areas and therefore whether there may be species which have specialised to take advantage of this source of food in the same way that deep sea hydrocarbon seeps support a specialised fauna. While this has not proved to be the case it is nevertheless apparent that the distribution and abundance of the benthos and some mobile species are affected by pockmarks. The presence of the hard substrate provided by the carbonate cement in an environment that is dominated by soft sediment is probably a factor, but there is also a higher diversity of species which colonise soft sediments or which are mobile in these areas compared to the surrounding sea-bed in the northern North Sea. Another factor may be less impact from the heavy demersal fishing pressure on the North Sea but this is speculation at the present time.

2.3.4 Conservation actions

The issue of whether any conservation action should be focused on the marine communities found in North Sea pockmarks has not been given any consideration to date. A number of reasons may account for this including the fact that no specialised fauna have been found in these areas and the fact that they are very common in some parts of the North Sea. The associations and density of marine life in these areas does, nevertheless, make them different from surrounding areas and a distinct habitat in the North Sea. Conservation programmes that seek to include representative examples of marine habitats and communities in networks of protected areas should therefore include such sites. Other considerations should be to continue to investigated aspects relating to the formation, longevity and ecology of pockmarks and whether the deeper pockmarks provide any refuge from fishing gears which impact the sea-bed.

The Norwegian Trench - Pockmarks exist along most of the Norwegian Trench including some parts of the Skagerrak. They are present throughout most of the area covered by the youngest sediments although generally most common along the western slope. Many of the examples are aligned parallel to the slope. The smallest examples have been found in the Tommeliten area whereas those in the Norwegian Trench are up to 15m deep and 100m wide formed in soft, silty clay.

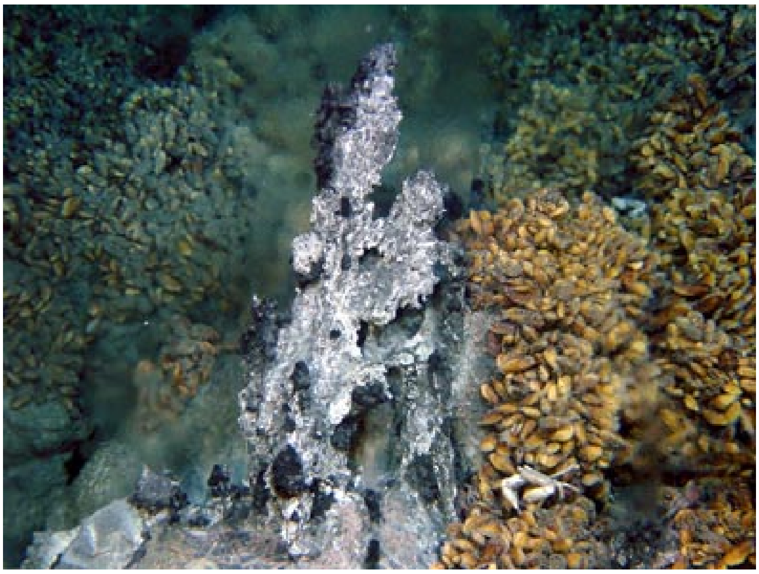
Witch Ground Basin - Pockmarks are common in the Witch Ground Basin, a depression in the plateau area of the central North Sea. They are typically 50-100m across and 2-3m deep although active pockmarks may be up to 400m wide and 17m deep. Many of the pockmarks in this area have a lengthy tail. Pockmarks have been recorded at densities of up to 40 per km^2 in this area.

North Sea plateau - The pockmarks in the North Sea plateau have been found in hollows and channels with reports of up to 20 per km^2 in one hollow.

2.4 Hydrothermal Vents

Deep sea hydrothermal vents and the marine life associated with them were discovered in 1977 during a manned submersible expedition off the Galapagos Islands. Since then the chemical, geological and biological characteristics of these areas have attracted a great deal of attention as they are dramatically different from other deep sea habitats. The most striking contrast is that water temperature in the deep sea is generally between 4°C and -1°C, but at hydrothermal vents superheated water emerges from the sea-bed in concentrated jets which can reach temperatures of nearly 400°C.

Plate 1a: Vent Species



Extremely dense musselbeds (Bathymodiolus azoricus) and deep-water scavenging crabs (Chaceon affinis) right next to the hot water source (copyright ATOS/Ifremer).

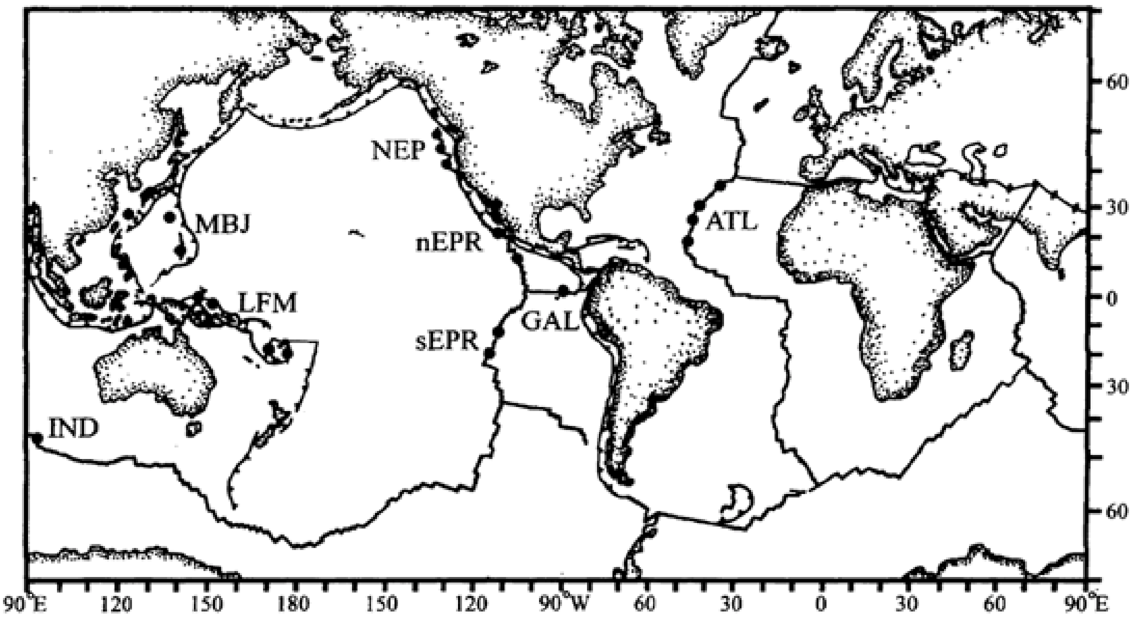
The hydrothermal activity around vents is caused by seawater penetrating the upper layers of the Earth's crust through channels formed in cooling lava flows. The water reacts chemically with hot basalt in the Earth's crust and then rises back to the sea-bed to emerge as superheated water containing compounds such as sulphides, metals, carbon dioxide and methane (Tunnicliffe *et al.*, 1998). The water may bubble out from cracks and crevices on the sea-bed as hot springs (5-60 ° C) or emerge in concentrated jets of very hot water (270-380 ° C). In the latter case, as the water cools, the dissolved minerals precipitate out in black clouds to form large chimneys which are known ‘black smokers’. At slightly cooler temperatures the sulphides are mostly precipitated within the rocks and sediment so the venting fluids appear cloudier and are known as ‘white smokers’ (Gage & Tyler, 1991). The tall chimneys formed around the vents and the surrounding sediments are almost pure metallic sulphides and are a unique geological feature of hydrothermal vents (Tunnicliffe *et al.*, 1998).

Hydrothermal vents are most commonly found where ridges of the Earth’s plates are actively spreading. On fast spreading ridges, such as the east Pacific rise at 13 ° N, vent sites appear to have a short lifetime (generally no longer than about 100 yrs) and the zone of hydrothermal activity shifts along the ridge. On slow spreading ridges such as the mid-Atlantic Ridge, the hydrothermal activity is spatially more focused and stable over the long term, even if the lifetime of an individual vent site is similar to that on fast spreading ridges (Comtet & Desbruyeres, 1998).

2.4.1 Occurrence in the OSPAR maritime area

Since hydrothermal vents were first discovered, researchers have found similar habitats in nearly all the areas of deep sea tectonic activity which have been investigated. Vents have been reported from the Pacific, Indian and Atlantic oceans and not only associated with spreading centres but also subduction zones, fracture zones and back-arc basins (spreading centres associated with subduction processes in deep trenches) (Gage & Tyler, 1991) (figure 17).

Figure 17: Distribution of major vent sites around the world (from Tunnicliffe *et al.,* 1998)



IND - south-east Indian Ridge, LFM - Lau, Figi, Manus Woodlark & Lihir sites, MBJ - Marianas, Bonin & Okinawa,
NEP - Explorer, Juan de Fuca & Gorda Ridges, nEPR - 9∞ -21∞ N East Pacific Rise,
GAL - Galapagos Rift, sEPR 17∞-25∞S, ATL - mid-Atlantic Ridge

Active hydrothermalism occupies only a small portion of the spreading ridges; thus the available habitat occurs at irregular intervals. The interval between vents depends on the nature of both volcanism and tectonism of that ridge. Searches for vents are concentrated within the axial valley of a ridge but off-axis venting may be more prevalent that currently appreciated as water does circulate on a large scale through the flanks of ridges (Hekinian & Fouquet, 1985).

Vents and their associated communities are transient and variable not only on short time scales of days and seconds but also over decades. Variability in the hydrothermal discharge causes changes in the animal communities associated with vents. As a consequence, the vent fauna must adapt to unstable environmental conditions and nutrient supply by rapidly colonising new vents (Comtet & Desbruyeres, 1998). Evidence for the longer term variability can be seen in accumulations of dead giant bivalve shells which, as they are known to only persist for about 15 years before being dissolved, must indicate quite recent change in conditions. Geophysical and geochemical evidence suggests short bursts of hydrothermal activity lasting decades or less. The habitat is neither permanent nor contiguous; dispersal and migration are the major links between neighbouring vents (Tunnicliffe *et al.,* 1998).

2.4.2 Vent communities

Hydrothermal vents support some of the most unusual animal communities on the planet. The species which survive in these surroundings must be able derive energy under conditions where photosynthesis is not possible, to tolerate great extremes and variability in the temperature and the chemical composition of the surrounding water, and cope with potentially toxic concentrations of various heavy metals. Animals which have adapted to this environment include the giant vent clam *Calyptogena magnifica,* the mussel *Bathymodiolus thermophilus*, the tube worm *Riftia pachyptila* , crabs such as *Cyanograea praedator* and *Bythograea thermydron*, and two species of shrimp from a new family (Bresiliidae) *Rimicaris exoculata* and *R.chacei*.

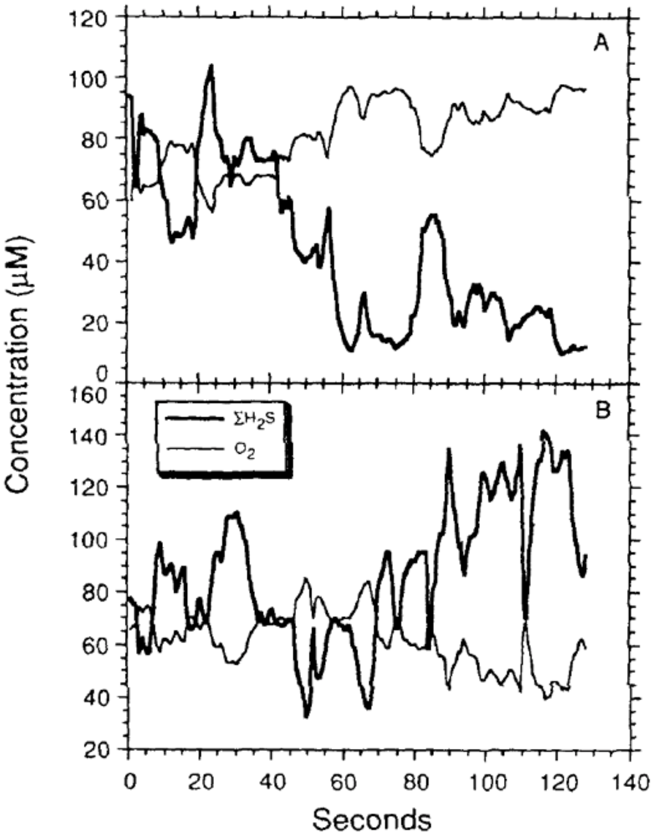
Plate 1b: Vent species

Photo by kind permission of Daniel Desbruyeres, IFREMER. (Lucky Strike hydrothermal vent showing densely populated mussel bed (Bathymodiolus azoricus) with associated shrimps (Charocaris fortunata)).

Most vent species occur where the temperature does not exceed 30°C and hydrogen sulphide content is less than 400µM although they can be found in areas where the water temperature is as high as 50°C (Childress & Fisher, 1992). The variable flow through the sides and top of the chimneys therefore supports a complex mosaic of animal patches in the vicinity of the vents but not in the vents themselves. The main reason for this is that primary production around the vents is dependent on chemoautotrophic bacteria that derive energy from sulphur-containing inorganic compounds. The bacteria, which are found in the gills and tissues of some vent species such as the clams and vestimentiferan worms, as well as being free-living on the basalt rock surfaces or the shells and tubes of nearby animals, use compounds from both the venting waters and the surrounding seawater to derive energy. The most favourable areas for colonisation by these primary producers is therefore near enough to the venting waters to take up sulphide before it is oxidised or too diluted, but far enough away to take up an oxidant from the surrounding seawater (Childress & Fisher, 1992).

In much of the deep sea, animals live with very narrow, stable temperature ranges. Vent animals, on the other hand, must be able to tolerate high concentrations of toxic metals and sulphides, low concentrations of O_2 and respond quickly to rapid fluctuations as well as a wide range of temperatures. Studies of the temperature and chemical composition of the water around vents have revealed that the vent and ambient waters are not well mixed in the areas where the animals live. This means that species colonising these areas are exposed to discrete parcels of water, of the more extreme properties over periods of seconds as well as on longer time scales, such as through daily variations in vent flows (figure 18). Because of these extremes it has been said that the thermal environment of vents has more in common with the high intertidal zone than the deep sea (Childress & Fisher, 1992).

Figure 18: Short-term fluctuations in H_2S and O_2 (from Childress & Fisher, 1992)



The specialised adaptations which allow organisms to exploit vent habitats include major reorganisation of internal tissues and physiologies to house microbial symbionts, biochemical adaptations to cope with sulphide poisoning, behavioural and molecular responses to high temperature, presence of metal-binding proteins and development of specialised sensory organs to locate hot chimneys (Tunnicliffe *et al.*, 1998). The result has been specialised faunas which are rarely found in other environments. They are also not a very diverse group of species but because they can exploit an abundant energy source around vents they are often present in very high densities (Childress & Fisher, 1992). The most numerous and conspicuous organisms are those which have developed symbiotic relationships with chemoautotrophic bacteria and it is these species which dominate the primary production in the vent community.

Vent waters throughout the world have great similarity from the point of view of organisms: the major controls on composition are seawater and host rock (basalt) chemistry neither of which shows gross differences around the globe. Biologically important factors such as heat and dissolved concentrations of sulphides, iron and manganese show far more change in the few years after an eruptive event on a single ridge segment than among sites around the world (Butterfield *et al.* 1997). Despite this, it is apparent from studies to date that the fauna on Atlantic vents are less varied and different from those in the Pacific.

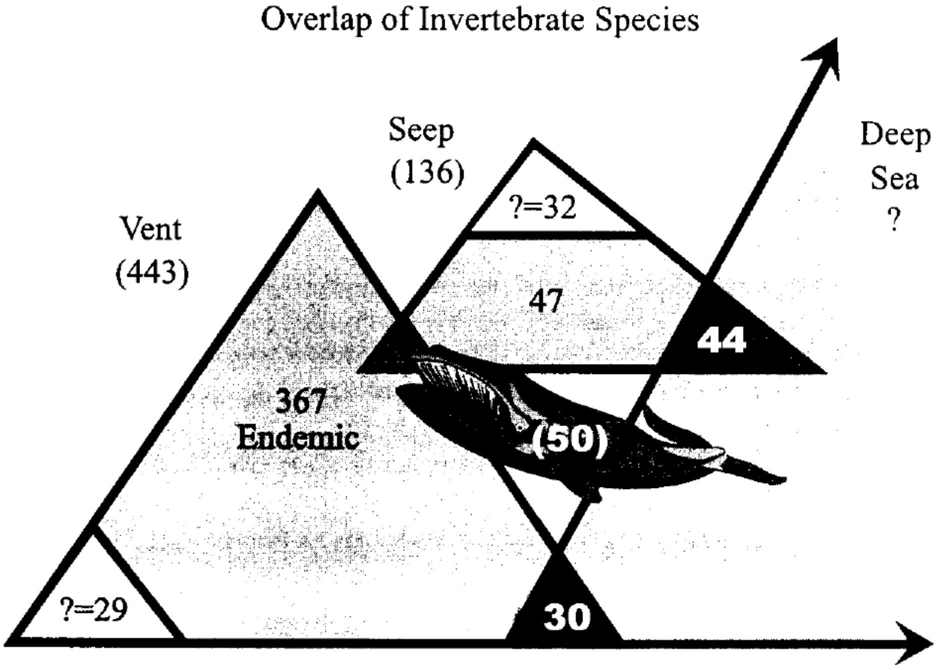
Vestimentiferan tube worms and bivalve molluscs which are common at Pacific sites are absent in Atlantic vents. Instead, the dominant animals are bresiliid shrimps with *Rimicaris exoculata*, a species whose adult stage appears to depend on exosymbiosis with sulphur bacteria, being particularly abundant. These shrimps ingest sulphide particles from 350°C black smoker chimneys from which they appear to graze associated free-living micro-organisms (Gebruk *et al.*, 1997). At the Luck Strike vent field the fauna is dominated by dense beds of a new species of mussel of the genus Bathymodiolus, as well as supporting a totally novel amphipod fauna including a new genus, and the echinoderm *Echinus alexandri* (Van Dover *et al.*, 1996). The presence of several new taxa and species emphasises that study of vent faunas is still at a relatively early stage. Undoubtedly further new species will be identified as exploration continues. At the same time, more needs to be learnt about major issues such as the role of invertebrate/bacteria symbioses in the trophic structure of the communities, the influence of depth on the community structure; reproduction and life history, and modes of dispersal of larvae and colonisation (Gebruk *et al.*, 1997). A long-term multidisciplinary research programme known as MOMAR (Monitoring on the mid-Atlantic Ridge near the Azores) has been set up for study of the biological and physico-chemical activity at the four known vent sites south of the Azores (Menez Gwen, Lucky Strike, Saldanha and the Rainbow vents).

Studies comparing vent faunas and those of other sulphide-rich environments show some similarities in their mode of nutrition but relatively little overlap in the species. Only a small percentage of more than 440 species recorded from hydrothermal vents have been found around hydrocarbon seeps or on decaying bones on the ocean floor (figure 19). Consequently these habitats are not currently considered to be dispersal stepping stones for vent fauna (Tunnicliffe *et al.*, 1998)

2.4.3 Conservation Issues

The unusual nature of the marine communities that occur around hydrothermal vents makes them particularly important areas in terms of the biodiversity of the deep sea as well as being a focus for deep sea research. There are regular expeditions to the well-known sites to make observations and measurements, deploy instruments and collect specimens of the marine life, seawater and rocks. As many of these sites only cover a small geographic area and include relatively fragile structures, they can be under considerable exploration pressure. At some sites this has already reached a point where man-induced changes in the distribution and occurrence of vent fluid flows, and of associated vent communities, have been documented (Mullineaux *et al.*, 1998). On the other hand scientists are now able to keep some species alive in aquaria for several months enabling longer-term studies to take place under laboratory conditions and providing study opportunities to more scientists without repeated disturbance to the biological communities *in situ* (Santos, *pers com*). A research programme is being established in the Azores to take this work to the next stage.

Figure 19: Overlap of invertebrate species among sulphide-rich habitats and the deep sea (from Tunnicliffe *et al.,* 1998)



The need for better co-ordination and co-operation between the different groups interested in hydrothermal vents has been recognised as has the fact that some research techniques are incompatible (monitoring undisturbed systems versus manipulation of the system, for example). As a consequence, a case has been made for establishing research reserves at hydrothermal vents (Mullineaux *et al.,* 1998). A web-based information site on deep sea reserves at hydrothermal vents has been set up on the InterRidge website as a forum where researchers can propose vent reserves and where others in the oceanographic community can respond to them. The Canadian government has proposed the Endeavour vent field on the Juan de Fuca Ridge in the Pacific as a pilot marine protected area while in the OSPAR area, co-operative sampling effort has been proposed to minimise disturbance of the Eiffel Tower and ‘PP24’ chimneys in the Lucky Strike vent field.

Apart from research expeditions, it can be expected that hydrothermal vents will also be subject to pressures from other activities. Tourist trips to hydrothermal vents were advertised for the first time in 1999 and there are proposals for the extraction of minerals and metals from vent habitats in the South Pacific. Where such activity is proposed for locations in the high seas voluntary agreement on procedures, limits and approaches is the first necessary step and one which is being pursued by the research community working on hydrothermal vents.

2.4.4 Conservation actions

The need for care in the exploration and research of hydrothermal vent communities has been recognised by those studying these unusual deep sea habitats. Research protocols, co-ordinated studies and protected areas are among the ideas being taken forward by scientists working on these communities. The three vent fields in the OSPAR maritime area which are most well known at the present time are Menez Gwen, Lucky Strike and the Rainbow vents (figure 20) and these are therefore the most likely focus for such actions at the present time.

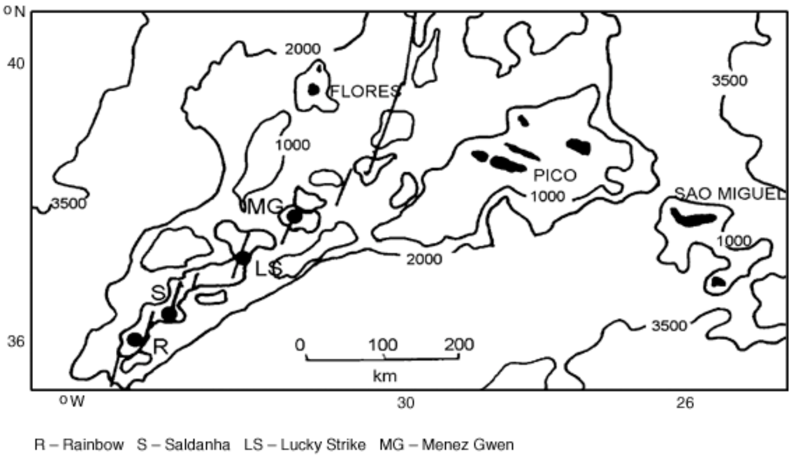
Menez Gwen (37° 51’N, 30° 02’W)

The Menez Gwen vent field lies in particularly shallow water at a depth of 855m extending over approximately 200m^2 which is a much smaller area than the other vent fields so far discovered on the mid-Atlantic Ridge. The fauna is dominated by mussels but is also colonised by crabs. It has been suggested that the hydrothermal activity at this site is relatively recent which provides an opportunity to study the early stages of hydrothermal activity at a slow spreading ridge. (MOMAR webpage).

Lucky Strike (37° 18’N, 32° 16’W)

The Lucky Strike vent field was discovered in 1993. It covers an area of approximately 150,000m^2 with 21 active chimney sites, making it one of the largest known hydrothermal areas discovered so far. The site extends over a depth range of 1,620-1,730m with the chimneys around a fossil lava lake in the central caldeira of an axial volcano. The marine life is concentrated on areas of the sea-bed where warm water emerges from cracks and chimneys and is dominated by dense mussel beds of a previously undescribed species. In some locations large numbers of small mussels were observed attached to large mussels indicating a recent recruitment event (Van Dover *et al.*, 1996).

Figure 20: Known vent fields to the west of the Azores.



Twenty-five invertebrate taxa are listed from the Lucky Strike hydrothermal area. Four are shared with other hydrothermal vent systems on the mid-Atlantic Ridge and seven are previously undescribed new species closely associated with hydrothermal activity. Several taxa, typical of eastern Pacific vents or western Pacific back-arc hydrothermal systems (tubeworms, vesicomyid clams and alviniconchid gastropods for example), are absent. Sixty-six species have been described from this site to date. The vent communities at Lucky Strike have a sufficiently unique fauna to be considered as representing a different biogeographic hydrothermal province to those previously described (Van Dover *et al.,* 1996).

Rainbow (36° 11'N, 33° 57'W).
This site, which is at a depth of 2,300m, has about 10 groups of very active black smokers. The hydrothermal fluids have a very high particle content and temperatures (360° C), enriched in copper, nickel, zinc and cobalt. Thirty-two species have been identified at the site which is dominated by shrimps. Many of the chimneys have no animals around them (MOMAR webpage).

There is an apparent long-term stability of the vent fields in the Atlantic. Lalou *et al.,* (1995) identified numerous cycles of venting using radiometric ageing of sulphids in the TAG vent field which suggested sporadic activity spanning a period of nearly 150,000 years. Fossil examples of vent communities have also been found indicating that there were marine communities associated with active sulphide mineralisation as far back as the Lower Carboniferous, at least 350 million years ago.

At the present time there are four known vent fields in the OSPAR area. These are the Menez Gwen, Lucky Strike, Saldanha and Rainbow vents (figure 20). In the Atlantic, the hydrothermal vents are associated with the mid-Atlantic Ridge and have been reported over a range of depths. The Menez Gwen vent field (37° 51' N, 30° 02' W) to the west of the Azores is a particularly shallow example at only 850m, whereas the TAG vent field (26° 08' N, 44° 49' W) further south is at a depth of 3,650m. The most recently discovered site is the Saldanha field at 2,200m and which was first encountered in 1998. Seawater has been observed emerging directly from the seafloor rather than through chimneys at this site but further exploration of the area is needed to confirm its main characteristics.

2.5 CORAL REEFS

The existence of corals in the deep sea has been known for more than a century. Precious corals (*Corallium* spp,) solitary stony corals (for example, *Flabellum goodei* & *Desmophyllum dianthus*) and colonial corals (for example, *Solenosmilia variabilis* & *Lophelia pertusa*) have all been found at a great depth and some, such as *Lophelia*, *Madrepora*, *Desmophyllum*, and *Solenosmilia* are found world-wide (Wilson, 1979a; Gage & Tyler, 1991; Koslow & Gowlett-Holmes, 1998). This section describes reefs formed by *Lophelia pertusa* although other hard corals such as *Madrepora oculata, Dendrophyllia cornigera* and *Solenosmilia variabilis* may also be present.