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The global importance and context of methane escape from the seabed

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Abstract Seabed fluid flow includes volcanic and hydrothermal fluid emissions from ocean spreading centres, island arcs, and intra-plate volcanism, and groundwater flows in some coastal areas. Of direct concern to this paper is the escape of methane from the seabed. Escaping methane may be of microbial, thermogenic or abiogenic origin. Escapes occur in all seas and oceans, in coastal waters, on continental shelves, slopes and rises, the deep oceans, and deep ocean trenches. These represent a variety of geological contexts on passive continental margins, at convergent plate margins (accretionary wedges) and transform plate boundaries. Seepage is clearly widespread, and it contributes methane to the biosphere, the hydrosphere and the atmosphere, thus making up an important part of the global carbon cycle.

Introduction

Pockmarks, seeps, mud volcanoes and other features associated with the flow of fluids from the seabed have been widely reported, particularly during the last three decades. Furthermore, processes associated with seabed fluid flow have been shown to affect benthic ecology, and to supply methane to the hydrosphere and the atmosphere. However, these effects would be of no more than academic interest unless seabed fluid flow is widespread. Only by understanding the context of seabed fluid flow can the importance of seabed fluid flow be assessed. The purpose of this paper is to address the following questions:

- What is seabed fluid flow?
- Is it widespread?
- Where does it occur?

The answers will enable the final question to be asked—is it important?

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What is seabed fluid flow?

'Seabed fluid flow' involves the passage of natural liquids and gases through the seabed, from rocks and sediments into the water column. Flow rates may vary between slow, inter-granular 'microseepage' and vigorous, even violent, eruptions; there have been numerous eyewitness accounts of violent eruptions of mud volcanoes (some of them submarine), with flames shooting hundreds of metres high. These were reviewed by Dimitrov (2002a) and Kopf (2002). Fluids of various natural origins may be involved.

Submarine volcanic activity is mainly confined to three plate tectonic settings: ocean spreading centres, island arcs associated with the convergence of oceanic plates, and intra-plate hot spots (submarine volcanoes, volcanic islands and seamounts). Hydrothermal activity is centred mainly, but not exclusively, around ocean spreading centres. Although this paper does not consider these types of seabed fluid flow in detail, the geographical extent of the plate tectonics contexts in which they occur (see Fig. 1) suggests that these are important contributors of various elements and compounds to the hydrosphere.

Water percolating into seaward-dipping aquifers on land may emerge through the seabed. The quality of the seeping water will be affected by the history of its passage from the recharge zone to its entrance into the sea. There are many examples, generally close to the coast, of groundwater seeps. Hovland and Judd (1988) mentioned examples in the Gulf of Astela, Adriatic Sea; Port-Miou Bay, Mediterranean coast of France; Chekka, Lebanon;

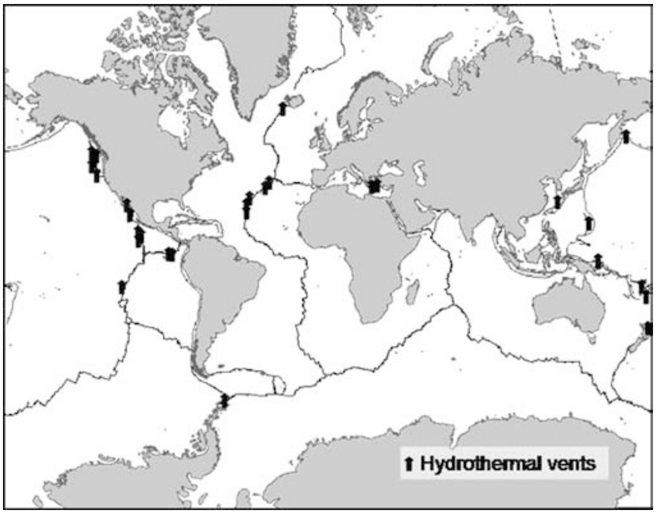

Fig. 1 Hydrothermal vents sites. These are associated mainly with divergent plate boundaries (data from various sources compiled using the MAGIC GIS database; see Judd et al. 2002a)

Bahrain Archipelago, Arabian Gulf; Cambridge Fjord, Baffin Island, Canada; off the eastern coast of Florida; and in the Perth area of western Australia. Other examples have been reported from Eckernförder Bay, Germany (Whiticar 2002). It is more unusual to find groundwater seeps in deep water, but they do occur. For example, sulphide-rich, hypersaline groundwater seeps from the seabed of the submarine Florida Escarpment in a water depth of about 3,260 m supporting a rich, chemosynthetic 'cold seep' community of benthic fauna (Paull et al. 1984).

Although volcanic, hydrothermal and groundwater fluid flow is important, this paper is particularly targeted on the escape of hydrocarbon gases, the most important of which is methane.

Hydrocarbon gas seeps

Methane is the most common hydrocarbon gas in marine sediments (Schoell 1988; Floodgate and Judd 1992). In seabed sediments there are three possible sources of methane:

- Microbial: organic matter buried in seabed sediments may be decomposed by microbial activity. Methanogenic microbes are most active close to the seabed. After formation, this methane may become trapped and buried with the sediments, or it may migrate towards the seabed. A significant proportion of the upward-migrating methane is oxidised within the overlying sediments. However, the rapid generation of methane in organic-rich sediments may result in the escape of free methane gas bubbles into the overlying water column.
- Thermogenic: organic matter not microbially degraded near the seabed but buried with the sediments may be degraded by thermocatalytic processes deep within the sediments. Depending upon the nature of the original organic material and the depth of burial (and therefore the temperature and pressure conditions), various hydrocarbon compounds may be formed. These include solid (asphalt), liquid (crude oil) and gaseous (natural gas) forms, but methane is the most abundant hydrocarbon gas, and the most mobile. After expulsion from the source rocks in which it is generated, methane is liable to migrate towards the surface, although entrapment may occur at any depth below seabed if the migration pathway is impeded, for example, by impermeable sediments.
- Abiogenic: methane may be derived inorganically either as a result of the degassing of mafic magmas and/or the cooling of mafic igneous rocks, and the serpentinization of ultramafic rocks within the oceanic crust (Apps and van de Kamp 1993). These origins are presumed to account for the methane content of hydrothermal vents. Also, it has been argued that primordial methane emanates from the Earth's mantle (Gold and Soter 1980; Gold 1999).

Because of the small molecular size, and the buoyancy in water-saturated sediments of free methane gas bubbles, methane tends to migrate towards the seabed. Methane may also be held in solution in migrating porewaters. Natural seabed seeps tend to occur where migration is focussed, for example, along faults.

Under certain conditions gas hydrates may form. These are natural, ice-like crystals which hold 'guest' molecules (commonly methane) with a cage-like crystal lattice (e.g. Kvenvolden 1998; Pellenbarg and Max 2000). In the marine environment gas hydrates are stable only in the low-temperature, high-pressure conditions found beneath deep (generally >500 m) waters (Kvenvolden 1998; Ginsburg and Soloviev 1998). Methane, formed by any of the processes outlined above, and migrating into sediments with adequate supplies of porewater (required for hydrate formation) under the required temperature and pressure conditions, may be sequestered by hydrates. So, contrary to the implications of some authors, gas hydrates are usually reservoirs, not sources of methane.

Are seabed methane escapes widespread?

Despite the many publications concerning the impact of seeping methane (and other fluids) on, amongst other, benthic ecology, if seabed fluid flow is rare, then it is not significant. A literature review reveals that methane seeps have been reported from:

- every sea and ocean;
- a broad range of oceanographic settings from the coast to the deep ocean;
- a wide variety of geological environments.

Judd et al. (2002a) described a GIS (geographic information system) database (MAGIC) compiled from

English language publications describing natural seabed gas seeps and associated features (pockmarks, seep-related biological communities, methane-derived authigenic carbonates, etc.). This database was used in the compilation of this paper.

Distribution

Various attempts have been made to map the distribution of natural seabed gas seeps, and features associated with them. Hovland and Judd (1988), and Fleischer et al. (2001) presented maps of the global distribution of pockmarks and seeps, and shallow gas respectively; Aharon (1994) and Sibuet and Olu (1998) focussed on the distribution of seep-associated chemosynthetic biological communities ('cold seep communities'); various authors, for example, Kvenvolden (1998), and Ginsburg and Soloviev (1998) have discussed the distribution of marine gas hydrates; the distribution of mud volcanoes (on land and submarine) has been described by Milkov (2000), Dimitrov (2002a) and Kopf (2002).

Although these studies have demonstrated the widespread occurrence of seabed methane escape, it is clear that only a small proportion of the world's seas and oceans have been studied in sufficient detail to reveal their presence. Furthermore, the results of many surveys, for example, the majority of those undertaken by the offshore petroleum industry, have not been released to the public domain. Also, the compilations have relied mainly on English language publications, so they are very unlikely to be comprehensive. However, it seems logical to conclude that seabed fluid flow involving methane occurs in every sea and ocean, in various oceanographic (Fig. 2) and plate tectonic (Fig. 3) settings.

Oceanographic settings

Coastal areas

The location of coastlines is transitory, varying over relatively short periods of geological time under the influences of tectonic processes and climate change. The most important changes in the recent geological past have been caused by variations in eustatic sea level during the glacial/interglacial cycles of the Pleistocene. During glacial periods, when eustatic sea level is relatively low, continental shelves are exposed and subjected to erosion; rivers cross the continental margins and deposit their sediments in the deeper waters of the shelf margin and the continental rise. When warmer conditions return, rising sea levels flood the continental shelf, and centres of deposition progress landwards. During periods of sea-level highstand, such as the last 8,000 to 10,000 years, sediments accumulate in shallow water and coastal environments (Haq 1991); all the major deltas of the world have been built since the last glaciation (Stanley and Warne 1994). These sediments tend to be rich in organic matter and, therefore, prolific sources of microbial methane. Equally important may be former land areas which had prolific growths of vegetation before being

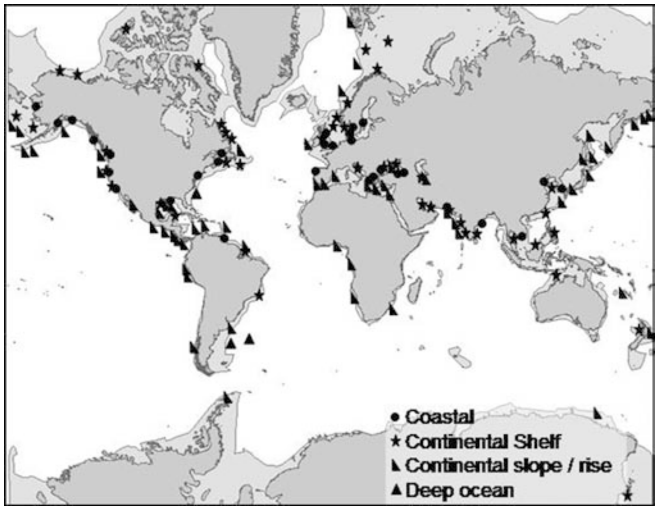

Fig. 2 The relationship between seabed fluid flow and oceanographic settings. Occurrences of seabed fluid flow (excluding hydrothermal fluids) are identified by one or more of the following features: gas seeps, chemosynthetic 'cold seep' biological communities, methane-derived authigenic carbonate (MDAC), pockmarks, shallow gas, gas hydrates. The continental shelves are *shaded* (data from various sources compiled using the MAGIC GIS database; see Judd et al. 2002a)

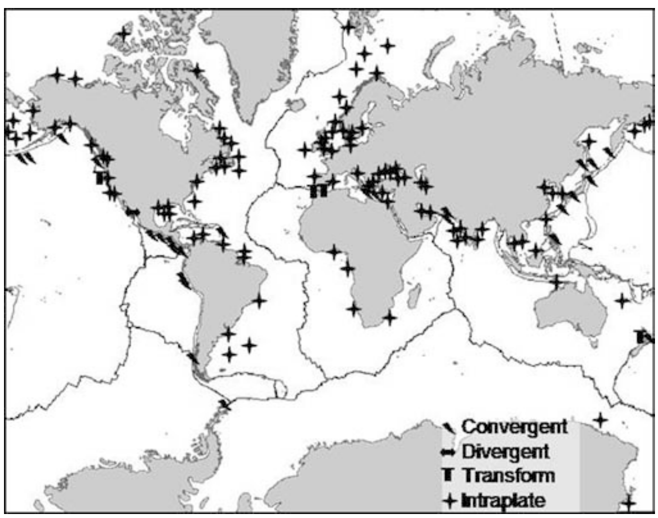

Fig. 3 The relationship between seabed fluid flow and plate tectonics settings. Occurrences of seabed fluid flow (excluding hydrothermal fluids) are identified by one or more of the following features: gas seeps, chemosynthetic 'cold seep' biological communities, methane-derived authigenic carbonate (MDAC), pockmarks, shallow gas, gas hydrates (data from various sources compiled using the MAGIC GIS database; see Judd et al. 2002a)

drowned during the marine transgression which occurred during the climatic amelioration after the last 'ice age'. Microbial decay of vegetable matter is an important source of methane.

Environments in which gas-rich (most likely methane-rich) sediments are likely to occur include:

- Estuaries and bays, for example, Penobscott Bay (Kelley et al. 1994; Gontz et al. 2001) and Cape Lookout Bight (Martens and Klump 1984; Martens et al. 1998) on the eastern coast of the USA; the Firth of Forth (Scotland) and Cardiff Bay (Wales; Taylor 1992).
- Rias (drowned valleys), for example, the Rias Bajas, NW Spain (García-Gil et al. 2002); Chesapeake Bay, USA (Hill et al. 1992); estuaries of the Plym and Tamar, England (Taylor 1992).
- Deltas, for example, Fraser, British Columbia (Hart and Hamilton 1993); Mississippi, Gulf of Mexico (Bryant and Roemer 1983); Yangtze, China (Milliman et al. 1985).
- Sediments from drowned coastlines, for example, peaty sediments of the outer Thames Estuary, southern North Sea (Hovland and Judd 1988), and Norton Sound, Alaska (Nelson et al. 1979); drowned coastal forests offshore western India (Karisiddaiah and Veerayya 2002).

Continental shelves

Continental shelves are effectively drowned areas of continental land masses. Many are underlain by deep sedimentary basins in which thermogenic hydrocarbons are generated.

The migration of hydrocarbons towards the surface may be impeded by impervious strata, leading to the formation of accumulations, including commercial oil and gas reservoirs. Where migration is not impeded, hydrocarbons may reach the surface to escape as natural seabed seeps. However, these are mainly found where migration has been focussed rather than diffused. Seeps are therefore most commonly associated with faults, breached antiforms, and salt diapirs.

Continental slopes and rises

Sediments accumulated on, and at the base of continental slopes are generally the products of sedimentation during periods of relatively low sea level. In recent years, the petroleum industry has moved into the deep waters of these areas to exploit petroleum reservoirs in sedimentary troughs (such as the Porcupine and Shetland-Faroes troughs to the west of the British Isles), and deep-sea fan deposits (such as those associated with the Amazon, Mississippi, and Niger rivers). Petroleum seeps are also associated with seabed exposures and sub-crops of some reservoir formations (such as in the Santa Barbara Channel, California).

Deep oceans

The most important deep-sea sediments for the formation of hydrocarbons, particularly methane, are deep-sea drift deposits, or contourites, which formed as a result of the interaction of water currents. Examples are the methane trapped in and beneath gas hydrates on the Blake Ridge, off the coast of South Carolina, and in the Argentine Basin, in the Atlantic to the east of Argentina. The organic matter from which this methane has been generated is probably of terrigenous origin (Manley and Flood 1989).

Deep ocean trenches

Cold seep communities and methane-derived authigenic carbonates associated with the seepage of methane-rich fluids have been reported from great depths in several ocean trenches, for example, >4,000 m in the Aleutian Trench (Suess et al. 1998); >5,400 m in the Peru trench (Olu et al. 1996); >7,300 m in the Japan Trench (Fujikura et al. 1999).

Geological environments

Geological environments are defined in terms of plate tectonics processes. It is clear from the available literature that seabed fluid flow involving methane occurs in most marine plate tectonic environments. Ocean spreading centres (constructive or divergent plate boundaries) are characterised by volcanic and hydrothermal activity which, as discussed above, involves substantial fluid flow. There are examples of hydrocarbon generation and methane seepage at divergent plate boundaries, and passive margins, where neighbouring plates move laterally past each other. Destructive margins, where plates converge, more commonly provide the conditions for methane generation, migration, and seepage. Hydrocarbon seeps in most of the oceanographic settings identified above (coastal environments, continental shelves, continental slopes and rises, and deep oceans) are not associated with plate boundaries but lie in intra-plate settings, as can be seen from Fig. 3.

Convergent plate boundaries

At convergent boundaries one of the converging plates is subducted beneath the other. When either or both of the plates is oceanic, the subducting plate is oceanic. Sediments lying on this plate may be scraped off to form an accretionary wedge which will be buried and compressed as subduction proceeds. Methane generated within the subducting sediments, along with porewaters squeezed from them, migrates towards the seabed. In many cases this combination of compression-induced high pore fluid pressure and methane results in the formation of mud diapirs and mud volcanoes. Also, the presence of methane-rich porewater in deep ocean sediments is conducive to the formation of gas hydrates. These features are associated with seabed fluid flow in numerous convergent boundaries, such as:

- the Barbados accretionary wedge where the Atlantic Plate is subducting beneath the Caribbean Plate;
- the Cascadia margin (Oregon Subduction zone) where the Juan de Fuca Plate is being subducted beneath the North American Plate;
- the Japan subduction zones where the Pacific and Philippine plates are subducting beneath the Eurasian Plate;
- the Mediterranean Ridge where the African plate is being subducted beneath the Eurasian plate.

Transform plate boundaries

Neither subduction nor extensive volcanism is associated with transform plate boundaries. However, rocks and sediments within the fault zones which define the boundary may be subjected to compression, and migration pathways provided by the faults enable fluid flow. This is demonstrated by two examples:

- the transform boundary between the Pacific and North American plates off Monterey Bay, California comprises several parallel fault zones. There is evidence of seabed fluid flow in several locations in this area (Orange et al. 1999, 2002).
- in the Gulf of Cadiz, on the Atlantic side of the Straits of Gibraltar where the African and Eurasian Plates are sliding past each other, there is an extensive area of mud volcanoes and other features associated with seabed fluid flow (Baraza and Ercilla 1996).

Is seabed gas escape important?

The processes involved in seabed fluid flow play significant roles in sediment dewatering and the expulsion of the degradation products of sedimentary organic matter. Seabed morphological features such as pockmarks, mud diapirs and mud volcanoes are formed by fluid escape (Hovland and Judd 1988). However, the consequences impact not only on the geosphere but also on the biosphere, the hydrosphere and the atmosphere.

Impacts on the biosphere

The anaerobic oxidation of methane by consortia of microbes near the seabed results in the generation of sulphides, themselves utilised by sulphide-oxidising microbes (particularly *Beggiatoa* sp.), and the precipitation of methane-derived authigenic carbonates (Boetius et al. 2000). The hydrogen sulphide, and some methane, support macrofauna which host endosymbiotic chemosynthesising microbes. In turn, the microbes and associated meio- and macrofauna support communities of carnivorous and scavenging meiofauna and macrofauna. Such 'cold seep communities' are clearly focussed around seeps and vents in deep water (see review by Sibuet and Olu 1998). In waters shallower than about 350 m, such communities are more difficult to distinguish from the 'normal' benthic communities supported, ultimately, by photosynthesis. However, the presence of methane-derived authigenic carbonates attracts benthic macrofaunal species which require a hard substrate (Dando et al. 1991). So, methane seeps are beneficial to the biosphere, even in shallow water. More controversially, Leifer and Judd (2002) suggested that nutrients lifted into the water column by rising gas bubbles, but deposited when the bubbles dissolve, support enhanced biological activity within the water column.

Impacts on the hydrosphere and the atmosphere

Under most conditions, most of the methane generated at, and migrating towards the seabed is oxidised by microbial activity (Reeburgh et al. 1993). Where fluid flow is focussed, however, flux rates may exceed utilisation rates, allowing methane to pass through the seabed into the hydrosphere. These emissions of methane seem to fall into two categories: gentle seepage and catastrophic gas escapes. There is plenty of evidence of normal, gentle seepage from the variety of water depths, oceanographic environments, and plate tectonic settings identified above (although in very deep water methane is released in solution rather than as free gas bubbles). With the exception of the numerous reports of violent mud volcano eruptions, evidence of catastrophic gas escapes is less easy to find. Indeed, the author has come across no reliable published reports. However, there is evidence that at least some pockmarks were initially formed by catastrophic gas escape events. Judd et al. (1994, 2002b) attributed the rapid formation of a very large North Sea pockmark to a major gas release event; lithified rock fragments in the base of similarly large seabed 'craters' in the Barents Sea are evidence of an explosive gas eruption (Solheim and Elverhøi 1993; Long et al. 1998). The formation of seabed craters by blowouts during offshore petroleum drilling (e.g. Bryant and Roemer 1983; Thatje et al. 1999) demonstrates that catastrophic gas release is an effective mechanism for pockmark formation, so it is surmised that natural 'blowouts' do occur from time to time.

The methane from catastrophic events may pass rapidly through the water column into the atmosphere. An example of such an event was related by Dimitrov (2002b, 2003, this volume). It occurred off the Kerch Peninsula, on the northern coast of the Black Sea in 1927, when a flame about 500 m tall was observed coming from the sea surface. Similar events have been reported from Trinidad (Kugler 1933), the Makran coast of Pakistan (Sondhi 1947), the southern Caspian

Sea (Sokolov et al. 1969), and Colombia (Hedberg 1980). Dimitrov (2002b, 2003, this volume) identified 11 reports of violent mud volcano eruptions which ignited during the calendar year 2001. Less spectacular eruptions may enable significant volumes of methane to pass rapidly through the water column and into the atmosphere. Gas has been observed bubbling from the sea surface from less dramatic eruptions, for example, in the Santa Barbara Channel, California (<50 m water depth; Hornafius et al. 1999). In deep waters, pieces of solid gas hydrate rise rapidly through the water, only starting to dissociate once they have passed the gas hydrate stability zone. Experiments described by Brewer et al. (2002) showed that large pieces of hydrate are likely to rise right up to the sea surface, releasing their methane directly into the atmosphere. This may explain the bubbles observed at the surface, 700 m above the seabed of the Sea of Okhotsk (Cranston et al. 1994).

Free gas bubbles, whether rising from depth with a protective coating of hydrate, or released from a seabed shallower than the gas hydrate stability zone will be subject to solution at a rate determined by water depth, bubble size, dissolved gas concentrations, temperature, surface-active substances, and bulk fluid motions, particularly the presence or absence of upwelling flows of water (Leifer and Patro 2002). The majority of methane bubbles from gas seeps in all but the shallowest waters will be dissolved in the water column.

Methane not surviving the passage to the atmosphere may contribute significantly to amounts in the hydrosphere. For example, Suess et al. (1999) reported a plume of methane-charged fluids rising "hundreds of metres high and several kilometres wide" from the Hydrate Ridge seeps in the Cascadia Margin (offshore Oregon). Although this plume did not rise above 400 m below sea level, its size and the concentration of methane (<74,000 nl l^{-1} compared to <20 nl l^{-1} in water away from the plume) clearly indicate that such seeps can make a considerable contribution to the hydrosphere. However, it is important to view such plumes in context as they are very localised, and clearly represent anomalous perturbations within a generally methane-deficient ocean.

These contributions, particularly those to the atmosphere, are most significant in shallow water.

The scale of methane escape

In order to provide an indication of the importance of the escape of methane (and other fluids) from the seabed, an estimate of the minimum number of occurrences has been compiled from the literature. The nature and size of these 'occurrences' varies from individual features, observed in isolated areas, to areas (such as the North Sea and the Gulf of Mexico) in which there is known to be a widespread distribution of individual occurrences and features. Bearing in mind that most of the seabed either remains to be surveyed or survey results have not been published, it is emphasised that the values presented in Table 1 are no more than indicative of the *minimum* number of areas in which methane escapes through the seabed. No attempt is made to estimate, for example, the number of seeps in any individual area. Suffice it to say that some individual areas represent significant sources of seabed methane, for example:

- Judd et al. (1997) estimated that there may be 173,000 individual gas seeps on the continental shelf of the United Kingdom;
- Dimitrov (2002a) estimated that there are probably more than 90 submarine mud volcanoes in the Southern Caspian Basin;
- Estimates quoted by Dillon and Max (2000) suggest that an area of between 3,000 and 100,000 km^2 is underlain by gas hydrates in the Blake Ridge area, off the south-eastern coast of the USA.

Table 1 The scale of methane escape. The values indicate the *minimum* number of occurrences in which seabed methane escape, or features associated with it (gas seeps, chemosynthetic 'cold seep' biological communities, methane-derived authigenic carbonate, pockmarks, shallow gas, gas hydrates) are known to occur. 'Occurrences' vary in size and importance from large areas, such as the North Sea, the Gulf of Mexico and the Southern Caspian Basin, with large-scale escapes to much smaller areas in which there may be only a small number of escapes (data from various sources compiled using the MAGIC GIS database; see Judd et al. 2002a)

Oceanographic settings, plate tectonic contexts		Minimum number of occurrences
Oceanographic settings	Coastal	30
	Continental shelf	44
	Continental slope/rise	58
	Deep ocean	2
Plate tectonic contexts	Intra-plate	102
	Divergent	1
	Transform	4
	Convergent	27
Minimum number of areas		134

No attempt is made to quantify the impact of seabed methane escapes on marine biology, although it is clear that the impact on the benthos is significantly greater in waters deeper than about 350 m than it is in shallow waters where energy supplies are dominated by photosynthesis.

Kvenvolden et al. (2001) estimated that geological sources (primarily seeps and mud volcanoes) of methane contribute 30 to 50 Tg of methane per year to the seabed, of which they estimated 20 Tg was oxidised and dissolved in the hydrosphere and the biosphere. The remaining 10 to 30 Tg was thought to enter the atmosphere. Estimates by Judd et al. (2002b) suggest that between 6.6 and 19.5 Tg is contributed to the atmosphere, with a similar amount going into the hydrosphere. These estimations are known to be no more than first approximations. However, when viewed in the light of the number of oceanographic and geological contexts in which they occur, and their apparent widespread occurrence, it is evident that important contributions are being made to the hydrosphere and the atmosphere.

Conclusions

In the preceding sections it has been shown that seabed fluid flow involving the seepage of free methane gas and/or water with a high methane concentration is found in every sea and ocean, and is associated with a variety of oceanographic environments and plate tectonic settings. It seems that natural seabed gas seeps, and methane-emitting submarine mud volcanoes are widespread. They contribute to the hydrosphere and the atmosphere. The biosphere is also affected, benthic productivity in deep water areas being significantly increased in the vicinity of methane escapes.

Because of the variety of contexts in which it occurs, and the vast geographical areas involved, it must be concluded that the escape of methane through the seabed is *not* a curiosity confined to unusual geological circumstances, but an important part of the global carbon cycle.

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