covering part of the Magellan mound province, overlain by bathymetry derived from the 3D seismic data (contour interval: 10 m). The location is indicated on Fig. 3.

Fig. 8 Caracole cruise, ROV Victor dive 127:
(a) Facies interpretation of the video data plotted along the dive track. Bathymetry derived from the 3D seismic data, contour interval 10 m, location indicated on Fig. 7.
(b) Detail of the facies interpretation of Mound Perseverance. Contour interval 5 m.
(c) The general background sediment in the area: heavily bioturbated fine-grained sediments.
(d) Abundant coral debris, covered with a thin veneer of hemipelagic sediment.
(e) Thicket of live coral on top of Mound Perseverance.
All photographs : ©IFREMER, Campagne CARACOLE.

Fig. 9 Coherence maps showing the distribution of different fault systems in the 3D area (after Bailey et al., 2003).
(a) Intraformational faults at the level of the Eocene reflector marked in Fig. 2a. The positions of mounds at the MS reflector are shown in white. The irregular SE boundary to the map is caused by erosion of the Eocene reflector by the C30 unconformity.

(b) Detail of the polygonal fault pattern that overlies the intraformational faults. Note the N-S trending basement reactivated fault to the far west. The south-easterly extent of the polygonal fault system is shown in (a) and is caused by erosion corresponding to C30 and Miocene erosional events.

(c) Map for an arbitrary reflector located 125 ms below the MB reflector, showing the distribution of small (>5 ms throw), shallow-level faults. Again the positions of the mounds at the MS level are plotted on top. Note that there is no direct spatial correlation between the faults (in (a), (b), or (c)) and the mounds.

Fig. 10

(a) Gradient map of the TS unconformity within the 3D seismic volume, indicating the slide toe and headwall scarp (strong gradients are darker). Mound positions are shown, mounds mapped from 2D seismic data appear as triangles. Red diamonds indicate the locations where the slide toe could be mapped from the 2D seismic data, the thick black line is a tentative indication of the extent of the slide toe.

(b) Amplitude map of the TS unconformity, shifted downwards by 43 ms (indicated on the profile in Fig. 2b), illustrating the blocky pattern of the slide interval. After Huvenne et al. (2002)

Fig. 11 Modelled gas (red arrows) and oil (green arrows) migration on profile MS81RE-94 through the Magellan and Hovland mound provinces. No obvious focussed flow is visible towards the mounds. After Naeth (2003).

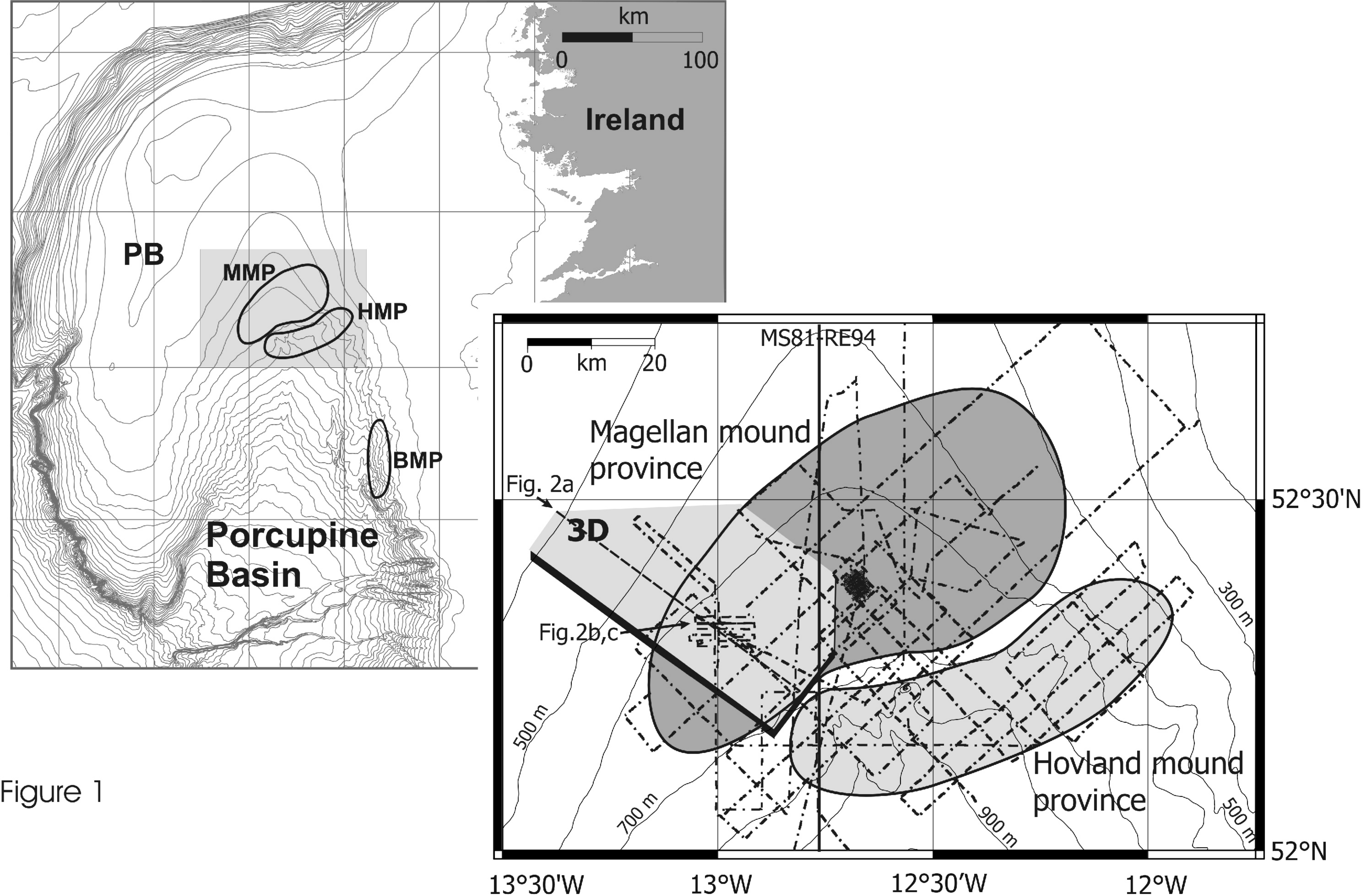

km
0
100
Ireland
PB
MMP
HMP
BMP
Porcupine
Basin
MS81-RE94
0
km
20
Magellan mound
province
Fig. 2a
3D
Fig.2b,c
Hovland mound
province
300 m
500 m
700 m
900 m
500 m
52°30'N
52°N
13°30'W
13°W
12°30'W
12°W

Figure 1

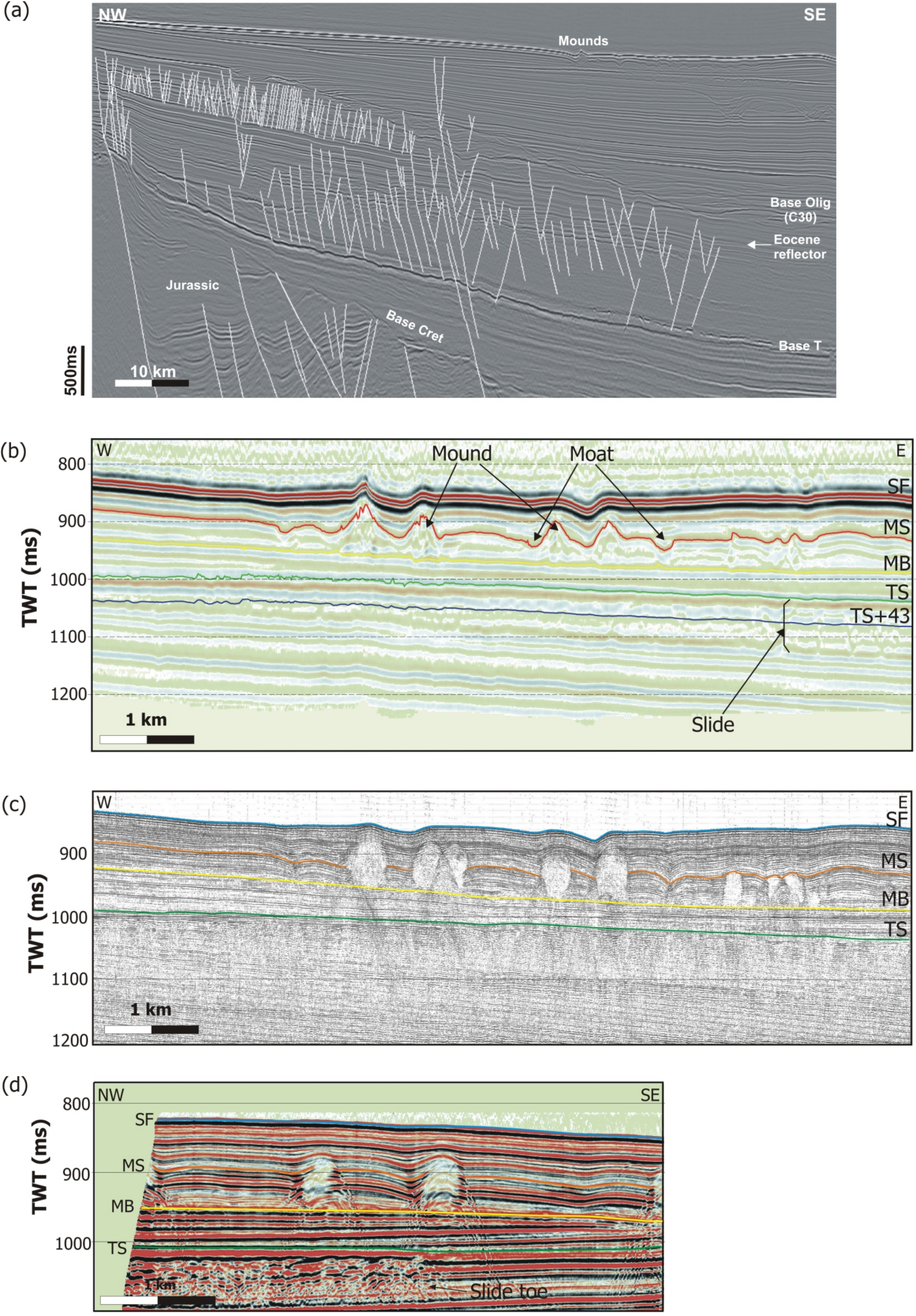

(a)
NW
SE
Mounds
Base Olig (C30)
Eocene reflector
Jurassic
Base Cret
Base T
500ms
10 km
(b)
W
E
Mound
Moat
SF
MS
MB
TS
TS+43
Slide
TWT (ms)
800
900
1000
1100
1200
1 km
(c)
W
E
SF
MS
MB
TS
TWT (ms)
900
1000
1100
1200
1 km
(d)
NW
SE
SF
MS
MB
TS
TWT (ms)
800
900
1000
1 km
Slide toe

Figure 2

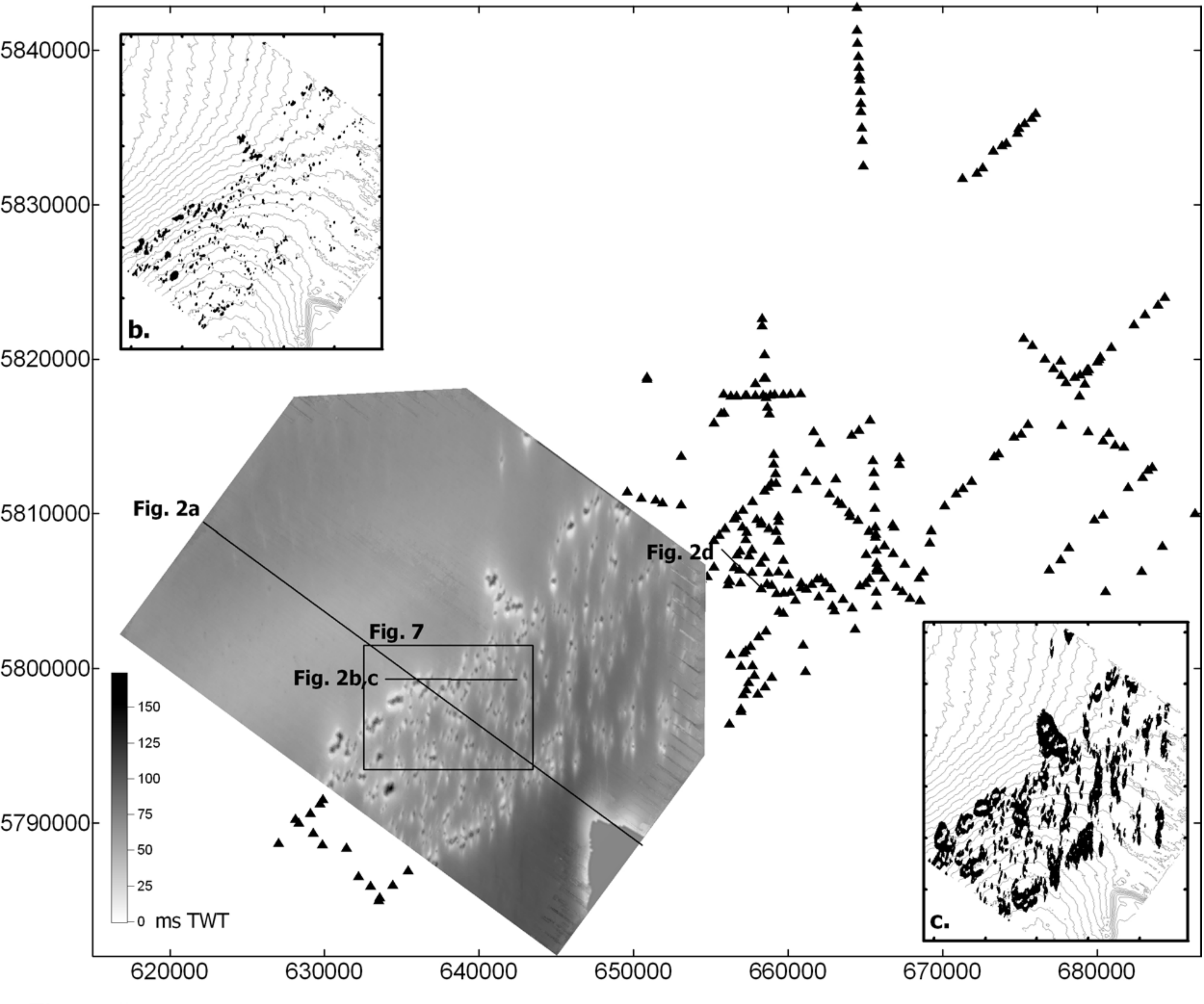
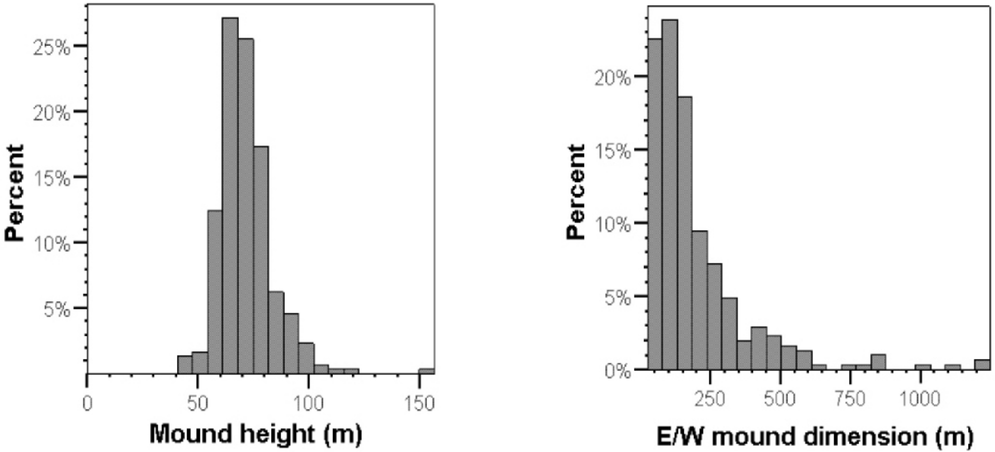

5840000
5830000
5820000
5810000
5800000
5790000
620000
630000
640000
650000
660000
670000
680000
b.
c.
Fig. 2a
Fig. 2d
Fig. 7
Fig. 2b,c
150
125
100
75
50
25
0
ms TWT

Figure 3



25%
20%
15%
10%
5%
Percent
0
50
100
150
Mound height (m)
20%
15%
10%
5%
0%
Percent
250
500
750
1000
E/W mound dimension (m)

Figure 4

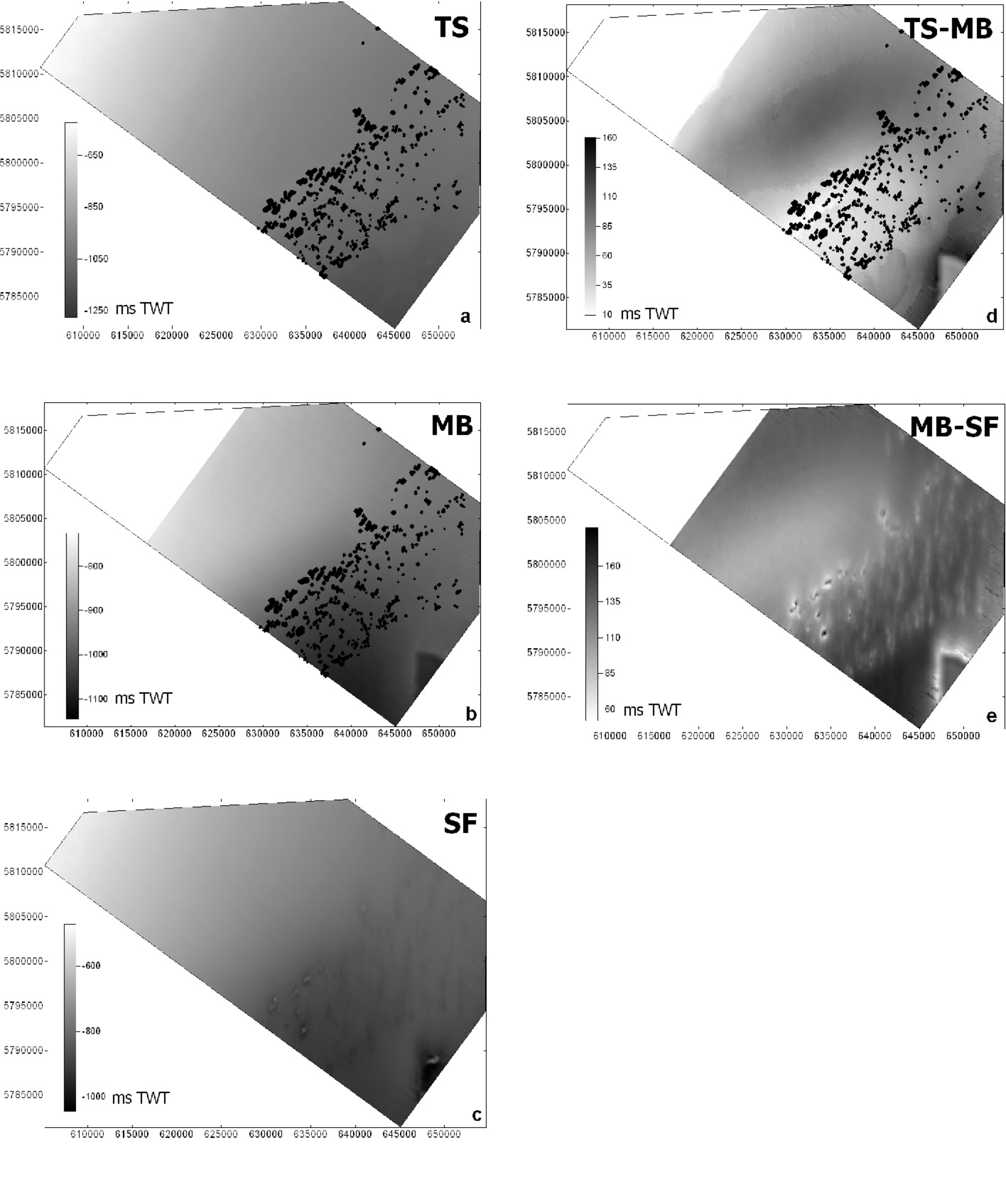
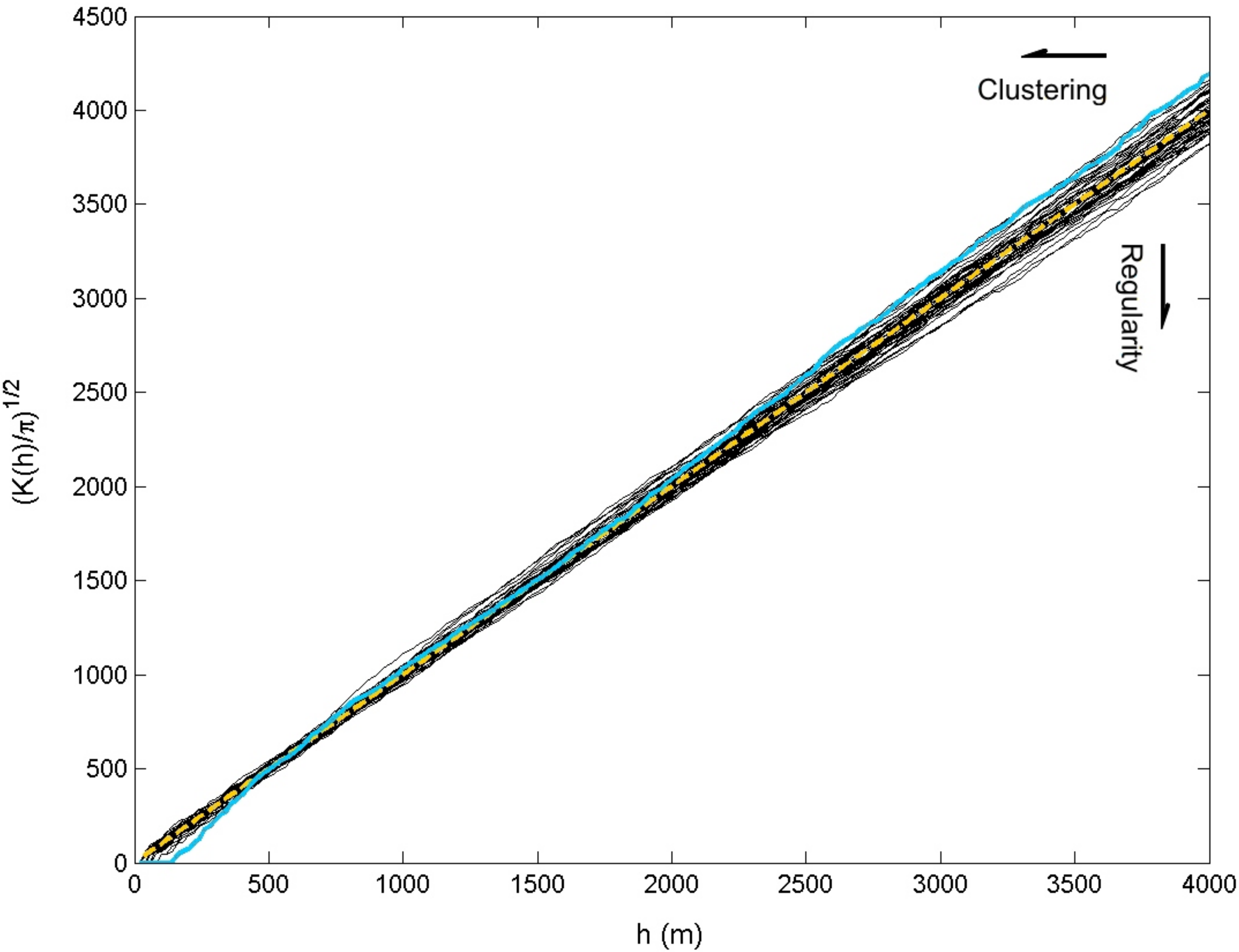
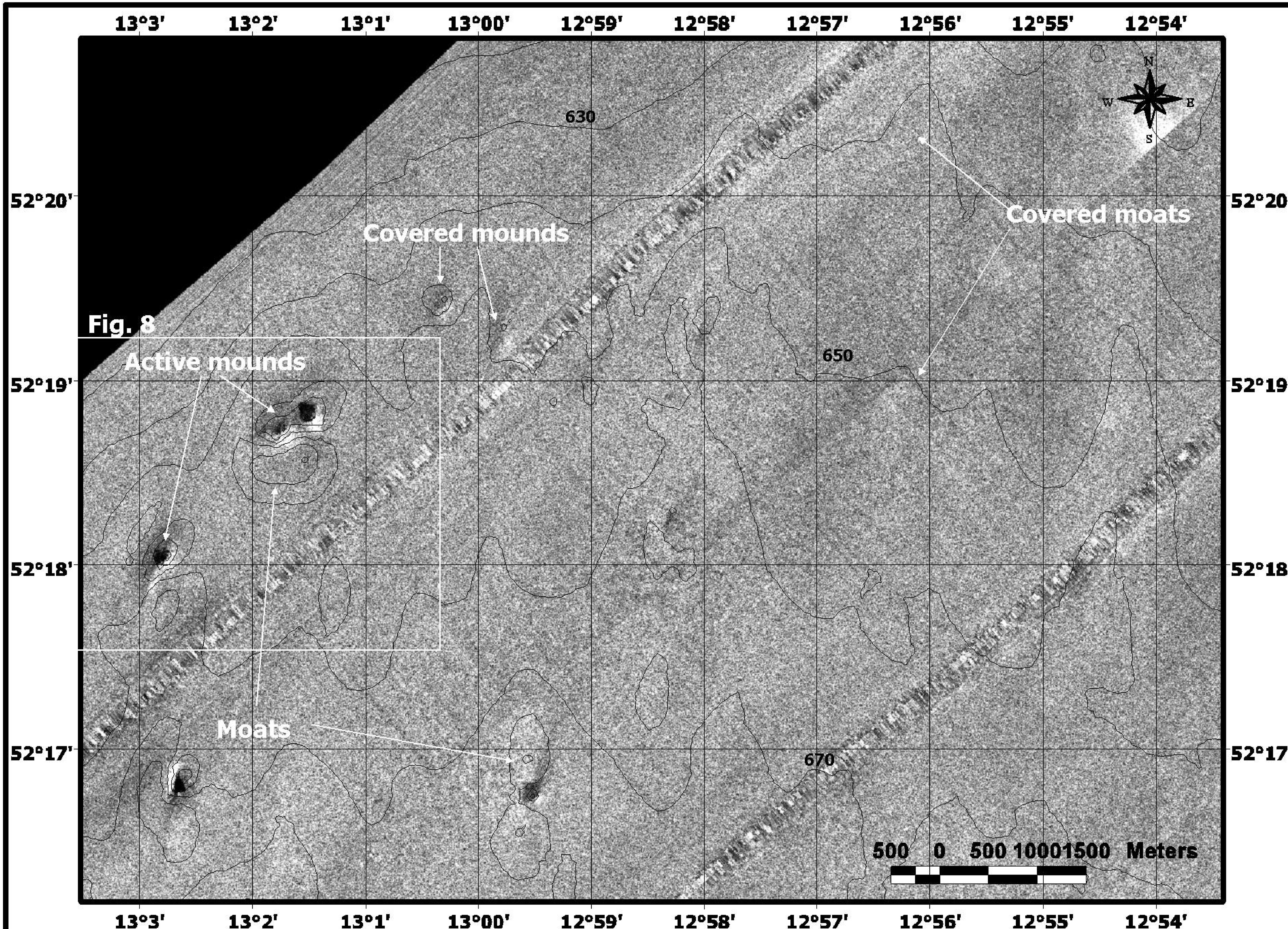

TS
a
-650
-850
-1050
-1250
ms TWT
TS-MB
d
160
135
110
85
60
35
10
ms TWT
MB
b
-800
-900
-1000
-1100
ms TWT
MB-SF
e
160
135
110
85
60
ms TWT
SF
c
-600
-800
-1000
ms TWT
5815000
5810000
5805000
5800000
5795000
5790000
5785000
610000
615000
620000
625000
630000
635000
640000
645000
650000

Figure 5



Clustering
Regularity
$(K(h)/\pi)^{1/2}$
h (m)
0
500
1000
1500
2000
2500
3000
3500
4000
4500



13°3'
13°2'
13°1'
13°00'
12°59'
12°58'
12°57'
12°56'
12°55'
12°54'
52°20'
52°19'
52°18'
52°17'
630
650
670
Covered mounds
Covered moats
Fig. 8
Active mounds
Moats
N
W
E
S
500 0 500 10001500 Meters

Figure 7

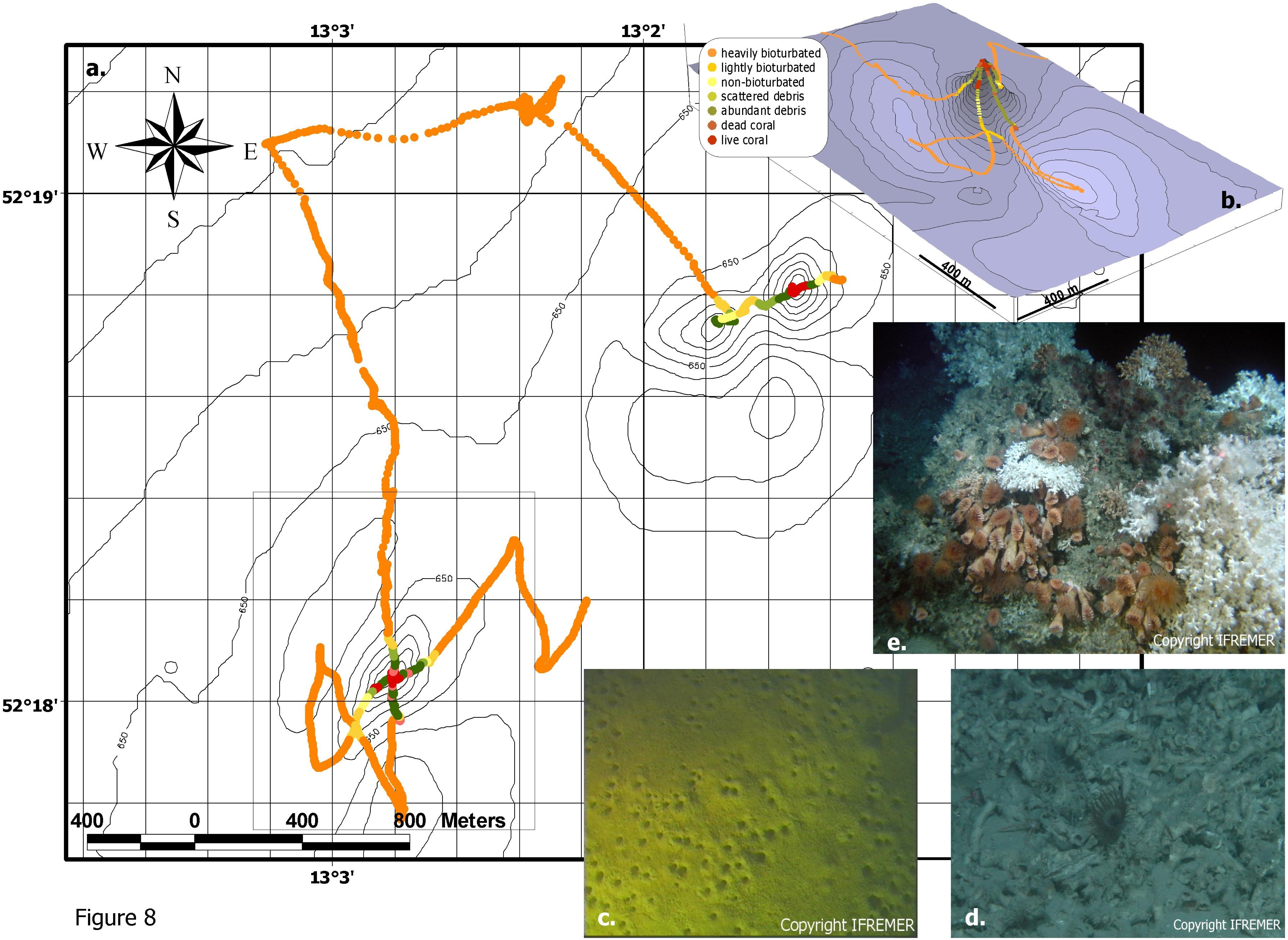

a.
b.
c.
d.
e.
13°3'
13°2'
52°19'
52°18'
N
S
W
E
650
400
0
800
Meters
heavily bioturbated
lightly bioturbated
non-bioturbated
scattered debris
abundant debris
dead coral
live coral
400 m
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Figure 8

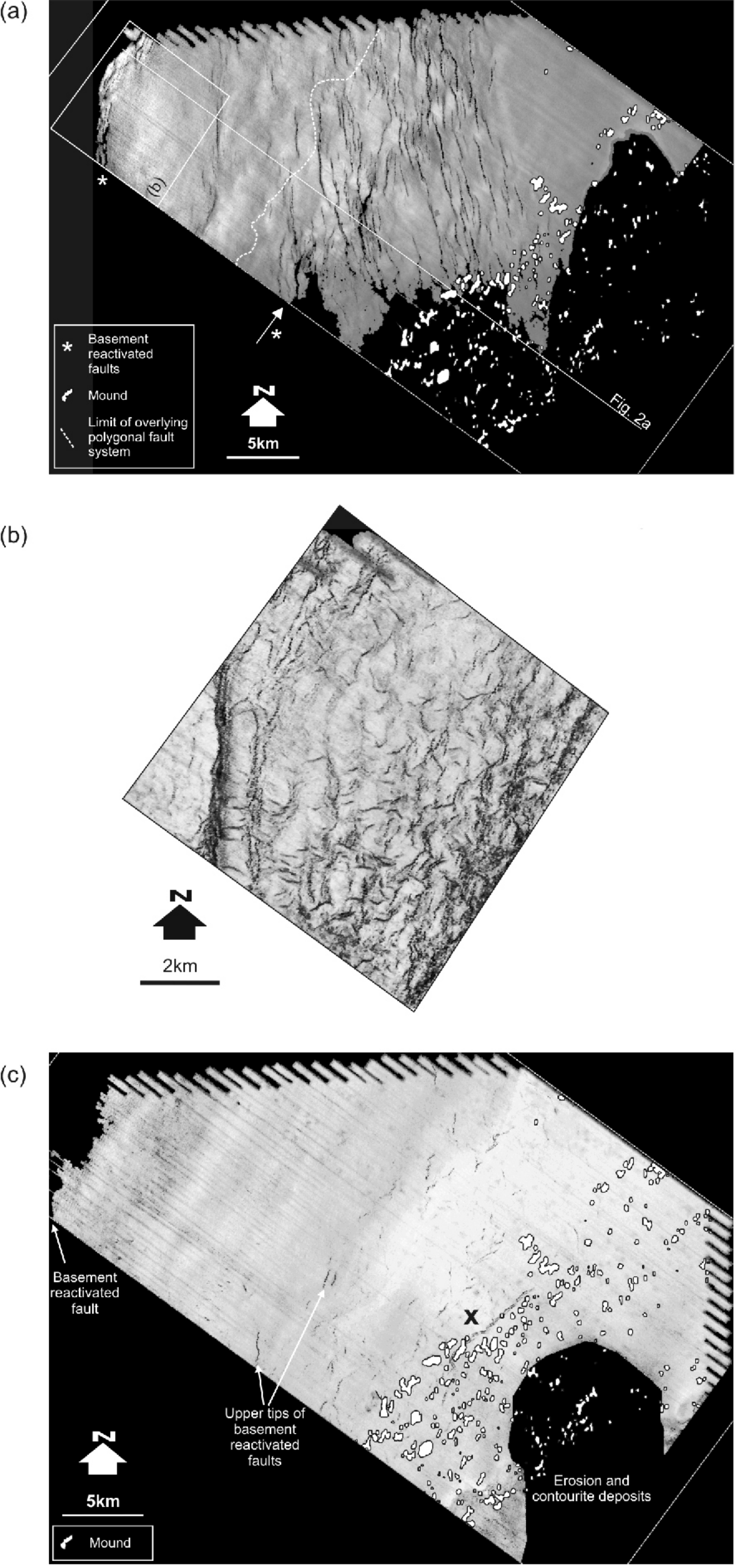
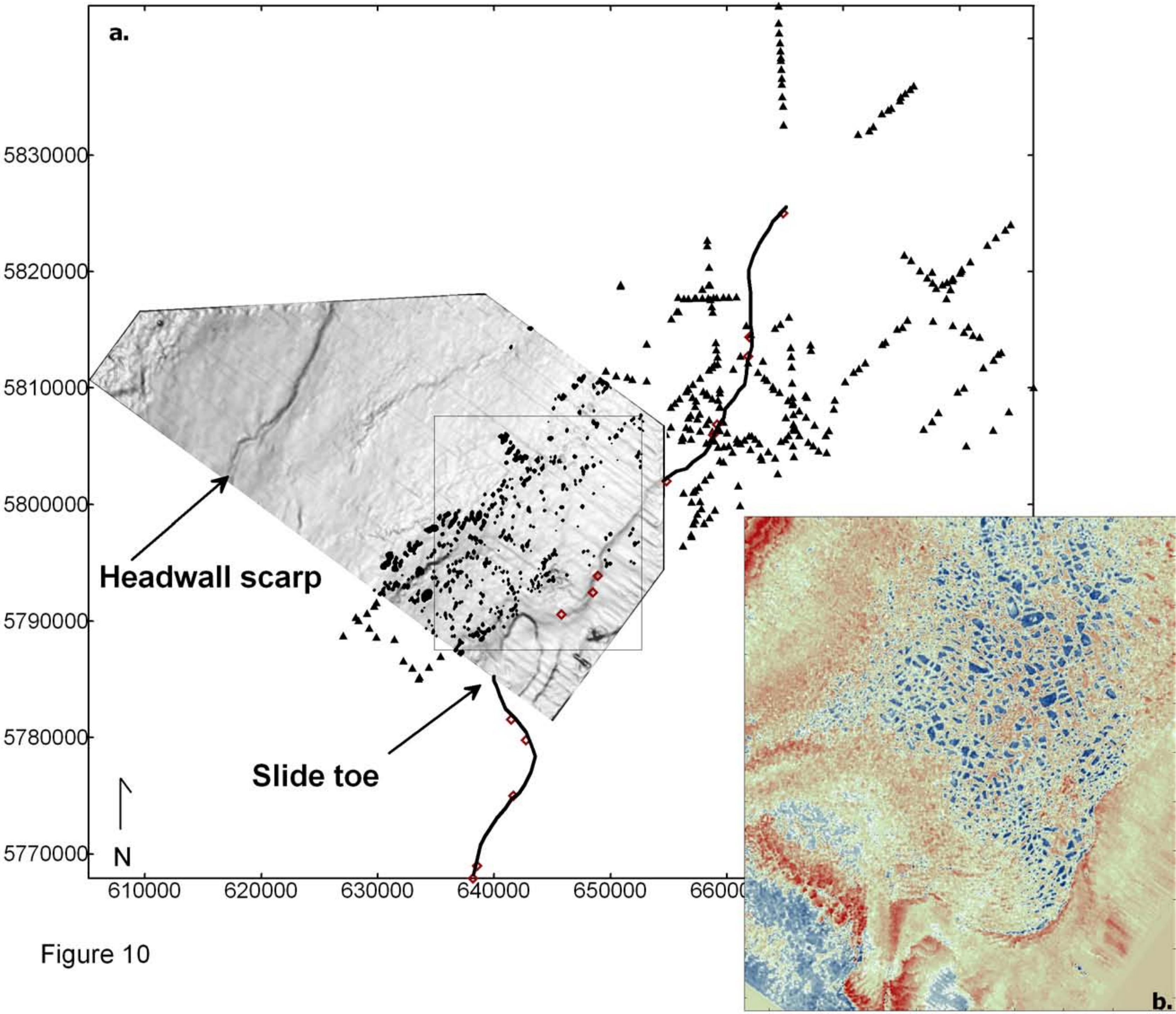
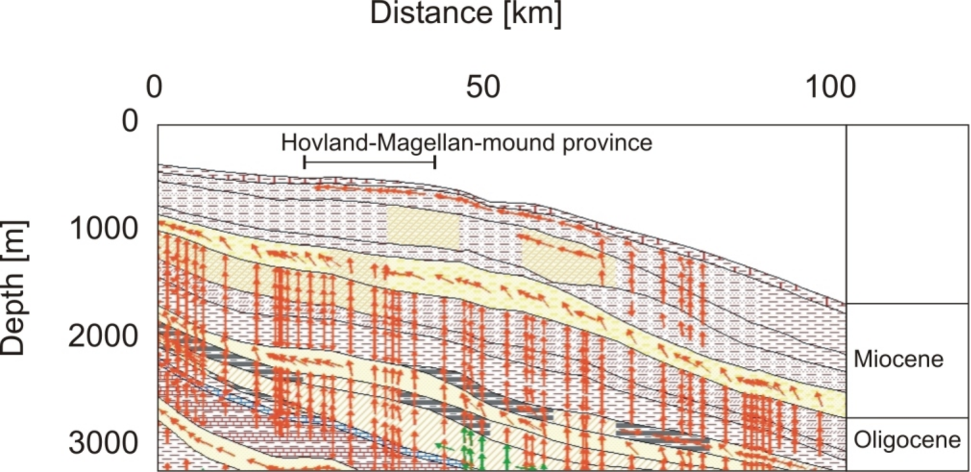

(a)
(b)
Basement reactivated faults
Mound
Limit of overlying polygonal fault system
N
5km
Fig. 2a
(b)
N
2km
(c)
Basement reactivated fault
Upper tips of basement reactivated faults
X
Erosion and contourite deposits
N
5km
Mound

Figure 9



a.
5830000
5820000
5810000
5800000
5790000
5780000
5770000
610000
620000
630000
640000
650000
Headwall scarp
Slide toe
N
b.

Figure 10


Distance [km]
0
50
100
Depth [m]
0
1000
2000
3000
Hovland-Magellan-mound province
Miocene
Oligocene