Major occurrences and reservoir concepts of marine clathrate hydrates: implications of field evidence

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Abstract: Questions concerning clathrate hydrate as an energy resource, as a factor in modifying global climate and as a triggering mechanism for mass movements invite consideration of what factors promote hydrate concentration, and what the quintessential hydrate-rich sediment may be. Gas hydrate field data, although limited, provide a starting point for identifying the environments and processes that lead to more massive concentrations. Gas hydrate zones are up to 30 m thick and the vertical range of occurrence at a site may exceed 200 m. Zones typically occur more than 100 m above the phase boundary. Thicker zones are overwhelmingly associated with structural features and tectonism, and often contain sand. It is unclear whether an apparent association between zone thickness and porosity represents a cause-and-effect relationship. The primary control on the thickness of a potential gas hydrate reservoir is the geological setting. Deep water and low geothermal gradients foster thick gas hydrate stability zones (GHSZs). The presence of faults, fractures, etc., can favour migration of gas-rich fluids. Geological processes, such as eustacy or subsidence, may alter the thickness of the GHSZ or affect hydrate concentration. Tectonic forces may promote injection of gas into the GHSZ. More porous and permeable sediment, as host sediment properties, increase storage capacity and fluid conductivity, and thus also enhance reservoir potential.

Evaluating the energy resource potential of gas hydrate in local areas, such as in the Blake Ridge area off the south-eastern United States (Dillon *et al.* 1995) or in the Japan offshore (Okuda 1996), is the first step towards developing an overall picture of clathrates as a viable energy source. How closely the assessments of these areas truly represent the population of hydrate-bearing strata is unknown. The framework of possible effects that methane hydrate dissociation might have on global climate has been constructed by Nisbet (1990), Englezos & Hatzikiriakos (1994) and Paull *et al.* (1991). As a potent 'greenhouse' gas, being 10 times more effective than CO_2 on a molar basis (Lashof & Ahuja 1990) but having a short residence time in the atmosphere (about 9 years), it is the rapid release of massive quantities of CH_4 that may well govern its relative importance on global climate. Without knowledge of what may constitute a major gas hydrate deposit, however, the possible impact of these effects cannot be prudently evaluated. The potential of gas hydrates and attendant processes to act as an important geological agent in transporting sediment and controlling continental slope and rise morphology depends on estimates of local hydrate concentration. Popenoe *et al.* (1993) and Booth *et al.* (1994) presented evidence of possible associations between gas hydrates and marine landslides. Gas hydrates were a major part of a sea-floor collapse event off the south-eastern United States (Dillon *et al.*, 1998). In addition, Kayen & Lee (1991) examined possible consequences of sea-level fall on slope stability if excess pore pressures accompany hydrate dissociation. Further effects may become apparent in conjunction with general geotechnical engineering and, if the case, with extraction of gas hydrate itself. The considerations of offshore engineering, and the possible magnitude of slope failures and their significance in the geological record, cannot yet be determined.

Accordingly, there are three first-order questions regarding marine gas hydrate that constitute the essence of our research:

(1) Can gas hydrate be an energy resource?
(2) Can there be places where the quantity of gas hydrate is such that its rapid dissociation would have a consequential effect on climate?
(3) Can gas hydrate deposits be large enough to serve as triggering mechanisms for major marine landslides and sea-floor collapses?

The answers to these questions necessarily involve a fundamental characterization of the

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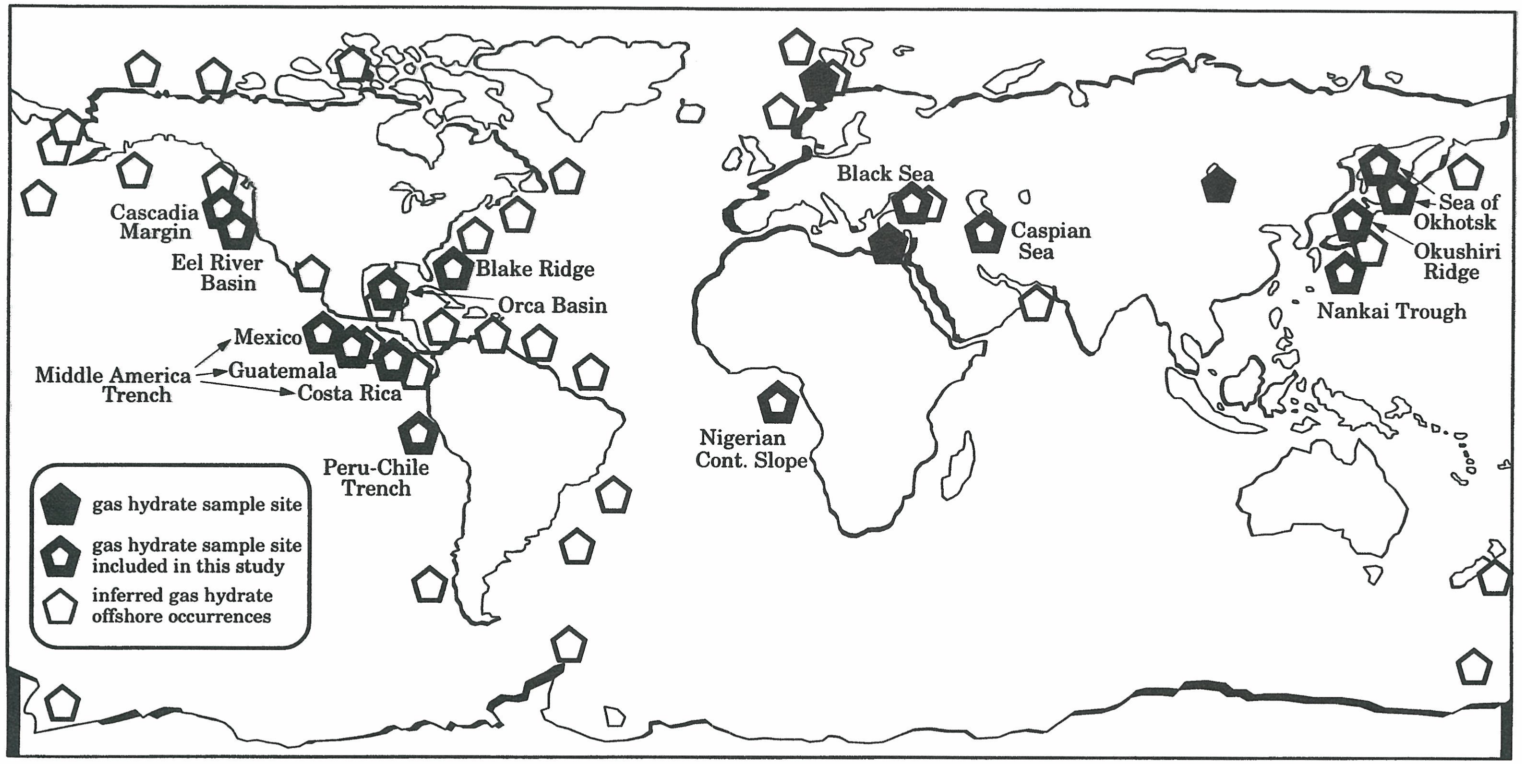

Fig. 1. World-wide distribution of confirmed or inferred offshore areas of gas hydrate-bearing sediments. Most areas contain more than one sample site. References to sites not specifically mentioned in the text may be found in Booth *et al.* (1996).

quintessential hydrate-rich sediment. Attempts have not yet been made to search for the most impressive hydrate 'reservoirs'; i.e. the thickest, most concentrated zones of clathrate hydrate that may have resource potential, may be vulnerable to sudden breakdown and release of massive quantities of CH_4 to the atmosphere, or may harbour enough gas to cause large-scale slope failures and mass movements.

A database of marine gas hydrates samples compiled by Booth *et al.* (1996) permits analysis of the gamut of natural occurrences and the characteristics associated with each. The data represent Deep Sea Drilling Program (DSDP) and Ocean Drilling Project (ODP) downhole samples, and samples from sea-floor gas hydrates (see Booth *et al.* (1996) for a complete list of references). The database comprises 15 areas (Fig. 1) and represents approximately 100 samples of gas hydrate. Because it is based solely on field samples and thus does not include inferred occurrences, it is conservative. It is also biased because of the nature of site selection, its data are often clustered (e.g. 20 of 28 downhole samples are from the Middle America Trench region) and somewhat qualitative, and the few data incorporated within it may not constitute a valid sampling of the marine gas hydrate population. Despite these limitations, the database serves as a starting point toward understanding the environments and processes that lead to the more concentrated and/or conspicuous deposits of marine gas hydrates. It reveals some plausible tendencies and associations, and permits preliminary characterization. In turn, inferences about geological settings, geological processes and gas hydrate host sediment properties that favour concentration of gas hydrates and development of thick zones of hydrate-bearing sediment may be deduced.

Summary of pertinent marine gas hydrate characteristics

Prominent samples, zones and ranges

Although the size of most pure gas hydrate samples is expressed in terms of millimetres or centimetres, a sample collected in the vicinity of the Middle America Trench off Guatemala (DSDP Site 570) was 1.05 m thick and may have come from a section of pure gas hydrate that is as much as 3–4 m thick (Shipboard Scientific Party Leg 84 1985). Also, a 14 cm thick sample of pure gas hydrate was taken from ODP Site 997 in the Blake Ridge area (off the south-eastern United States) (Shipboard Scientific Party Leg 164 1996*b*). A 9.5 m thick bed of coarse sand completely cemented by gas hydrate (i.e. 100% occupancy of pores) was also discovered off Guatemala (Shipboard Scientific Party Leg 66 1982*b*) and two other, similar, sub-seabed gas hydrate-cemented sands were cored that were about 0.5 m thick.

Individual samples often constitute a part of thicker zones of gas hydrate-bearing strata, where a zone is a unit in which there is a conspicuous and essentially uninterrupted presence of gas hydrate. Seven zones identified from DSDP and ODP data are greater than 1 m thick and four zones are greater than 10 m thick. Several sea-floor sites are more than 1 m thick as well. Gas hydrate zones vary in thickness up to as much as 30 m (zone in Okushiri Ridge, Sea of Japan (Shipboard Scientific Party Leg 127 1990). Other zones more than 10 m thick are located in Orca Basin (Gulf of Mexico) – 20 m, the Cascadia margin (Pacific–US) – 17 m and the Middle America Trench region (Pacific–Guatemala) – 15 m. A zone about 33 m thick may exist at the last site listed (Shipboard Scientific Party Leg 84 1985).

'Range' is the sub-seabed depth over which clathrate occurs. Often, this is the vertical distance spanned by multiple zones at one site. Near the Middle America Trench off Guatemala (DSDP Site 570) six zones of hydrate exist from 192 to 338 mbsf (146 m range) (Shipboard Scientific Party Leg 84 1985). Off Mexico in the same region (DSDP Site 490) four zones are present from 140 to 364 mbsf (224 m range) (Shipboard Scientific Party Leg 66 1982*a*).

The relative frequencies of occurrence of these three levels of hierarchy for different size/thickness categories are shown in Fig. 2. The inference is that grains, or thin veins or laminae, of pure gas hydrate may be common in many zones but that typically they may be only a minor constituent (small percentage of total sediment volume) of the thicker zones in which they occur. Some zones may show substantial concentrations, however. Concentrations of clathrate tend to be in zones less than 10 m thick, although the inset (Fig. 2) shows that more than a quarter of the zones and most of the ranges have greater thicknesses.

Tendencies in spatial distribution

The primary controls of hydrate occurrence at a given site in the marine environment are: (1) an ample source of methane (references to a gas herein mean methane gas; marine hydrates are typically ≈99% methane) which can exist

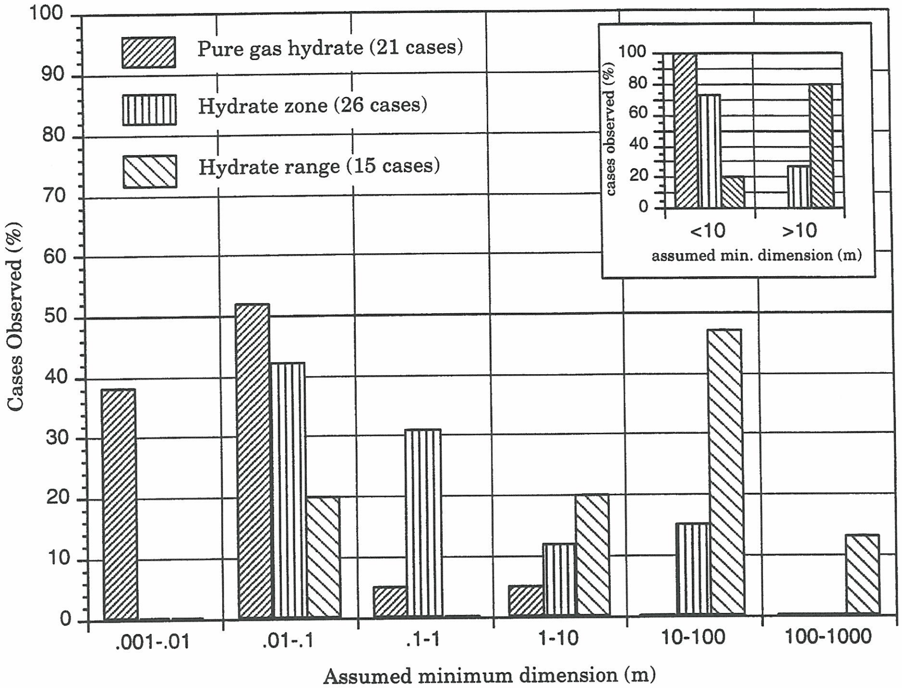

Fig. 2. Frequency distribution of presumed minimum dimension of pure gas hydrate samples, thickness of gas hydrate-bearing zones and vertical range at a sample site over which gas hydrate occurs (may include multiple zones). Inset shows the frequency of occurrence of each category using 10 m as the sorting criterion.

almost anywhere where organic matter and suitable reducing conditions or sufficient heat are juxtaposed (Demaison & Moore 1980; Hunt 1995), along with appropriate pathways for fluid migration; and (2) a specific range of pressure and temperature conditions (generally >5 MPa (≈500 m water depth) and <25°C) within which gas hydrates are stable; i.e. a gas hydrate stability zone (GHSZ). Such combinations of pressure and temperature are pervasive in world ocean sediments to sub-seabed depths of 100 to perhaps 1000 m or more, depending upon the geothermal gradient. Accordingly, gas hydrate sites are geographically widespread but not ubiquitous. Continental margins or areas near land masses, which tend to develop thick sedimentary sections that are relatively rich in organic matter, favour hydrate accumulation (Fig. 1).

In addition to the bias in global surface distribution, there is a vertical bias imposed by the phase boundary: that is, with reference to Fig. 3a, even at extremely low geothermal gradients the rise in temperature with increasing sub-bottom depth will ultimately yield a P–T combination that precludes gas hydrate formation. Because this temperature is associated with a sub-bottom depth, this depth is the base of the GHSZ. The position of this 'floor' establishes a site's absolute potential to develop a 'rich' gas hydrate deposit because it defines the vertical range over which a hydrate may exist in the sediment column. A general model asserts that clathrates form when an ample supply of gas has migrated upward from some source, encountered the phase boundary (base of the GHSZ), and been encaged there. This implies that gas hydrates occur in a somewhat narrow band at or proximal to the base of the GHSZ.

Most gas hydrate samples taken from DSDP and ODP drill holes show that *in situ* they were situated well above the base of the GHSZ (Fig. 3a). No samples were found below the calculated position of this base at any site. The average position of a sample was approximately 300 m above the base, and about three-quarters of the samples came from more than 100 m above the base's assumed position (Fig. 3b). However, drilling to the bottom simulating reflector (BSR), which may indicate the presence of a gas hydrate layer at the base of the stability zone, was prohibited in DSDP operations as a safety precaution.

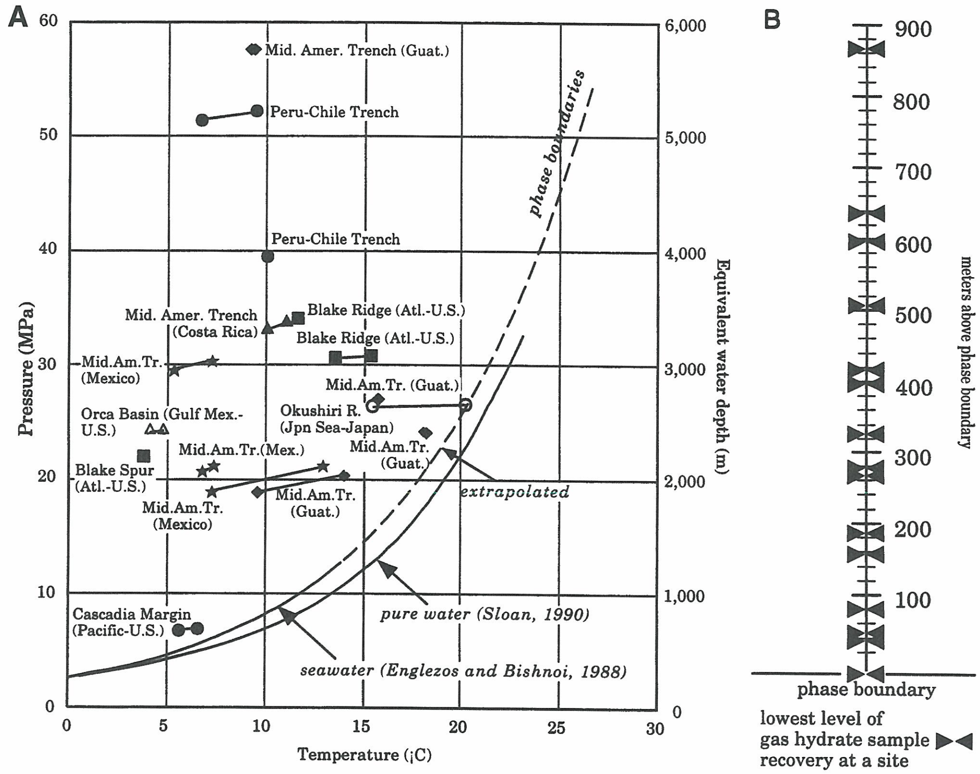

Fig. 3. (A) Approximate positions of gas hydrate samples with respect to the methane clathrate hydrate phase boundary. Two symbols connected by a line indicate the *in situ* P–T range from which gas hydrate samples were recovered from one site. Only borehole data were plotted. (B) Difference between borehole gas hydrate sample recovery depth and calculated depth of the regional phase boundary.

Borehole sampling was thus skewed away from the boundary, and this alone would tend to mask the frequency of hydrate occurrence at that boundary if there were such an association. This not withstanding, at five of six gas hydrate-bearing sites, in which corers penetrated the assumed depth of the base of the GHSZ, there was no evidence of gas hydrates. In addition, an analysis of sites based on standardizing geothermal gradients (i.e. comparing distances of gas hydrate occurrence above the base of the GHSZ if all sites had the same geothermal gradient) showed that there was no obvious relationship between the position of hydrate zones and the base of the GHSZ. Not only does the base of the GHSZ make an unreliable 'containment' zone, but it does not necessarily make a good criterion for locating hydrate-bearing sediments either.

Analysis of the gas hydrate zone and the range of vertical distribution shows no conspicuous tendencies. Of the hydrate-bearing zones thicker than 1 m and the ranges of occurrence greater than 10 m, there may be a slight tendency for them to exist relatively high (toward the sea floor) in the sedimentary column.

Associations with structural features

There is a clear association between gas hydrate occurrence and fault zones, as well as other tectonically related features, as has been observed by Hyndman & Davis (1992), Soloviev & Ginsburg (1994), and others. Approximately three-quarters of the gas hydrate-bearing sites in the database (including both seabed and sub-seabed sites) are within or proximal to features that may promote upward migration of gas or gas-rich fluids. All but one of the 15 drill hole sites in which hydrates were present lie within tectonically active continental margin environments. The Blake Ridge off the south-eastern United States is the only site in a passive

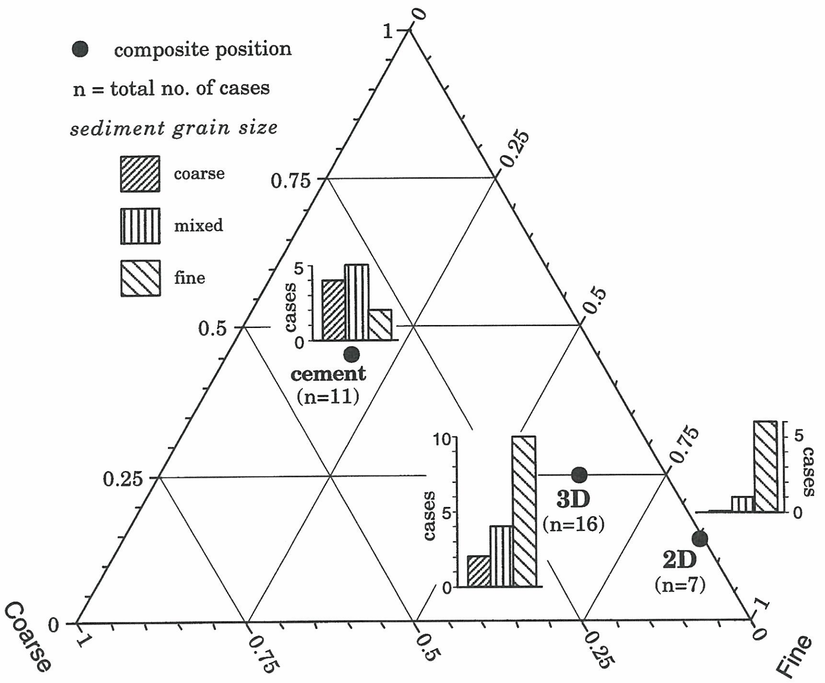

Fig. 4. Composite relative frequency of occurrence of different gas hydrate forms (habit) with respect to sediment type (borehole samples only). Insert shows the specific grain size associations for each gas hydrate habit. '2D' refers to planar form hydrates (e.g. laminae, lenses, layers); '3D' refers to hydrates described as grains, particles, blebs, nodules, massive, etc.; 'cement' are hydrates that act as a matrix for included sediment particles. Sediment types are: coarse – sand or larger grain sizes (includes volcanic ash); fine – silt and clay grain sizes (includes fine ash); mixed – both coarse and fine sediment mixed or juxtaposed where the hydrate sample was found.

margin. It is nonetheless characterized by the presence of extensive fault zones (Dillon *et al.* 1994; Rowe & Gettrust 1994). The presence of vents, seeps and mud volcanoes near many sea-floor gas hydrate sites (e.g. Brooks *et al.* 1986; Soloviev & Ginsburg 1994; Shipboard Scientific Party Leg 164 1996*b*; Basov *et al.* 1996) verifies that gas(es) have moved up conduits and locally breached the sea floor at these locales.

Associations with sediment properties

Natural gas hydrates typically exist as individual grains or particles disseminated throughout the sediment, but also commonly exist as cements, nodules and as laminae or layers. Figure 4 shows the relationships between habit and grain size for sub-seabed samples. The drill hole data show that no particular category (habit) was dominant. As indicated by Fig. 4, almost all of the two-dimensional samples (layers, laminae, etc.) were associated with fine sediment, either intrinsically or in fractures. Three-dimensional samples (granules, nodules, etc.) were numerous in fine sediments as well, but were also identified in sediment of more than one basic grain size. Clathrate cements clearly are more associated with coarser material. The two largest pure samples (1.05 m apparent layer from DSDP Site 570 and 14 cm thick borehole sample from ODP Site 997) formed at the contact between an indurated dolomite and a mudstone, and in a silty clay, respectively. As stated, a sand layer 9.5 m thick was cemented with clathrate hydrate in DSDP Site 498.

Porosities determined proximal to the hydrate samples in drill holes ranged from just above 40% at 364 mbsf (DSDP Site 491 in the Middle America Trench (Shipboard Scientific Party Leg 66 1982*b*)) to nearly 75% at 161 mbsf (ODP Site 688 in the Peru–Chile Trench (Shipboard Scientific Party Leg 112 1988)). An average porosity for sediments above and below gas hydrate zones is about 55%. The sediments from which the two largest samples of pure gas hydrate were recovered had porosities slightly higher than the average. Because the data are too few and there are other shortcomings in the database, a rigorous statistical analysis of porosity values above and below gas hydrate zones was not attempted. Nonetheless, DSDP/ODP data show that thicker gas hydrate zones are associated with more porous sediment. Five of the seven thickest zones (1.5–29.3 m thick) have the five highest porosities among the borehole gas hydrate zones for which there are data. Values are close to or in excess of 60%. The porosity of the sixth zone (20–40 mbsf in Orca Basin, Gulf of Mexico) is estimated to be similar. Porosities were not determined by the site investigators for the remaining (seventh) zone, which is the 9.5 m thick zone discovered at DSDP Site 498 (Middle America Trench). Figure 5 is a plot of zone thickness vs porosity for zones >0.1 m thick.

Given that in two of the three outliers the host sediment are sands, which characteristically have much lower porosities than unconsolidated cohesive sediment, the apparent correlation between porosity/permeability and hydrate concentration is noteworthy. However, because this apparent relationship may represent an effect (of gas expansion in the sediment once on deck) as well as a cause, and because of other factors, it is considered more of a justification for research than it is a prospecting criterion.

Field data and gas hydrate reservoir concepts

Potential gas hydrate 'reservoirs' are defined by their storage capacity and capability to concentrate clathrates, as well as being within the GHSZ. Whereas petroleum traps have to leak to function as a trap – a petroleum trap must allow water to be expelled (Roberts 1980) – water must be present for a gas hydrate to form. Also, gas hydrate reservoirs can be self-sealing. The filling of sediment interstices with clathrate can prevent further migration of the source fluid and thus set up further production of clathrate hydrates. We focus on three main factors which bear on reservoir potential: geological setting, geological processes and host sediment properties. Discussion is limited to

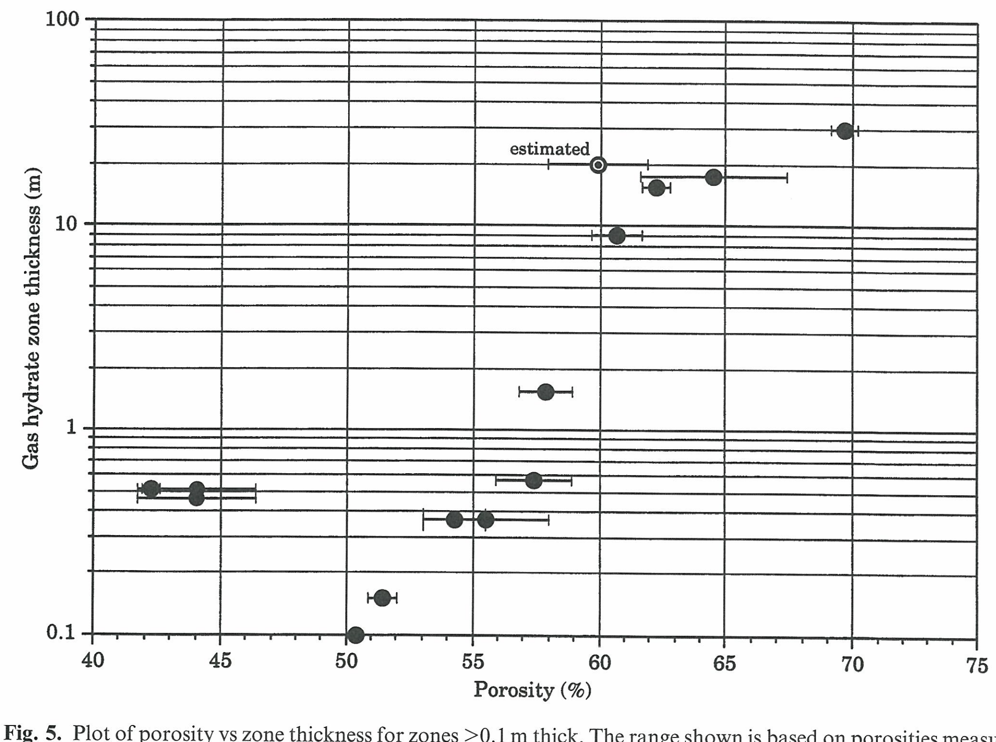

Fig. 5. Plot of porosity vs zone thickness for zones ≥0.1 m thick. The range shown is based on porosities measured above and below, but not within, the gas hydrate-bearing zone. Solid circles are the range midpoints. The estimated porosity range is for the Orca Basin site (Gulf of Mexico). The gas hydrate zone at this site is 20–40 mbsf. Not included: porosities associated with 9.5 m thick zone of gas hydrate-cemented ash in the Middle America Trench off Guatemala. Porosities were not determined near this zone.

concepts for which data can be presented in the context of existing gas hydrate sites.

Geological setting

This factor includes water depth and geothermal gradient, which together are the primary controls of the absolute thickness of the GHSZ, and hence, without known variability in lateral dimensions, the absolute storage capacity of the site. The thickness of the GHSZ is consequential because it sets the overall site potential for hydrate concentration and may affect the probability of including more favourable host sediment within the GHSZ. Figure 6 is a plot of the relationship between water depth and thickness of the GHSZ for specific geothermal gradients. As shown, the GHSZ thickens with increasing water depth and decreasing geothermal gradient. The DSDP/ODP sites are also plotted in Fig. 6 to show the thicknesses of their GHSZ and so that site comparison is possible. The sites with the two largest ranges and the most gas hydrate zones (DSDP sites 490 and 570) have GHSZ thicknesses of more than 500 m. Both sites are also relatively shallow (<2000 m), but, given the non-linear (approximately exponential) relationship between P and T that sets the phase boundary, they are deep enough to avoid significant constraints on the thickness of their GHSZs. Figure 6 also shows that although a greater GHSZ thickness may be inherently more desirable, it may not be required for a substantial gas hydrate deposit to accumulate. The Okushiri Ridge and Cascadia margin sites have two of the thicker gas hydrate zones described, but have the two thinnest GHSZs.

Fault zones, joint and fracture systems, and other features that are potential pathways for upward migration of methane or other gases can be an important facet of a possible gas hydrate 'reservoir', as has been previously recognized in gas hydrate field studies (e.g. Brooks *et al.* 1986, 1994; Soloviev & Ginsburg 1994). Such conduits additionally provide a means for transporting methane considerable distances into the GHSZ. In some of these systems, fluids can be injected into more horizontal pathways as well, but such flow must be hydraulically driven to counter the strong vertical component of movement associated with free methane due to its buoyancy. Data from field studies can support these possibilities, as is the case historically for the numerous studies on secondary oil and gas migration (e.g. see Roberts & Cordell 1980; England & Fleet 1991; Hunt 1995). Rowe & Gettrust (1994) and Dillon *et al.* (1994) present high-resolution seismic profiles from the Blake Ridge gas hydrate area that show indications of gas hydrate penetration of fault zones. In the Cascadia margin gas hydrate area, Zwart *et al.* (1996) have thermal evidence that fault zones are acting as conduits for warm fluids. Seabed sites are direct evidence of the migration of gas and may well reflect processes of clathrate formation in zones penetrated by these conduits before they reach the sea floor (Soloviev & Ginsburg 1994; Ginsburg & Soloviev 1997). Veins, ash layers (sands) and silty sands are prevalent in the Middle America Trench area, and their connection to the widespread occurrence of gas hydrate there has been examined (Taylor & Bryant 1985).

There are several other geological features that affect hydrate accumulation within a GHSZ, but they are not inherently a factor in hydrate occurrence. Among these are diapirs. During piercement, diapirs often generate fault networks and cause radial fracturing. Sea-floor gas hydrates in the Gulf of Mexico (Brooks *et al.* 1986), the Blake Ridge area (Paull *et al.* 1995), and the Black, Caspian and Okhotsk seas (Soloviev & Ginsberg 1994) are linked to diapirs.

Geological processes

That geological processes can shape a potential gas hydrate reservoir is evident by the explanations required for why gas hydrates occupy positions well above their present regional phase boundary. If phase boundary gas hydrates (gas hydrates at or proximal to the present base of the GHSZ) are truly subordinate in frequency to internal gas hydrates (gas hydrates that are well above the present base of the stability zone), why is this latter category dominant? Four possible types of explanations for an internal gas hydrate are: (1) it formed as a consequence of localized pressure, temperature or pore water chemistry effects, rather than as a consequence of regional geothermal and hydrostatic conditions; (2) it formed by site-specific gas enrichment, either in the absolute or relative sense; (3) it formed at a time when the base of the GHSZ was shallower; it is relict; and/or (4) it formed elsewhere and was transported to its present location by mass movement processes; it is allochthonous.

A comprehensive discussion of the possibilities associated with each of these types is beyond the scope of this paper. Rather, two separate scenarios based on these possibilities

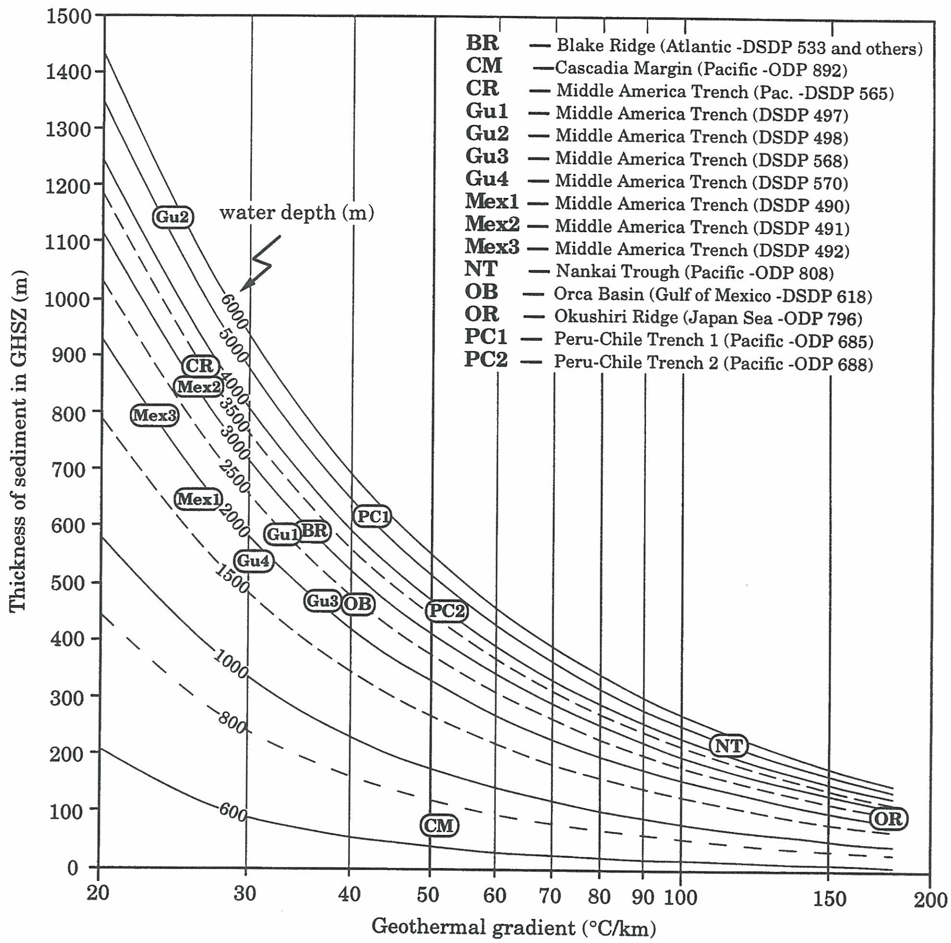

Fig. 6. Thickness of sediment in the gas hydrate stability zone (sediment height above the phase boundary) as a function of pressure (water depth + sub-bottom depth, assuming normal consolidation) and temperature (geothermal gradient). Thicknesses of GHSZs and DSDP/ODP sites are plotted for comparison.

will be examined to show their relevance in a potential hydrate enrichment process. The first one involves Type 1 ('localized phase boundary') internal hydrates. Field evidence indicates that anomalously warm, presumably methane-rich fluids can rise in conduits in gas hydrate areas (Zwart *et al.* 1996). These fluids ultimately produce clathrates when they achieve thermal equilibrium with respect to regional isotherms; that is, they create their own localized, moving phase boundary front until they dissipate their excess heat. If this fails to happen, as near Paramushir Island in the Sea of Okhotsk, the gas escapes into the overlying water column (Basov *et al.* 1996). The Type 3 'relict base of the GHSZ' scenario applies to, for example, the last major eustatic event, subsidence or a decrease in the geothermal gradient (e.g. due to moving away from a hot spot or spreading centre). The effect of such processes could make a pre-existing hydrate the top of an ever-thickening zone as the base of the GHSZ moved lower in the section, or it could 'strand' a pre-existing hydrate zone with respect to the new regional position of the GHSZ base. For predicting sites that may have more potential to bear hydrate-rich sediment, it is again noteworthy that the *P–T* relationship approximates an exponential curve. A consequence of this is that a eustatic rise or seabed subsidence, which would both cause an increase in pressure at a given sub-surface depth, could result in a significant thickening of a shallow-water GHSZ, but only a slight thickening in deep-water GHSZ

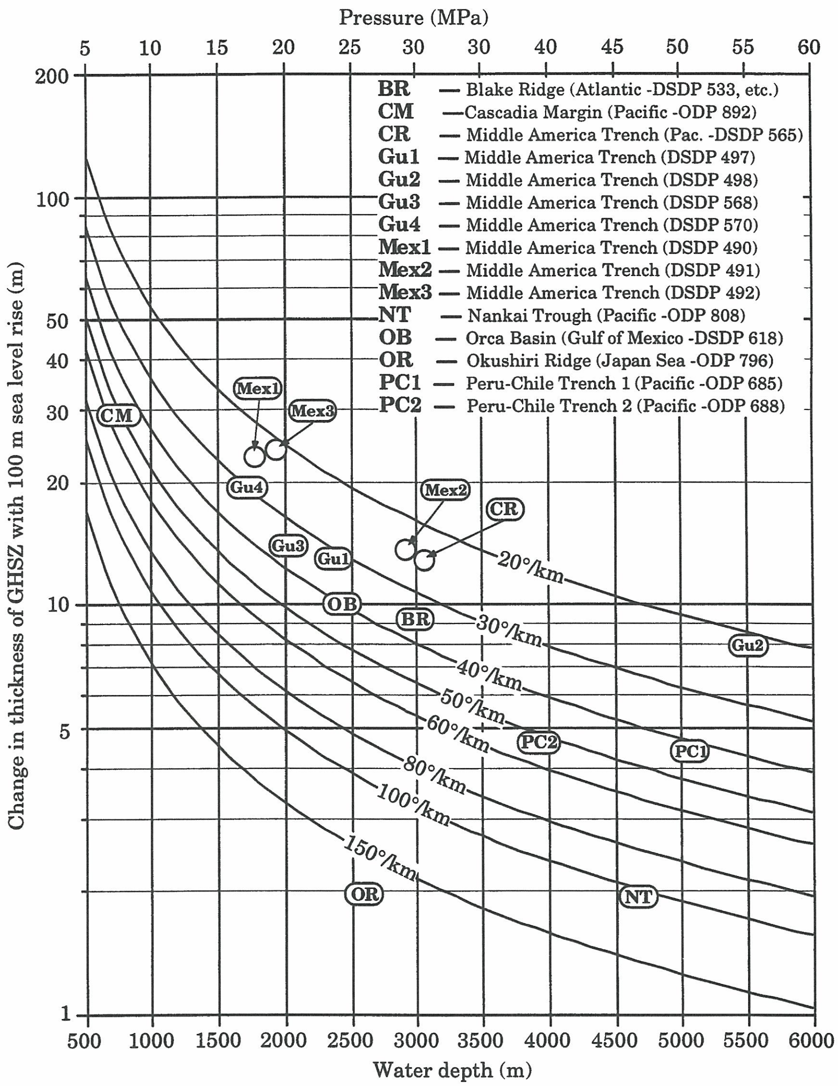

Fig. 7. Increase in GHSZ thickness with increase in pressure equivalent to a 100 m sea-level rise. Deeper gas hydrate zones or those associated with high geothermal gradients are marginally affected; shallow sites can show a significant increase.

(Fig. 7). Conversely, a decrease in the geothermal gradient could substantially increase the thickness of a hydrate in deep water, but have much less an effect on a shallow-water hydrate (Fig. 7). A plot of the ODP data in Fig. 6 shows which sites have the greater potential to change their GHSZ thicknesses based on Type 3 possibilities. The GHSZ on the Cascadia Margin, for example, would have almost doubled its thickness in response to last major eustatic event; conversely, the Japanese sites (Okushiri Ridge and Nankai Trough) and the Peru sites would have been virtually unaffected.

The potential reservoir thickness of a site can be analysed in a similar way for depositional and erosional processes. Paull *et al.* (1994) show how the phase boundary alone could be a zone of increasing concentration of gas hydrate through depositional processes. Similarly, slope failures and mass movements may also induce changes in reservoir thickness, even if only temporarily.

Geological processes not only promote access of gas to the entire GHSZ, but can alter the thickness of the potential reservoir. Tectonism, besides its possible role in establishing favourable attributes in the geological environment and in aiding gases to bypass the base of the GHSZ or in enlarging the GHSZ, also can improve the reservoir potential of a site by creating forces that actively inject gases into it. Hyndman & Davis (1992) propose that large-scale compression associated with tectonically induced thickening of sediment wedges or subduction can expel fluids into the upper parts of the sediment section. They infer that convergent margins are not only typified by the presence of pathways for fluid movement, but provide mechanisms to move the fluids as well.

Host sediment

If we assume a basic proportionality between porosity and permeability (the Kozeny–Carman equation), then higher porosity would also suggest a greater capability to transport fluids. Simplistically, high porosity and permeability favour the accumulation of clathrates. Because permeability tends to be anisotropic (more permeable normal to the direction of compaction) in consolidating sediments (e.g. Vasseur *et al.* 1995), more porous beds may also favour clathrate accumulation through fluid pathways that may trend toward horizontal. Extrapolation of the findings of Clennell *et al.* (1995) infers that when a pore throat (capillary) diameter fails to exceed a threshold

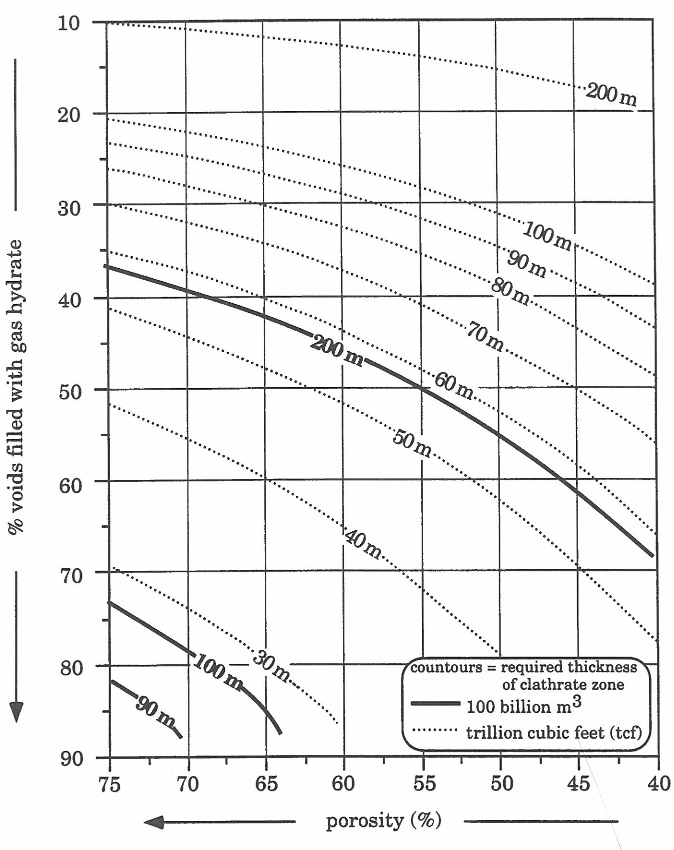

Fig. 8. Thickness of the zone required to yield 100 billion cubic metres or a trillion cubic feet (tcf) of methane for different combinations of porosity and percentage of voids filled with gas hydrate. All values of porosity, percentage of voids filled and possible thicknesses are within boundaries established by field data. Calculations are based on a cylindrical gas hydrate zone with a radius of 2000 m. For a typical porosity associated with gas hydrates (55%), if 50% of the voids are filled, the gas hydrate would have to be present over a vertical range of 200 m to yield 100 bcm, or about 57 m thick to yield a tcf of natural gas.

Table 1. *Gas hydrate zone facts*

Area	Site identification	Zone thickness (m)	Site near land mass?	Porosity $\gtrsim 60\%$?*	Proximal to phase boundary?	Tectonic features present?	Sand present?	Habit
Okushiri Ridge	Sea of Japan ODP Site 796	29.3	yes	yes	yes	yes	yes	mixed
Orca Basin	Gulf of Mexico DSDP Site 618	≈20	yes	yes†	no	yes	yes	grains
Cascadia Margin	Pacific–US ODP Site 892	≈17	yes	yes	no	yes	no‡	mixed
Middle American Trench	Pacific–Guatemala DSDP Site 570 (zone b)	≈15	yes	yes	no	yes	no	discrete
								10 m
Middle American Trench	Pacific–Guatemala DSDP Site 489	9.5	yes	–	no	yes	yes	cement
Middle American Trench	Pacific–Guatemala DSDP Site 570 (zone c)	≈9	yes	yes	no	yes	no	discrete
Middle American Trench	Pacific–Guatemala DSDP Site 568	1.5	yes	yes	no	no	yes	discrete
								1 m
Blake Ridge	Atlantic–US ODP Site 997	0.55	yes	yes	no	yes	no	discrete
Middle American Trench	Pacific–Mexico DSDP Site 490 (zone d)	0.5	yes	no	no	no	yes	cement
Middle American Trench	Pacific–Mexico DSDP Site 491 (zone c)	0.5	yes	no	no	yes	no	mixed
Middle American Trench	Pacific–Mexico DSDP Site 491 (zone b)	0.45	yes	no	no	yes	yes	cement
Middle American Trench	Pacific–Mexico DSDP Site 490 (zone c)	0.35	yes	no	no	no	yes	cement
Middle American Trench	Pacific–Mexico DSDP Site 490 (zone b)	0.35	yes	no	no	no	yes	cement
Middle American Trench	Pacific–Mexico DSDP Site 492 (zone a)	0.15	yes	no	no	no	yes	cement
Middle American Trench	Pacific–Mexico DSDP Site 491 (zone a)	0.1	yes	no	no	yes	no	discrete
								0.1 m

* Based on values above and below zone; † estimated; ‡ sand rare.

Habits: mixed – two or more of grains, 2D, 3D, cement; grains – ≈equant forms ≤1 cm; discrete – 2D or 3D forms with mic. $D > 1$ cm; cement – matrix for sediment particles.

size (perhaps less than 1 μm), intergranular hydrate growth can be greatly inhibited. Clennell *et al.* (1995) argue that under these conditions growth is a function of the ability of the clathrate to displace the surrounding sediment grains that form the pore space. Constraints on growth are also discussed by Harrison & Curiale (1982), who suggest that a pore diameter of 100 Å may be a limiting size to hydrate formation. We speculate that if there is a limiting capillary diameter with respect to hydrate growth, and if there is a limit to the capability of a nucleated hydrate to displace sediment, then gas hydrate growth would be precluded in some sediments, regardless of gas supply, in all but the most severe hydraulic gradients.

Pure sand layers facilitate fluid flow but generally have lower porosities than fine-grained sediments in the upper few hundred metres of a section; i.e. above the position of most regional phase boundaries. These sand layers also tend to be thin, reducing their overall potential to hold large volumes of gas hydrate compared to the much more prevalent cohesive sediment. The 9.5 m thick cemented sand (DSDP 498) was the thickest zone of sand discovered and was unique among the zones thicker than 1 m.

Work by Clennell *et al.* (1995) also lays a thermodynamic foundation for pore-geometry control of gas hydrate growth behaviour and infers that nodules or interstratal occurrences of gas hydrate would tend to form in finer sediments (typified by smaller pores), whereas intergranular growth (cements) may be more likely in sands or sediments with larger pore sizes. We also speculate, therefore, that more massive, pure gas hydrates would tend to be located either relatively deep in a sediment column or in overconsolidated sediment. Grains of gas hydrates or gas hydrate cement could occur at any level within the same sediment column.

Implications with respect to massive gas hydrate occurrence

Based on the field evidence and reservoir concepts, what could be expected in terms of gas hydrate concentration and what would the attributes of the site be? Estimates of the potential of a gas hydrate to concentrate to the degree that such a deposit would achieve the label 'significant' would be both tenuous and variable, depending upon whether in the context of energy resource, global climate or slope stability. Despite this, a hypothetical scenario provides a starting point for discussion. Figure 8 is an attempt to construct a framework for scenarios that may be possible. It shows, for different combinations of porosity and gas hydrate infilling of the pores (% voids filled), the thickness of the hydrate zone that would yield 100 billion cubic metres (100 bcm) or trillion cubic feet (tcf) of CH_4. The boundary conditions were set using borehole data from gas hydrate sample sites. Porosities range from 40 to 75%. Zones ranged to 30 m or more in thickness and ranges exceeded 200 m. Infilling ranged to apparently 100% in some zones and some samples were pure gas hydrate. The model used for Fig. 8 assumes a borehole site is the axis of a cylinder of gas hydrate-bearing sediment that is 2000 m in radius. This radius is well within the lateral extent of gas hydrate occurrence implied by site clusters in several regions (Blake Ridge, Middle America Trench regions off Guatemala and off Mexico).

Regardless of whether a gas hydrate deposit could attain 'significant' volumes, a profile of the more impressive deposits yet to be discovered may be foreshadowed in Table 1. It is a summary of common attributes among the more prominent gas hydrate zones. Most, particularly those greater than 10 m thick, possess many of the attributes of the conceptual 'gas hydrate reservoir'. All of the zones greater than 10 m thick are located within or proximal to features that may promote fluid migration and are in tectonically active areas. Interestingly, sites not associated with tectonic features have some percentage of sand in the clathrate-bearing zone. There are no gas hydrates among the top four that are characterized as cements. All but one zone are relatively high in the sedimentary column with respect to their GHSZ base.

In considering the types and amount of data available, Table 1, rather than taken as research findings, is meant to be viewed as a source of research directions: it shows common characteristics, not innate criteria.

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