

# SIGNIFICANCE OF MUD VOLCANISM

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Received 10 November 2000; revised 11 December 2001; accepted 12 December 2001; published 6 September 2002.

[1] Mud volcanism and diapirism have puzzled geoscientists for ~2 centuries. They have been described onshore and offshore in many places on Earth, and although they occur in various tectonic settings, the majority of the features known to date are located in compressional tectonic scenarios. This paper summarizes the main thrusts in mud volcano research as well as the various regions in which mud volcanism has been described. Mud volcanoes show variable geometry (up to tens of kilometers in diameter and several hundred meters in height) and a great diversity regarding the origin of the fluid and solid phases. Gas (predominantly methane), water, and mud may be mobilized at subbottom depth of only a few meters but, in places, can originate from several kilometers depth (with minor crustal or mantle input). The possible contribution of mud extrusion to global budgets, both from quiescent fluid emis-

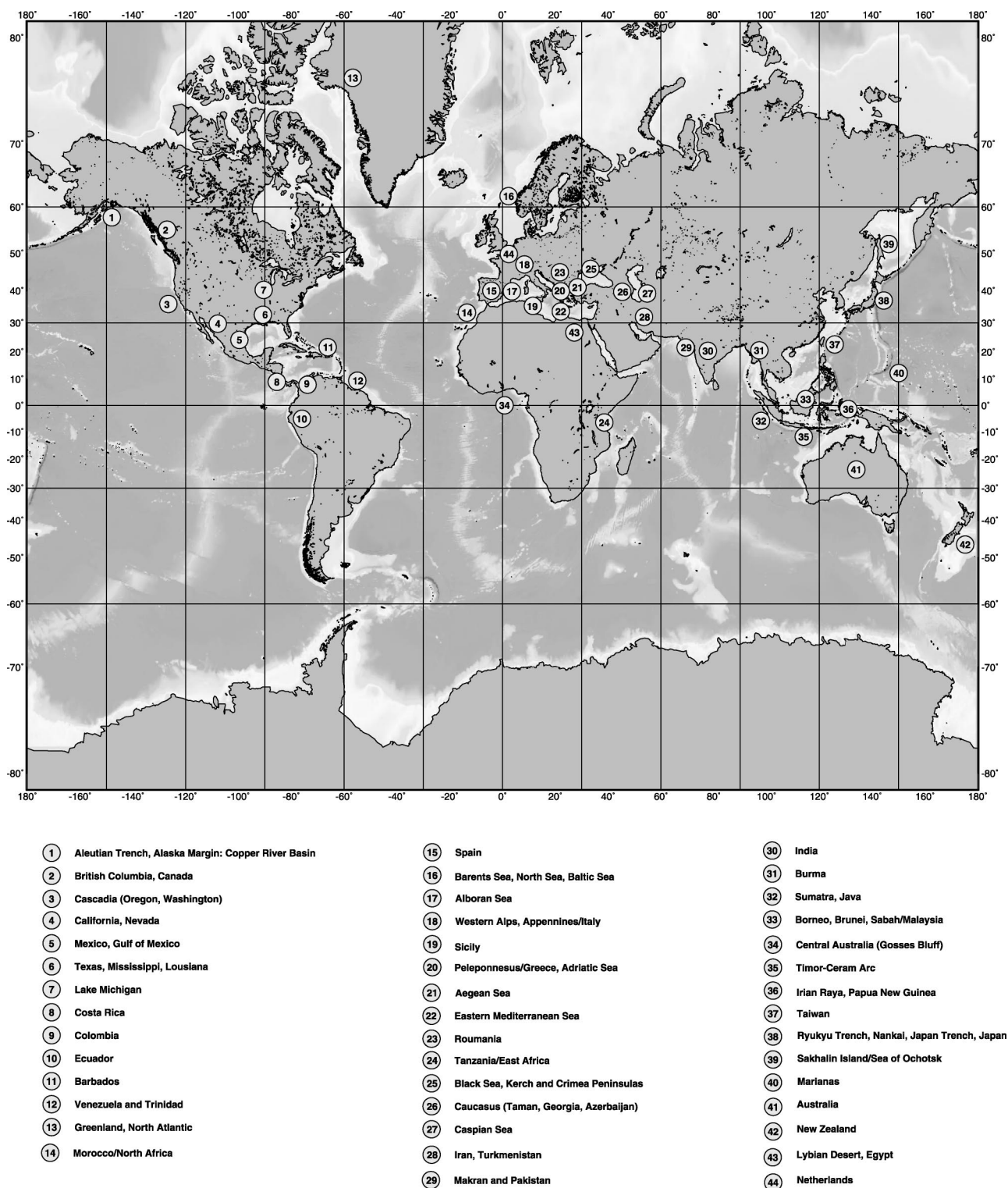
sion and from the extrusive processes themselves, is important. In regions where mud volcanoes are abundant, such as the collision zones between Africa and Eurasia, fluid flux through mud extrusion exceeds the compaction-driven pore fluid expulsion of the accretionary wedge. Also, quiescent degassing of mud volcanoes may contribute significantly to volatile budgets and, hence, to greenhouse climate. *INDEX-TERMS*: 4835 Oceanography: Biological and Chemical: Inorganic marine chemistry; 8122 Tectonophysics: Dynamics, gravity and tectonics; 8045 Structural Geology: Role of fluids; 8102 Tectonophysics: Continental contractional orogenic belts; *KEYWORDS*: mud volcanism; extrusion; fluid venting; convergent margin; diapirism

**Citation:** A. J. Kopf, Significance of mud volcanism, *Rev. Geophys.*, 40(2), 1005, doi:10.1029/2000RG000093, 2002.

## 1. INTRODUCTION AND STRUCTURAL OUTLINE

[2] Mud intrusion and extrusion are well-known phenomena whereby fluid-rich, fine-grained sediments ascend within a lithologic succession because of their buoyancy. These processes have long been recognized as related to the occurrence of petroleum, regional volcanic and earthquake activity, and orogenic belts (see the enlightening presentation by *Ansted* [1866]). The abundance of *mud volcanoes* (terms in *italic* are defined in the glossary, after the main text) was first examined systematically on a broad scale by *Higgins and Saunders* [1974]. These authors mostly focused on mud volcanoes on land, and they used industry drill-hole data to establish relationships between mud volcanism, hydrocarbons, and regional tectonics. The onshore mud volcanoes and their important role in predicting petroleum reservoirs have been summarized by *Rakhmanov* [1987]. Recent improvements in seafloor imagery and seismic exploration led to the discovery of countless mud extrusive provinces all over the world (Figure 1). In fact, compared to the compilation by *Higgins and Saunders* [1974], more than twice as many occurrences are presently known, the number gradually increasing through time. Most importantly, mud volcanoes occur along convergent plate margins where fluid-rich sediment is accumu-

lated in deep-sea trenches at high rates. Such deposits then enter the subduction factory, where liquids and volatiles are released due to increasing compactional stress and temperature. Studies of geophysical data and samples of mud volcanoes have considerably improved the understanding of the mechanics, driving forces, and evolution of the features through the most recent Earth history [e.g., *Barber et al.*, 1986; *Brown*, 1990]. In addition, deep ocean drilling and submersible studies shed crucial light on eruptivity, emission of volatiles, and potential hazard originating from violent mud extrusion [e.g., *Robertson et al.*, 1996; *Bagirov et al.*, 1996a; *Kopf*, 1999]. The wealth of results attests that mud extrusion predominantly occurs in collisional settings, with mostly pore fluids during early (often marine) stages and with hydrocarbons at later stages (often on land [e.g., *Jakubov et al.*, 1971; *Tamrazyan*, 1972; *Speed and Larue*, 1982]). Although quantification of fluid and mud discharge in mud volcanoes is not easy because of their short-lived nature and inaccessibility on the seafloor, first-order estimates regarding flux rates have recently been attempted for various features and regions [e.g., *Henry et al.*, 1996; *Kopf and Behrmann*, 2000; *Etiopie et al.*, 2002]. When put into a broader context, such estimates indicate that mud extrusion contributes significantly to fluid back flux from the lithosphere to the hydrosphere.



**Figure 1.** Occurrence of mud volcanoes (MVs) on Earth. Numbers refer to section heading nomenclature of Appendix A as well as to Table 1.

Along wide parts of large *accretionary prisms* (like the Barbados or Mediterranean Ridges), hundreds of features can cause fluid expulsion at rates exceeding those at the frontal part of the prism (see discussion by Kopf *et al.* [2001]). Provided that the process of mud volcanism has been equally common in the past, these features have been

major players in fluid and gas budgets and in geochemical cycling in collision zones.

[3] In this paper, the general terminology, as well as the distribution of mud volcanism on Earth in its tectonic context, is introduced (section 2). Key issues concerning the nature of mud extrusion dynamics will be

**Table 1. Selected MV Phenomena at Modern Convergent Margins<sup>a</sup>**

<i>Convergence Margin</i>	<i>Rate of Convergence, mm yr<sup>-1</sup></i>	<i>Subducting Plate</i>	<i>Overriding Plate</i>	<i>Type of MV Feature; Position</i>	<i>Section Number for References</i>
Aleutians	60	Pacific	North American	domes; F	A1
Barbados	37	North American, Atlantic	Caribbean	domes, ridges, pies; O, F, I	A11
Cascadia	34	Juan de Fuca	North American	domes; F	A3
Costa Rica	88	Cocos	North American	domes; F	A8
Japan	13	Philippine	Eurasian	domes; F, I	A38
Java, Timor	82	Indian	Eurasian	domes, ridges; O, B, F	A32, A35
Makran	50	Indian	Eurasian	domes; O, F	A29
Marianas	77	Pacific	Philippine	seamounts; F	A40
Mediterranean	7 (50°)	African	Eurasian	domes, ridges, pies; F	A22

<sup>a</sup>Plate kinematic rates were taken from *Jarrard* [1986]. See detailed descriptions in the given sections of Appendix A for details.

<sup>b</sup>F denotes forearc, B denotes back arc, O denotes onshore, and I denotes incoming plate.

<sup>c</sup>This is strongly dependent on view, as net rate has to include half of the spreading rate of the Aegean Sea.

discussed. These include the influence of the physical properties of the gaseous, aqueous, and solid phases, as well as processes like rapid sediment accumulation, enhanced fluid pressures, gas hydrate stability, and geochemical processes (see section 3). Combined with geophysical investigations and results from modeling, quantitative studies estimate (1) mobilization depth of the different phases (section 4), (2) material flux with time, and (3) the impact of mud volcanism on global budgets (section 5). Finally, a compilation of the literature on mud volcanoes appears in Appendix A. This summary closely resembles the review by *Higgins and Saunders* [1974], with the more recent discoveries added. Appendix A covers the early description of enigmatic mud features [e.g., *Goad*, 1816; *Abich*, 1857] up to the most recent studies [e.g., *Bouriak et al.*, 2000; *Delisle et al.*, 2002; *Etioppe et al.*, 2002] and is divided into regional sections.

## 2. GENERAL RELATIONSHIPS AND TERMINOLOGY

[4] The wealth of data and extensive investigations both onshore and offshore make a compilation of mud volcanic occurrences on Earth a lengthy endeavor. Hence the majority of the material is found in Appendix A. There, known mud extrusive expressions are listed by area of occurrence.

[5] As can be seen from the map in Figure 1, mud volcanoes (MVs) are found almost everywhere on Earth. However, they predominantly occur at convergent plate margins, toward which about half of the ocean sediment travels due to plate kinematics. Although there are approximately as many regions onshore as there are offshore, the actual number of features as well as the amount of material involved is much larger (about twice as high) in the marine realm. Partly, this may be a result of the relatively poor consolidation of the features, so

that many of them were eroded before they were compacted or lithified. As a consequence, fossil mud volcanoes have rarely been preserved.

[6] Mud volcanoes in collisional settings show a broad range of similarities regarding geometry, age, materials extruded, and volatile emission (see Appendix A and Table 1 for a short summary of the most important margins). The region with by far the most mud extrusions known to date is the Mediterranean Sea and Tethyan Belt, spanning from south of Greece over the Black and Caspian Seas into Azerbaijan, the Crimea and Taman Peninsulas, Iran, and Turkmenistan into the Makran coast (Figure 1, locations 17, 20–23, and 25–29). Here collisional manifestations of incipient convergence are accentuated compared to other accretionary margins. Because of the closure of the Tethys (see detailed reconstruction by *Dercourt et al.* [1986]), only remnants of the initial basin (eastern Mediterranean Sea) and back arc basins (Black Sea and Caspian Sea) remain. These undergo enhanced lateral tectonic shortening, with mud volcanoes known in the frontal and central accretionary wedge [*Masclé et al.*, 1999], its backstop [*Kopf et al.*, 2001], the back arc [*Limonov et al.*, 1997], and the Caucasus orogenic belt [*Jakubov et al.*, 1971; *Lavrushin et al.*, 1996; *Jevanshir*, 2002]. The area is ideal for reviewing mud extrusive processes for two reasons: First, it provides examples of early dewatering to intense deformation in an amphibic setting of deep marine to on land exposures. Second, it has been studied for a long time [e.g., *Kulschin*, 1845; *Abich*, 1863], with a large number of recent expeditions, including hydrocarbon exploration and deep ocean drilling [e.g., *Jakubov et al.*, 1971; *Robertson et al.*, 1996] (see also references in sections A22 and A25–A27). Many of the aspects tackled in this manuscript are hence exemplified by results from studies of these areas, with frequent cross-references to similar regions elsewhere. The reader is referred to the respective sections in Appendix A and the references to the related literature therein.



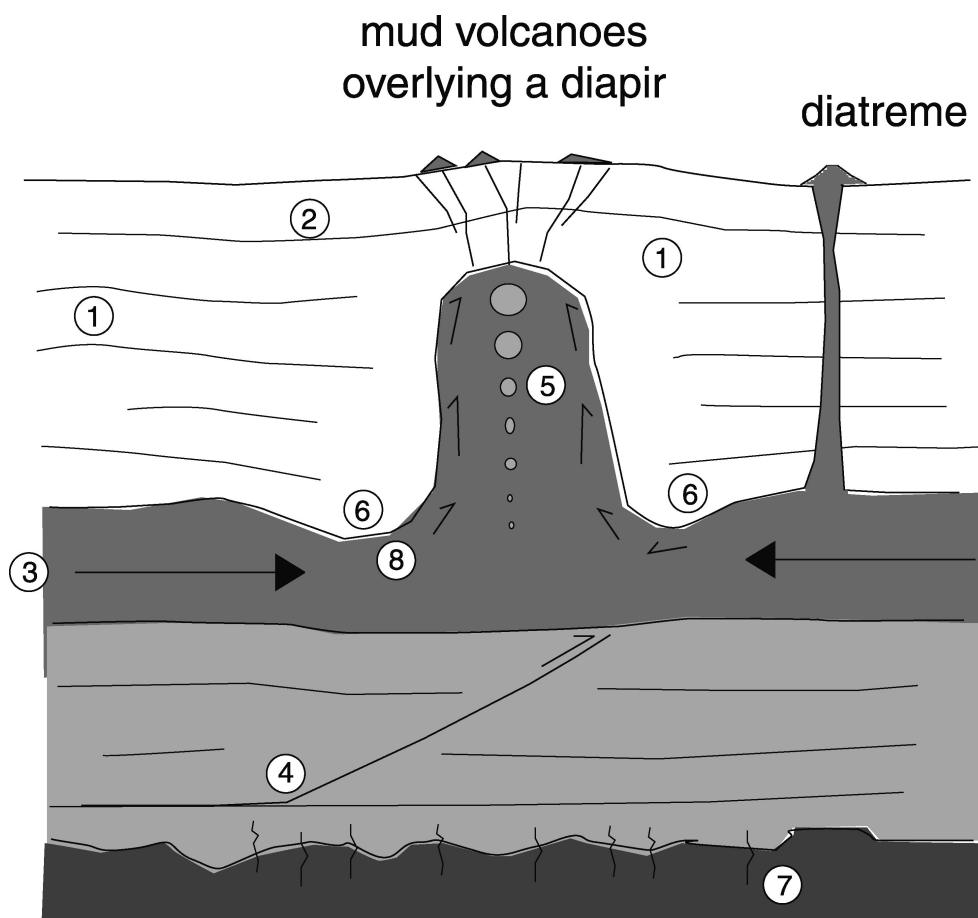
[7] Given the large, diverse body of publications over 2 centuries, a wealth of terms specific to mud extrusive processes has been introduced. This manuscript attempts to provide a guide through the maze regarding terminology of features and processes.

[8] By definition, the Greek “*diapirein*” means “to pierce” and was first excessively used by *Mrazec* [1915]. However, the first mention of diapiric structures dates back to *Leymerie* [1881], who suggested the word “*tiphon*.” This nomenclature was adapted by *Choffat* [1882] when describing sedimentary diapiric manifestations in Portugal, calling these small domes “*tiphonique*.” *Mrazec*’s [1915] definition of *diapirism* as the process of forceful movement of a more or less plastic body from areas of greater pressure to areas of less pressure has since then been widely accepted. It has often been restricted to salt structures instead of having been applied on mechanical grounds, although some workers used it for effusive or intrusive magmatic processes [e.g., *Wegmann*, 1930]. The term “sedimentary volcanism” supposedly (J. B. Saunders, personal communication, 2000) goes back to *Kugler* [1933].

[9] From a global compilation of mud processes and their products reported in the literature, one may get the impression that mud volcanoes are more abundant than *mud diapirs*. There seems to be a commonly accepted agreement that diapirs are noneruptive. If related back to mud mobilization, researchers imply an intrusive rather than an extrusive mechanism of a moving mass of clay-bearing sediment when they favor mud diapirism over mud volcanism. However, such a finding is somewhat dubious given that in the majority of the cases, intrusion does almost necessarily precede extrusion. As a consequence, mud (or, more generally speaking, sedimentary) volcanism has to be viewed as the surface manifestation of intrusive processes like mud or shale diapirism. The term mud diapir is hence used in this manuscript for a slowly upward migrating mass of buoyant, clay-rich sediment, which does not pierce all of its overburden. By contrast, the (part of a) diapiric mass and the forceful injected mud from depth that reach the surface are both referred to as mud volcanoes. Mud diapirs and *diatremes* (see Figure 2) have been neatly distinguished on the grounds of the mechanical stress state of the mud intrusion they originate [*Brown*, 1990]. In mud diapirs the mud behaves as a single-phase viscous fluid, while for diatremes, flow of water and/or gas through sediment causes fluidization. When such *liquefaction* of the mud occurs, particle interaction may even equal zero (all stress is taken temporarily by the fluid, so that the effective stress is zero [e.g., *Terzaghi*, 1947; *Bachrach et al.*, 2001]). However, the surface expression of the extruded mud may be very similar, whether extrusion is preceded by an unconfined, confined, or released (i.e., vertically constrained, forceful) intrusion (see *Bishop* [1978] and section 3.3). Also, there is no necessity for diatremes to originate from a diapir in the first place (Figure 2).

[10] In this summary, the term mud volcanism will be used throughout, except when evidence suggests otherwise. Apart from the concerns outlined above, there is one main reason for such a simplified terminology: the scale problem. If a mud feature onshore or offshore is identified, in a compressional setting it is dominantly sourced along narrow zones of weakness (e.g., faults). Following *Bishop*’s [1978] models, such a scenario may meet the requirements for either the unconfined, the confined, or the released case, at least temporarily (see *Clennell* [1992, p. 324] and section 3.3). To overcome such imprecision, other categories have been based on geometry of the surface expression of mud *extrusiva* [*Brown*, 1990]. Topographically speaking, mud volcanoes, domes, and ridges are positive features, while *mud pools*, basins, and *pockmarks* are negative phenomena (i.e., depressions). As they are all surface expressions, the term mud volcanism applies, despite the possibility that an initially intrusive component facilitated mud extrusion (see Figure 2). With a few exceptions, strict dewatering features without fluid influx from elsewhere (e.g., in Alpine fluvial deposits [*Fenninger and Scholger*, 1994]), soft sediment deformation (slumping, slides, etc.), and *mud mounds* (in the sense of *Wilson* [1975]) are not granted particular attention; they are reported, however, when found associated with mud volcanism (see, e.g., sections A13 and A22).

[11] The following abbreviations will be used throughout: MV for mud volcano, MVs for mud volcanoes, and MVism for the process of mud volcanism in the broader sense. Given the variety of MVs, no strict classification seems useful or possible. However, two typical features are schematically shown in Figure 3 and are referred to below. The distinction between cones (domes) and pies is made on the grounds of angle of the flanks. Pies generally have  $<5^\circ$  slopes (similar to class C mud volcanoes in *Shih*’s [1967] classification scheme). The feeder, or *conduit*, is the central feature through which mud extrusion is facilitated. It may be either cylindrical, irregularly shaped, or a slit (i.e., a fracture, fault, etc.). The area where the central conduit crops out at the surface is called the crest, being generally the most elevated point. If the crest region shows a depression, this is referred to as the *crater*. If this crater is filled with soupy mud, this feature is called a mud pool. It has also been termed a *tassik* in pioneer MV studies (e.g., amid otherwise dense vegetation in the southeast Moluccas [*Heim*, 1940]). If the main conduit of the MV terminates as a crater, it may also have been termed a *pingo* or *cauldron* (Portuguese for caldera), on occasion. Splays of the main conduit may result in small craters somewhere off the center (or even on the flank) and are referred to as *gryphons*. Both the main conduit and the gryphons are the locations from which mudflows originate (Figure 1). The composition of the mudflows can be highly variable and usually corresponds directly to the nature of the conduit and the lithology of the mobilized sediments. The latter are referred to as *parent beds* (or sometimes as



### fluid sources for overpressuring and mud extrusion:

- (1) pore fluid expulsion from compaction
- (2) biogenic methane from degradation of organic matter
- (3) lateral fluid flux through stratigraphic horizons or fault zones
- (4) fluid migration along deep seated thrusts
- (5) thermogenic methane and higher hydrocarbons
- (6) fluids from mineral dehydration (opal, smectite)
- (7) hydrothermal fluids, alteration of crustal rock
- (8) fluid expulsion from internal deformation within the diapiric intrusion

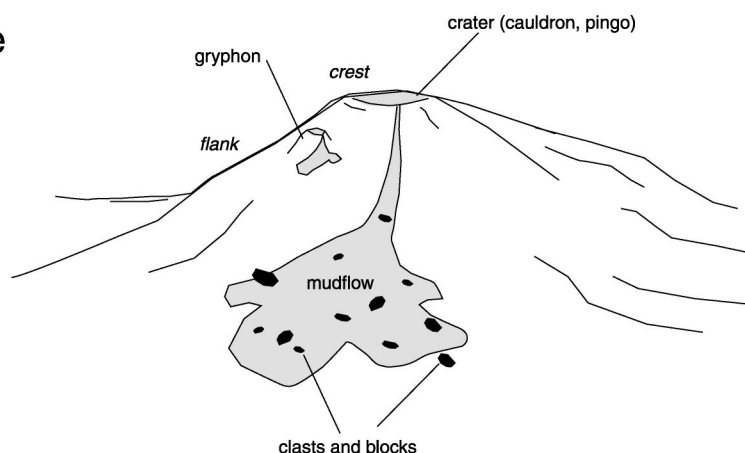
**Figure 2.** Schematic diagram of a mud diapir, MV extrusions (mud volcanoes), and diatremes, including possible fluid sources (numbered 1–8). Geochemically mature fluids may be found among categories 3, 4, and 7, while in categories 1, 6, and 8, water from dissociated gas hydrates may provide “freshened” fluids.

source layers or mud reservoirs), and one of the prerequisites is the presence of a thick, undercompacted series of clays or shales (see also the beginning of section 3 and Yassir [1987]).

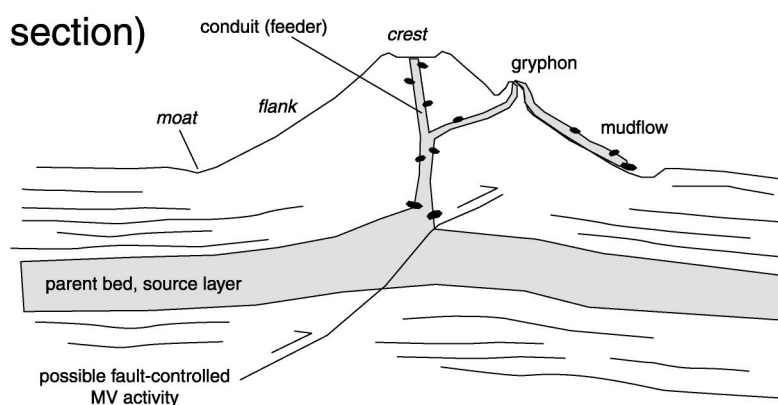
[12] The deposits forming MVs are astonishingly similar all over the world, although no systematic nomenclature exists in the literature. They generally comprise a variety of clasts and rock fragments in a clay mineral-rich matrix. The ratio of clasts to matrix covers the entire spectrum from clast-supported deposits to virtually clast-

free homogeneous muds (the latter are often related to the final phase of an eruptive cycle, when loose wall rock along the conduit has already been removed by the ascending mud [e.g., Kopf *et al.*, 1998]). The most common terms used for the *ejecta* of MVs as well as of diapirs are *mud breccia* or *conglomerate* (depending on the shape of the fragments), *olistostromes/olistoliths*, mud debris flow deposits, scaly clay (here the fragments are sheared, strongly dewatered matrix material), diapiric *mélange* [e.g., Orange, 1990], or argille scaliuse [e.g., Agar *et al.*, 1988]. A compi-

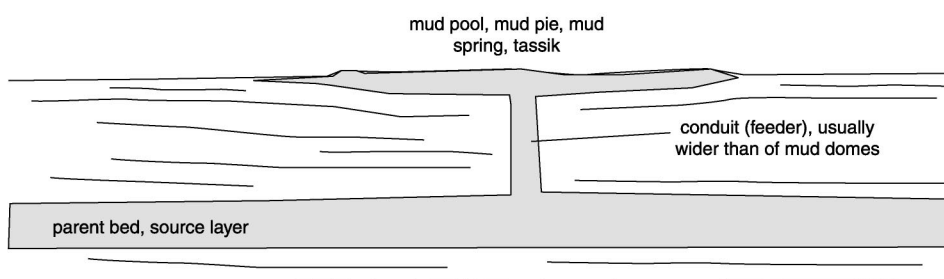
## A mud dome



(in cross section)



## B mud pie, less than 5° slope angle (in cross section)



**Figure 3.** Schematic diagrams of (a) cone-shaped and (b) pie-shaped mud feature with main applicable termini; see also the glossary.

lation of such rocks related to diapirism is given by *Clennell* [1992, Table 7.5a]. A useful distinction between mud volcanism, shale diapirism, and mélanges is given by *Barber et al.* [1986] for Timor as well as by *Barber and Brown* [1988].

### 3. NATURE OF MUD VOLCANISM

[13] The term “sedimentary volcanism” refers to the similar geometry of many mud extrusions and igneous

volcanoes, and only very rarely are MVs connected with igneous activity [e.g., *von Gumbel*, 1879; *White*, 1955; *Chiodini et al.*, 1996]. More often (and this is especially true for deep-seated features), MV occurrences have the following aspects in common: (1) an origin from thick, rapidly deposited sequences of marine clays; (2) a Tertiary age; (3) a structural association due to tectonic shortening and/or earthquake activity; (4) sediment overpressuring and accompanying fluid emission (gas,

brines, gas hydrate water, or, rarely, oil); and (5) polymictic assemblages of the surrounding rock present in the ejected argillaceous matrix [e.g., *Ansted*, 1866; *Higgins and Saunders*, 1974; *Fertl*, 1976; *Yassir*, 1987].

### 3.1. Sediment Mineralogy, Burial, and Overpressure

[14] In order to allow a buried body of sediment to ascend, the prerequisite is density inversion. This inversion may either be primary, i.e., as a result of grain density contrasts in the deposits, or secondary in origin. Secondary buoyancy can be caused by lateral influx of low-density fluids, variation in sedimentary dynamics, hydrocarbon formation, diagenetic and metamorphic processes, or tectonic processes that remove material or otherwise modify the overburden stress field. In other words, if a primary density inversion exists within a stratigraphic succession, no additional driving force for diapirism is needed. Conversely, no density contrast is necessary if other processes generating buoyancy are operating (e.g., gas flux). However, the majority of the MV areas known to date have more than this gravitational instability operating to facilitate extrusion.

[15] As for the primary density inversion, mineralogical differences as a function of sediment provenance may cause density differences within a sedimentary column. Minerals with low densities, like some evaporitic and clay minerals, are predestined to eventually ascend. They include gypsum, halite, and some clay minerals of the kaolinite, smectite, and vermiculite groups that all have densities lower than quartz or feldspar. In addition, these clay minerals are very common in marine environments and have the capability to incorporate large volumes of water into their mineral structure (for quantitative estimates, see X-ray diffraction results by *Fitts and Brown* [1999]). Consequently, clays are often found to have both low grain densities and low bulk densities. Hence their buoyancy relative to most other (sedimentary) rocks suggests that strictly, no additional driving force other than this density inversion is needed to allow ascent. On the other hand, such diapirism would be rather slow, because the density of a clay having undergone compaction dewatering may be close to that of quartz, feldspar, or other major rock-forming minerals overlying the clay [e.g., *Deer et al.*, 1992]. Hence most of the mud volcanoes and all diatremes require additional driving forces to explain their origin.

[16] Sedimentation, especially in the marine environment, represents the link between primary and secondary density inversion. When sediments are deposited, a considerable amount of seawater is trapped in the intergranular space. For clays the initial porosity may be as high as 80%. This pore volume, or porosity, is mainly a function of grain size and sedimentation rate. When settling and pore water expulsion occur simultaneously, hydrostatic pore fluid pressures are maintained throughout. If, however, rapid burial or overlying low-permeability layers cause slow pore fluid dissipation, pore pressures soon exceed hydrostatic, and the sediment is

overpressured or undercompacted [e.g., *Maltman*, 1994]. In other words, a clay-rich sediment may preserve abnormally high porosities for its depth. Early geophysical surveys detected numerous areas where early postdepositional rise of undercompacted sediment occurred [*Lancelot and Embley*, 1977]. These authors related the piercing of overlying strata to the rapid burial of fluid-rich hemipelagic sequences by terrigenous sedimentation (i.e., turbidites). Later, numerous workers attested to elevated porosities in trench fill deposits, which then undergo rapid dewatering due to tectonic stresses when accretion takes place [e.g., *von Huene and Lee*, 1982]. The effect of pore pressure transients increases within the accretionary wedge, where it facilitates imbrication and shortening [*von Huene and Lee*, 1982]. Fluid overpressures are known to play a crucial role in faulting and have been demonstrated to reach values near lithostatic pressure in places [e.g., *Hubbert and Rubey*, 1959; *Moore and Shipboard Party ODP Leg 156*, 1995].

[17] The possible causes of undercompaction are numerous, and sediment loading is one mechanism that may apply in any setting. It can be enhanced by rapid plate motion in a subduction zone setting, because dewatering may not keep pace with the rate at which the undercompacted material is underthrust beneath the overriding plate. However, among the numerous other possibilities causing undercompaction, the most prominent are gas hydrate dissociation, tectonic loading, diagenesis and mineral dehydration reactions, hydrocarbon generation, aquathermal pressuring, and osmosis [e.g., *Yassir*, 1989]. Several of these processes may act simultaneously in MV areas at depth, so that distinction between them is difficult. A summary of various origins for elevated pore pressures is given in Table 2.

[18] The possible significance of gas hydrate dissociation in MV processes has been discussed (see summary by *Milkov* [2000]). Several workers imply that warm fluids from great depth may migrate upward and release large amounts of methane when they “melt” solid gas hydrate in the subsurface sediments [*De Lange and Brumsack*, 1998; *Aloisi et al.*, 2000a, 2000b]. Given the rapid increase in temperature below the seafloor, gas hydrates are only stable at shallow depth [e.g., *Sloan*, 1990]. In addition, pore volume requirements suggest that considerable amounts of massive gas hydrate are restricted to shallow, moderately consolidated sediment [e.g., *Clennell et al.*, 1999]. As a consequence, gas hydrates more likely enhance rather than cause undercompaction, which has originated from fluid migration. While gas hydrate may play a role in some areas of mud volcanism, it is methane that drives MVism at depth, and gas hydrate may form temporarily when this gas passes through the gas hydrate stability field at shallow depth.

[19] Porosity-depth relationships due to uniaxial compaction of fine-grained sediments generally show exponential decays [*Athy*, 1930], with the maximum pore space reduction taking place in the upper few tens of



**Table 2. Causes for Overpressuring, Distinguished by Origin, Mechanism, and Corresponding Geological Setting<sup>a</sup>**

<i>Origin</i>	<i>Mechanism</i>	<i>Environment</i>	<i>Significance</i>	<i>Selected References</i>
Burial	sedimentary loading, compaction/settling	any sedimentary setting (i.e., deltas and active and passive margins)	major in such settings	<i>Braunstein and O'Brien</i> [1968] <i>Morgan et al.</i> [1968] <i>Moon and Hurst</i> [1984]
	slumping, sliding	marine slopes of active and passive margins	major on slopes	<i>Hovland and Judd</i> [1988]
Tectonic	tectonic loading	any compressional margin, thrust zones, and wedges	major in such settings	<i>Shipley et al.</i> [1990] <i>Westbrook and Smith</i> [1993]
	deep level ducting	accretionary complexes	major in such settings	<i>Moore</i> [1989]
Thermogenic	smectite dehydration	accretionary complexes	can be major	<i>Fitts and Brown</i> [1999]
	opal/quartz reactions	any setting with biosilica	usually minor	<i>Kastner</i> [1981]
	smectite dehydration	any setting with abundant clay deposition	can be major	<i>Schoonmaker</i> [1987] <i>Colten-Bradley</i> [1987]
	other diagenesis metamorphism	deeper subduction zone deep subduction zones and other collision zones	minor? usually minor, but locally important	<i>Moore and Saffer</i> [2001] <i>Bebout et al.</i> [1999]
Biogenic	methanogenesis/hydrocarbon generation	any setting and reservoirs	can be locally important	<i>Ridd</i> [1970] <i>Hedberg</i> [1974]
	thermal expansion; hydrothermal pressuring	magmatic arcs and ridges	can be locally important	<i>Barker and Horsfield</i> [1982]
	methanogenesis	shallow marine settings and accretionary prisms	can be very important	<i>Ritger et al.</i> [1987] <i>Suess et al.</i> [1999]
Other	osmosis	clay-bearing sedimentary environments	very minor	<i>Fertl</i> [1976]

<sup>a</sup>Table is modified from *Clennell* [1992].

meters of burial. Extrapolated to the third dimension, tectonic shortening (normal as well as lateral stresses) has similar effects. In an accretionary prism in the upper subduction zone, the amount of water expelled from tectonic loading decreases exponentially with distance from the deformation front [*Moore and Vrolijk*, 1992, Figure 9]. For fluid overpressures, such trends have an interesting drawback. The more efficient dewatering has been in the frontal and upper part of such a deforming wedge, the more profound a change in pore pressure (of the then well-consolidated, less permeable sediment) will be if additional fluid is generated. Such fluids can be derived from early diagenetic dehydration reactions (clay mineral dehydration [e.g., *Colten-Bradley*, 1987], opal A/CT-quartz reactions [e.g., *Kastner*, 1981], and decay of organic matter), late diagenesis and low-temperature metamorphism (clay mineral and zeolite transformation [*Moore and Saffer*, 2001]), and dissolution of quartz [e.g., *Guangzhi*, 1996]. The chemical interaction of fluids and muds during burial will be further discussed in the context of fluid origin in MVism (see section 4.2).

[20] As has recently been shown on accreted mudstones elsewhere [*Fitts and Brown*, 1999], stresses equal to an overburden of only several hundred meters (i.e., 1.3 MPa) are sufficient to shorten the lattice distance of smectite, either due to vertical compaction or lateral tectonic shortening. In the deeper part of the subduction zone, or generally at greater burial depth, metamorphic reactions [e.g., *Bebout*, 1995; *Moore and Saffer*, 2001], hydrothermal pressuring [e.g., *Barker and Horsfield*,

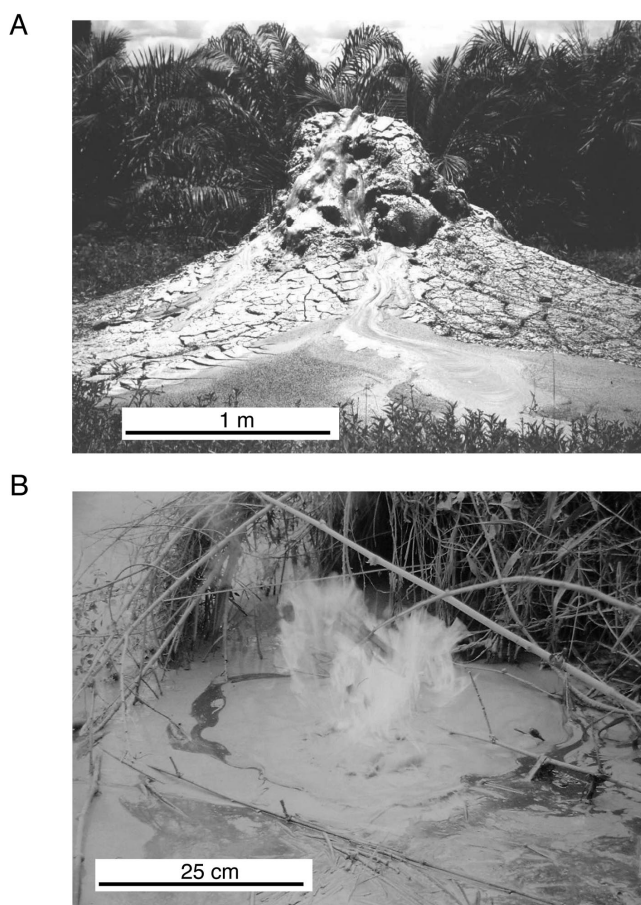
1982], or maturation of organic matter to generate hydrocarbons [e.g., *Hedberg*, 1974] may cause fluid overpressure. However, one rarely finds a single process in operation. Most of the time, a combination of two or several processes is met. The most common cause of fluid supply, enhanced pore pressures, and lowered effective viscosities are of sedimentary and tectonic origin, with smectite dehydration naturally being the dominant mineral reaction in argillaceous rocks. Deep-seated MVs are frequently triggered by hydrocarbon gases (see section 4.3), but are very rarely triggered by oil or hydrothermal liquefaction.

### 3.2. Geometric Constraints on the Mechanism of Eruption

[21] The study of the geometry of mud extrusions, which in pioneer studies was almost purely descriptive, has recently focused on the relationship between evolution of MVs through time and the related geometry. The shape of the feature reflects to some extent the physical properties of the extruded material and points indirectly to the width of the conduit having facilitated the eruption (see also section 3.4).

[22] Surface expressions of MVism are highly variable and depend primarily on the fluid content of extruded mud [*Brown*, 1990]. The “classic” mud volcano has a central vent with mudflows building the edifice predominantly by the addition of material to the edifice’s outer slopes [*Higgins and Saunders*, 1967]. The morphology of the edifice is largely controlled by the viscosity and





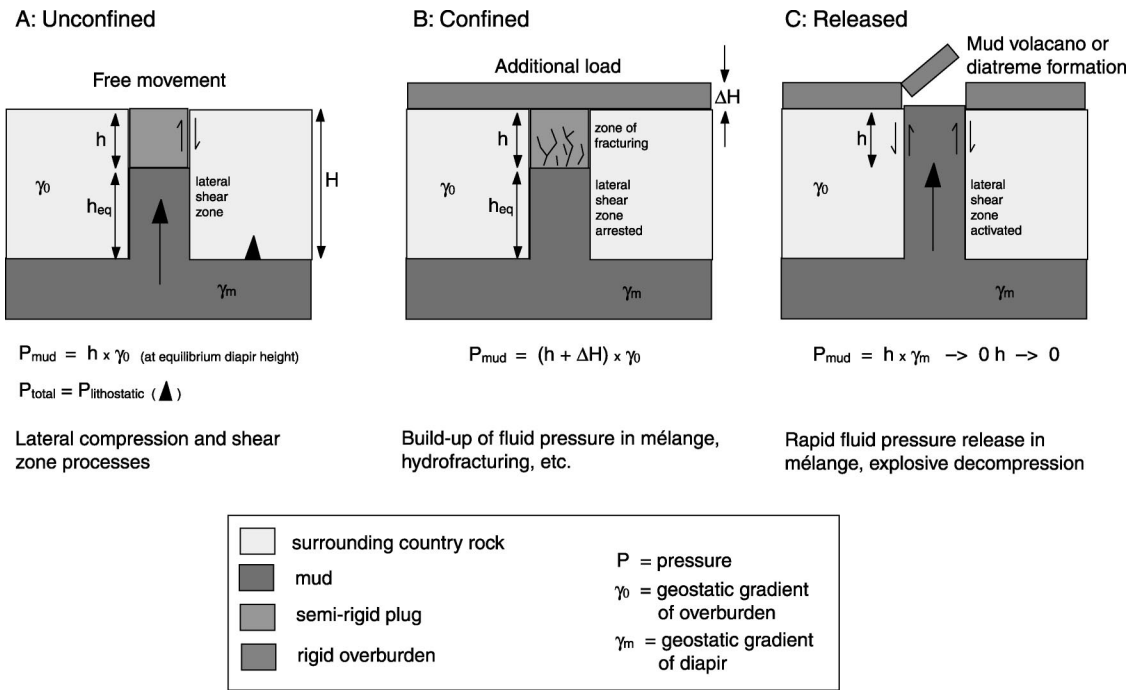
**Figure 4.** Examples of onshore mud volcanoes: (a) small onshore mud volcano, Jeroco, at Sabah, Malaysia [from Clennell, 1992]; (b) burning methane seeping out of a small MV in Taiwan (photograph is courtesy of Kevin Brown).

consolidation of the extruded material. Muds with low porosities (<50%) form mud domes or ridges, more cohesive muds with intermediate fluid content can give rise to mud volcanoes with large diameters (1–2 km) and elevation above the seafloor (>50 m), and high-porosity muds create *mud pies* [Lance *et al.*, 1998] on the seafloor. The primary mechanism of the upward flow of plastic mud is a reaction to buoyancy forces caused by the bulk density contrast between overpressured mud at depth and the sedimentary burden of greater density. The continuous supply of pressurized pore fluids in convergent margin settings provides a powerful driving force for the mobilization of fluidized mud, causing the mud to rise through diatremes over several hundred meters to the seafloor.

[23] As can be seen from the regional summaries in Appendix A, as well as from Figure 4 showing two onshore MV examples, the geometry of mud extrusions is highly variable. Domes and cones range from only meters in both diameter and height [Sturz *et al.*, 1992] to several kilometers in diameter and hundred meters in height (e.g., in Azerbaijan [Jakubov *et al.*, 1971]). The biggest marine cones observed are the serpentinite sea-

mounts in the Mariana forearc, exceeding 30 km diameter and 2 km relative height [Fryer *et al.*, 1985]. On the Barbados Ridge, diameters exceed 6 km in places, with several hundred meters relative height [Brown and Westbrook, 1988]. *Mud ridges* can often occur along anticlinal crests in limited size, but they are reported to reach 18 km in length onshore (Timor [see Clennell, 1992]). Seafloor features may be even larger, although sometimes evidence is lacking regarding a mud intrusive origin. Mud pools reach several hundred meters in Trinidad [Higgins and Saunders, 1974], while submarine mud pies are >30 km in diameter on the Mediterranean Ridge [Kopf *et al.*, 2001]. There is evidence from preserved fossil MVs that their geometry is not dissimilar to active features at present. Indeed, the 1200-m diameter of the Moruga Bouffe in Trinidad [Higgins and Saunders, 1974] and the 5-km diameter in British Columbia [Slack *et al.*, 1998] are equivalent to modern counterparts. Only scant information exists concerning the geometry of the conduit (or feeder channel) for ancient and modern examples. Surface observations indicate small diameters of 15 cm (Taiwan MVs [Yassir, 1989] and Apennines MVs, Italy (A. Kopf, unpublished data, 2002)) and 30 cm (Greece [Stamatakis *et al.*, 1987]) to 1.5 m (Burma [Pascoe, 1912]) and 2 m (Sakhalin [Gorkun and Siryk, 1968]). The first values agree well with cemented *chimneys* in the ancient Verrua MV in Italy [Cavagna *et al.*, 1998]. Also, theoretical considerations and calculations based on Stokes' law indicate similar diameters of 2–3 m for the Mediterranean Ridge MVs [Kopf and Behrmann, 2000]. However, some controversial data are reported for the feeder geometry at depth. From seismic data, conduits of 1.5–3.5 km width have been proposed for the Black Sea area [Ivanov *et al.*, 1996; Limonov *et al.*, 1997]. Similarly, a width of 2 km for the bigger of the Barbados Ridge features (6 km across [Griboulard *et al.*, 1998]), the Alboran Sea [Perez-Beluz *et al.*, 1997], and other areas seem common (see, e.g., sections A11 and A17). The interpretations are based on the diffuse borders of the seismically opaque mud intrusions when in contact with the structured country rock of the region. Assuming a slowly ascending diapiric intrusion without considerable overpressure, this may well be a reasonable conclusion. At shallow depth and close to the surface, however, these conduits must narrow considerably; otherwise, astronomical flow rates would result even when small density contrasts (not to mention an excess hydrostatic head) exist as a driving force (see section 3.4). In contrast with the deep seismic example, Gorkun and Siryk [1968] propose only 30-cm-wide conduits at depth, which then widen to 2 m surface diameter at the various gryphons of Sakhalin MVs. Despite the mechanical grounds on which the narrow width at depth is apparently based, no explanation is given for their inference.

[24] From the compiled evidence on MV geometry, two main conclusions can be drawn. First, the size (and volume) of the individual features are mainly a function of the size of the conduit and the driving force behind



**Figure 5.** Schematic diagrams explaining the basic mechanical models of mud intrusion/extrusion under (a) unconfined, (b) confined, and (c) released pressures. Figure is modified from *Bishop [1978]* and *Clennell [1992]*.

MVism in the area. Large features generally relate to wide conduits and to an efficient trigger at depth. The latter may be considerable fluid influx (in the case of diatremes) or generation (mud volcanism in a broader sense). Second, the consistency of the mud, although of minor importance for the sheer size, is suggested to be the controlling parameter for the height of the MV [Huguen, 1998]. Judging from backscatter reflectivity of abundant features on the Mediterranean Ridge, steep cones correspond with strong reflectivity (i.e., indurated material), while flat mud pies are hardly recognizable against the unconsolidated sediment apron of the wedge [Kopf et al., 2001]. As demonstrated by drilling and submersible studies, the highly reflective domes contain mud breccia with up to >65% lithified clasts [Flecker and Kopf, 1996] and are often covered with carbonate crust on their crest [Aloisi et al., 2000a, 2000b]. MVs composed of these mélangé-type deposits are generally more long lived [Robertson et al., 1996] and resist erosion even when undergoing intense deformation [Cavagna et al., 1998]. However, if no clasts are present in the extruding mud, the dimension of the conduit has some control on the geometry of the feature. Analog modeling of MVism in the laboratory has yielded flat mud pies for wide feeders and cones for narrowing feeders when using the same material [Lance et al., 1998]. The cross-sectional area of the conduit also has some important control on the extrusion dynamics (see sections 3.3 and 3.4).

### 3.3. Diapiric and Other Models

[25] As has been established in section 3.1, clay-bearing strata are often found to have low bulk densities.

Hence their buoyancy relative to most other (sedimentary) rocks suggests that strictly, no additional driving force other than the density inversion is needed. However, in the majority of the MV areas known several secondary processes are operating simultaneously to facilitate extrusion.

[26] Diapiric models for the origin of mélanges arose partly because of the shortcomings of tectonic models to explain their geometric and spatial occurrence. This also reflects the increasing recognition of the role played by overpressuring in their evolution (see section 3.2 and Table 2). Among the factors controlling mud extrusion, there are tectonic compression, density inversion, gas generation or fluid influx, and temperature. Their interrelationship is immediately obvious and so is their overlap with factors common to areas of MVism. Grain density inversion due to mineralogy (see section 3.1) as well as extensional forces are neglected in this paragraph, although they are certainly applicable in places (e.g., giant mud pies on the Mediterranean Ridge accretionary wedge (see Kopf et al. [2001] and section A22).

[27] Regardless of whether buoyancy models or hydraulic models are considered, density inversion is not required to drive diapiric emplacement if an excess hydrostatic pressure is present [Bishop, 1978]. Of the possibilities discussed by Bishop [1978], unconfined extrusion (i.e., thin or missing overburden; see Figure 5a) seems the most suitable mechanism to explain diapiric, slow emplacement, while mélanges are more likely to result from vertically constrained intrusions (i.e., thick overburden; see Figure 5b). Here pressure buildup

causes *hydrofracturation* and fragmentation of mélange blocks and may occur in temporarily arrested fault and shear zones as well as in diapiric dykes. The mechanism closest to diatremes and mud volcano formation is confined emplacement and sudden release of excess pore pressures (explosive decompression; see Figure 5c and Clennell [1992]). Although not explicitly stated in the first case, this basic mechanical approach is in agreement with Yassir's [1989] and Brown's [1990] work. Fluidization added to the third model inarguably involves diatremes [Brown, 1990]. Depending on the amount and velocity of a fluid entraining a mud, different surface expressions follow the vigorous eruption. When flow is high, pockmarks will form, while thick sedimentary sequences and/or lower fluid flux will cause mud mound formation [Brown, 1990]. For detailed outlines of such mechanical concepts, the reader is referred to Lorenz [1975] or Brown [1990].

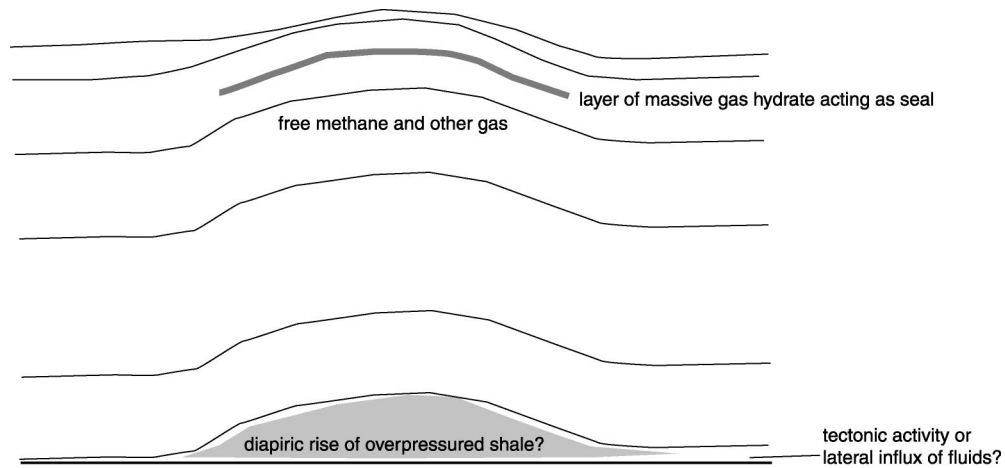
[28] Coming back to diapiric mélanges under vertically confined conditions, several refinements to existing models have been proposed in the various settings where mud breccias were encountered. Reed *et al.* [1990] hypothesized that massive gas hydrates may temporarily be able to act as a seal in the upper part of the MV conduit (Figure 6a). Although plausible in an environment of hydrate stability entrained by a (warmer) fluid from depth (thus destroying the hydrate cap), the physical properties of gas hydrates are only incompletely understood [e.g., Stoll and Bryan, 1979; Zhang *et al.*, 1999]. On the Mediterranean Ridge (Figure 7), where the fluids triggering MVism may be either ancient pore waters or mineral water from near the backstop, the mélange-type breccias are believed to be the product of efficient removal of the fault breccia by the ascending mud [Kopf *et al.*, 1998]. The release mechanism for excess mud pressures is tectonic forces, which episodically unlock the shear zone juxtaposed by the MV (Figures 5b, 6b, and 8). At a later stage, periods of extrusive activity alternate with quiescence, during which hemipelagic background sedimentation causes interbeds in the mud debris-flow deposits [Kopf *et al.*, 1998]. Similar interfingering patterns may result from the combined diapiric and fault-induced mobilization of mud, as has been proposed for offshore Brunei by Van Rensbergen *et al.* [1999]. These authors initiate shale diapirism by faults that weaken the overburden (Figure 6c). Mud then intrudes into the overlying sedimentary rock and may or may not reach the surface. MVs that pierce the entire succession may be buried again at a later stage during their evolution, so that the overall result is an interbedding of extrusiva and surrounding rock [Van Rensbergen *et al.*, 1999]. In the Black Sea region a hydrothermal model has been suggested by Slack *et al.* [1998] to relate tourmalinites and ore deposits to MVism. The authors argue that deep-seated faulting and continuous hydrothermal activity will create black smoker-type Fe-Mn-exhalites and sulfate precipitates, depending on oxic or anoxic bottom water conditions (Figure 6d). While conditions for deep-

seated faulting ( $>100^{\circ}\text{C}$  hot brines and anoxic bottom water) are rarely met, the latter may play a minor role and has been observed rarely (see sections A20, Greece [Stamatakis *et al.*, 1987], and A25, Taman Peninsula [Shnyukov *et al.*, 1986]). However, the model by Slack *et al.* [1998, Figure 3] fails to propose a mechanism to maintain supply of such peculiar fluids through a fault zone over time (Figure 6d). Finally, numerous detailed models have been put forward by various workers to explain certain types of mélanges, be it the "colored mélange" of the Makran [Stöcklin, 1990] or various mélanges in Indonesia [e.g., Barber *et al.*, 1986; Clennell, 1992]. The basic principles of their formation, however, closely resemble what is shown in Figure 5.

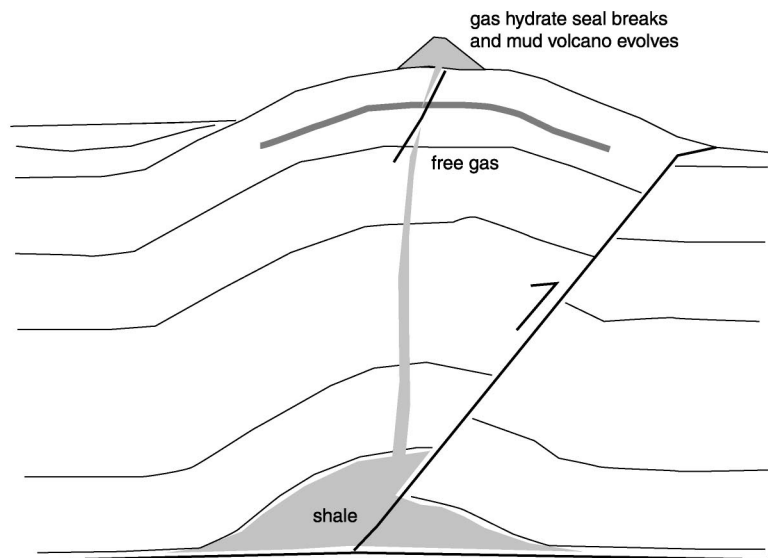
### 3.4. Mechanical Aspects, Mud Flux, and Episodicity/Duration

[29] One may now wonder which physical property is the most crucial in controlling extrusion behavior, under both constrained and, then, released conditions. Grain size variation (especially clay content and composition) and *plasticity* are interrelated and so are viscosity, coefficient of friction, and shear strength [e.g., Lambe and Whitman, 1979]. Grain size variations have been examined for several areas of MV abundance. For Taiwan, half a dozen samples from different MVs gave a more or less homogeneous composition of silt with  $<25\%$  sand and  $<35\%$  clay [Yassir, 1989]. By contrast, Yassir [1989] found a profound variation in particle size when investigating MVs in Trinidad. Here clay contents ranged from  $<10\%$  to  $>65\%$ , in agreement with earlier results by Higgins and Saunders [1974, Figure 17]. For two MVs on the Mediterranean Ridge accretionary complex, a transect of deep drill holes provided the opportunity to characterize evolution with time. Grain size was found coarsest in the basal deposits, where the ejecta of a violent initial eruption are found [Flecker and Kopf, 1996]. At shallower depth and especially in the upper part of the crestal holes (i.e., in the conduit), particles were much smaller and better rounded. Clay contents of dominantly smectite and kaolinite [Zitter *et al.*, 2001] reach up to  $>80\%$ , with clasts almost absent in the gassy muds. This has been interpreted as a more quiescent stage of MVism and degassing, with mud viscosities and excess pressure head too low to allow clasts to float in the matrix [Flecker and Kopf, 1996]. It is difficult, however, to directly relate particle distributions to the geometry or history of a given MV. Indeed, it is suggested from the results reported that the grain size may shed light on regional differences between features and their evolution, but fails to represent a proxy on a more global scale. Brown [1990] suggests that fluid influx has a more profound effect on MV formation than grain size can possibly have; in other words, no matter how coarse and permeable a sediment is, it will be liquefied when sufficiently high fluid velocities are reached. As for plasticity, i.e., the range of water content from the liquid to plastic limits of a mud, results are a direct function of the clay





Inactivity (prior to MV formation)



Post-eruptive stage: Hydrate seal may be episodically broken to allow mud and/or fluid expulsion from below

**Figure 6a.** Model for MV evolution proposed by *Reed et al.* [1990] for a seal of massive gas hydrate destroyed by deep, warm fluid, reprinted with permission from Elsevier Science.

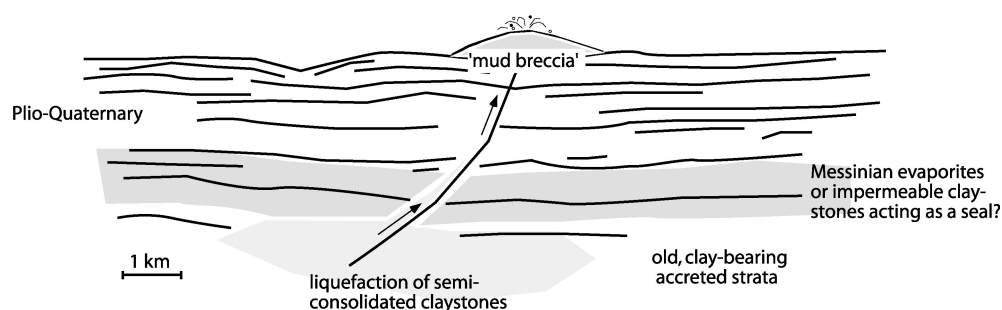
content and of local differences in the parent bed composition. *Yassir* [1989] found plasticities of Trinidad muds of ~30%, but of <20% for the Taiwan features (with <35 wt % clay; see above). The sample with the highest clay content (71.6 wt % at Digny MV in Trinidad) had the highest plasticity (47.8 %), in agreement with maximum values of 41 wt % clay and 42 % plasticity at Napoli MV on the Mediterranean Ridge [*Kopf et al.*, 1998].

[30] Drained and undrained shear strength has been

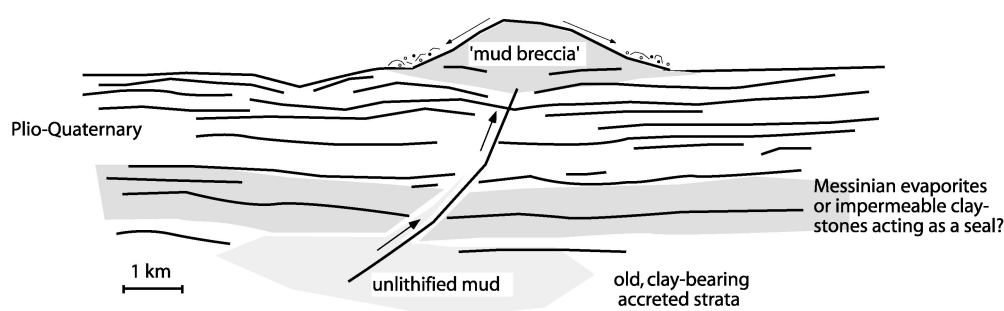
subject to laboratory studies of onshore and offshore MV deposits as well as of serpentinite mud mound samples. Undrained strength determined with a torsion-vane shear apparatus showed values well below 100 kPa for both marine clays and serpentinite diapiric clays [*Phipps and Ballotti*, 1992]. Drained shear strength tests (1.2 MPa) on muds from Mediterranean Ridge MVs using a standard geotechnical shear box had peak values of 200–380 kPa at friction angles typical for smectite-rich material [*Kopf et al.*, 1998]. The mud was found to



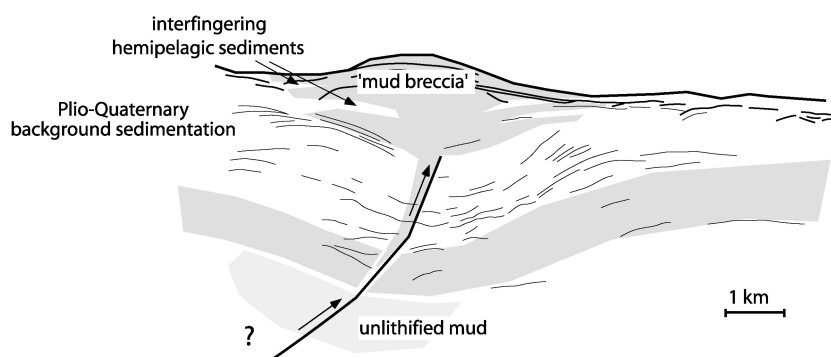
### Eruptive phase, early clastic cone



### Turbidity currents, mud debris flows



### Subsidence, continued mud flows

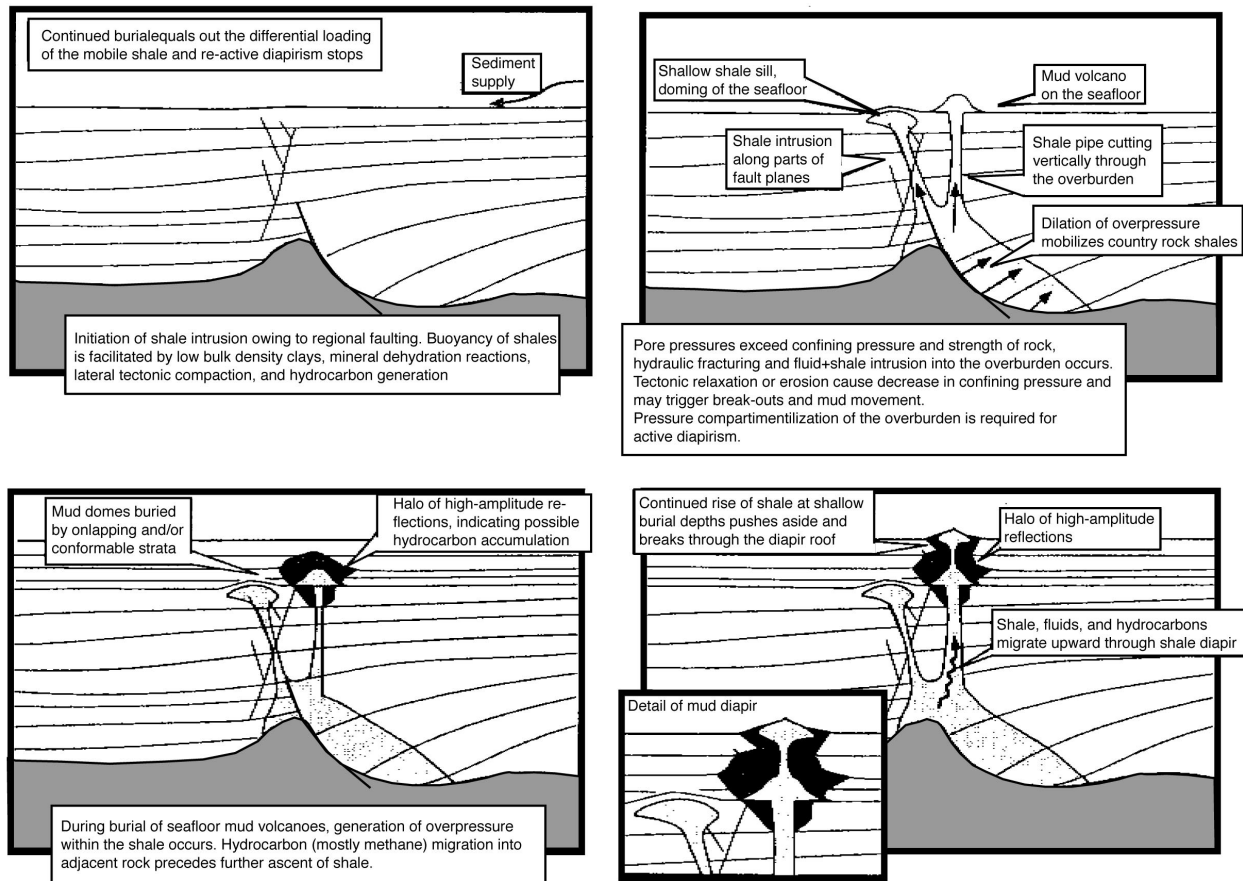


**Figure 6b.** Model for MV evolution proposed by Kopf *et al.* [1998] for a violent eruption with numerous debris-flow events in the Mediterranean, reprinted with permission from Springer-Verlag.

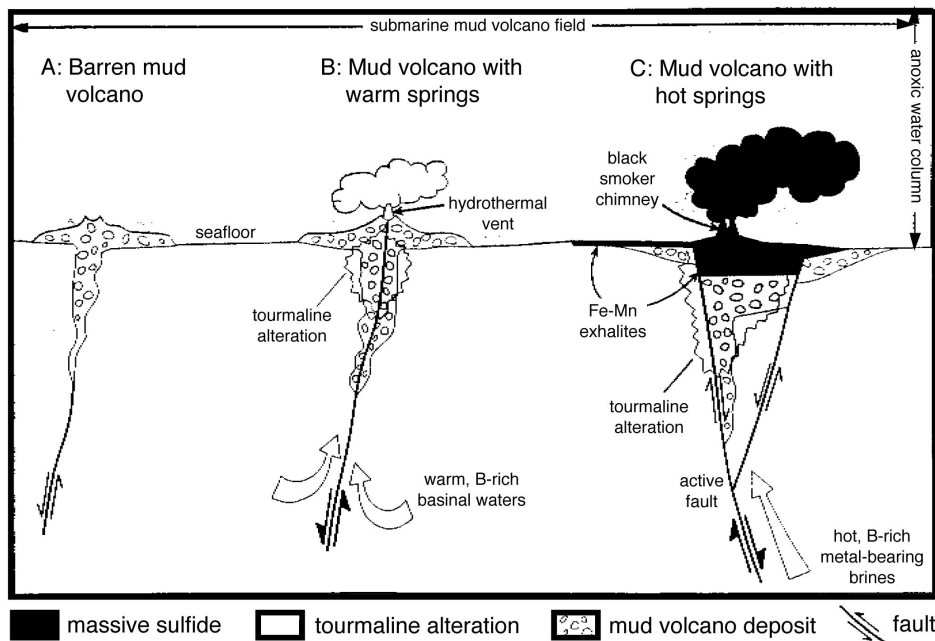
be considerably weaker than the surrounding sediment. High-stress triaxial tests (110 MPa) on heated serpentinite also showed a weak response, with friction coefficients as low as 0.17 [Moore *et al.*, 1997]. Moore *et al.* [1997] demonstrated that increasing temperature at depths strengthens the material, especially when exceeding 150°C. Serpentinite, which extrudes locally like mud volcanoes (e.g., in the Marianas or California; see sections A4 and A40), also shows velocity strengthening during shear at high rates. By performing high-stress triaxial (5–50 MPa) consolidation tests on Trinidad and

Taiwan MV muds, Yassir [1989] demonstrated the positive relationship between plasticity, tendency for dilation during shear, and pore pressure response. Also, samples having suffered anisotropic stresses (which can be reasonably inferred in many tectonic environments) showed a stronger pore pressure response (up to >30 MPa excess pore pressures [Yassir, 1989]). During undrained normal consolidation, excess pore fluid pressures are caused by shear stress, which is a function of volume loss during shear and is important in a mud volcanic system.

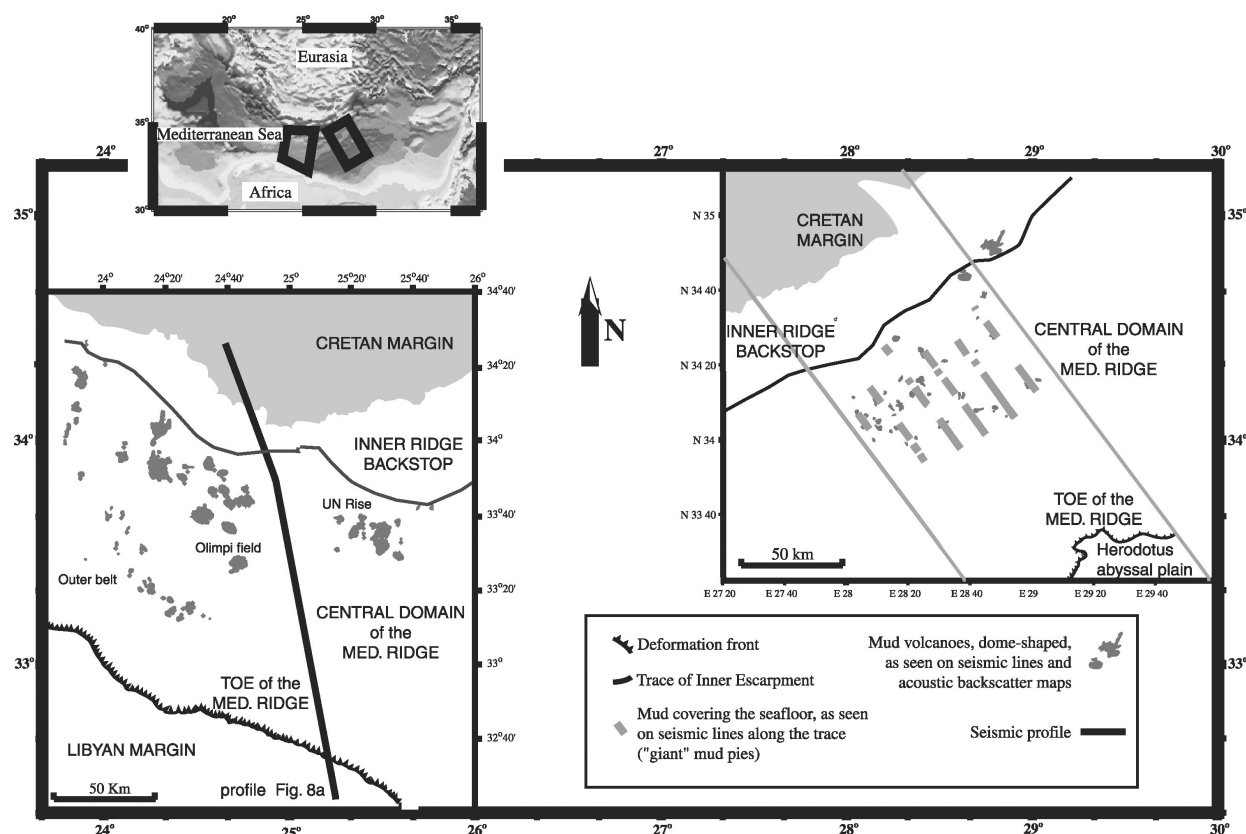
[31] Viscosity tests are more delicate to conduct, as



**Figure 6c.** Model for MV evolution proposed by *Van Rensbergen et al.* [1999] (modified from their Figure 15) for a combined diapiric and fault-induced mobilization of mud offshore of Brunei, reprinted with permission from the Geological Society (London).



**Figure 6d.** Model for MV evolution proposed by *Slack et al.* [1998] for a hydrothermal seafloor extrusion in the Black Sea. See section 3.3 for further explanation.



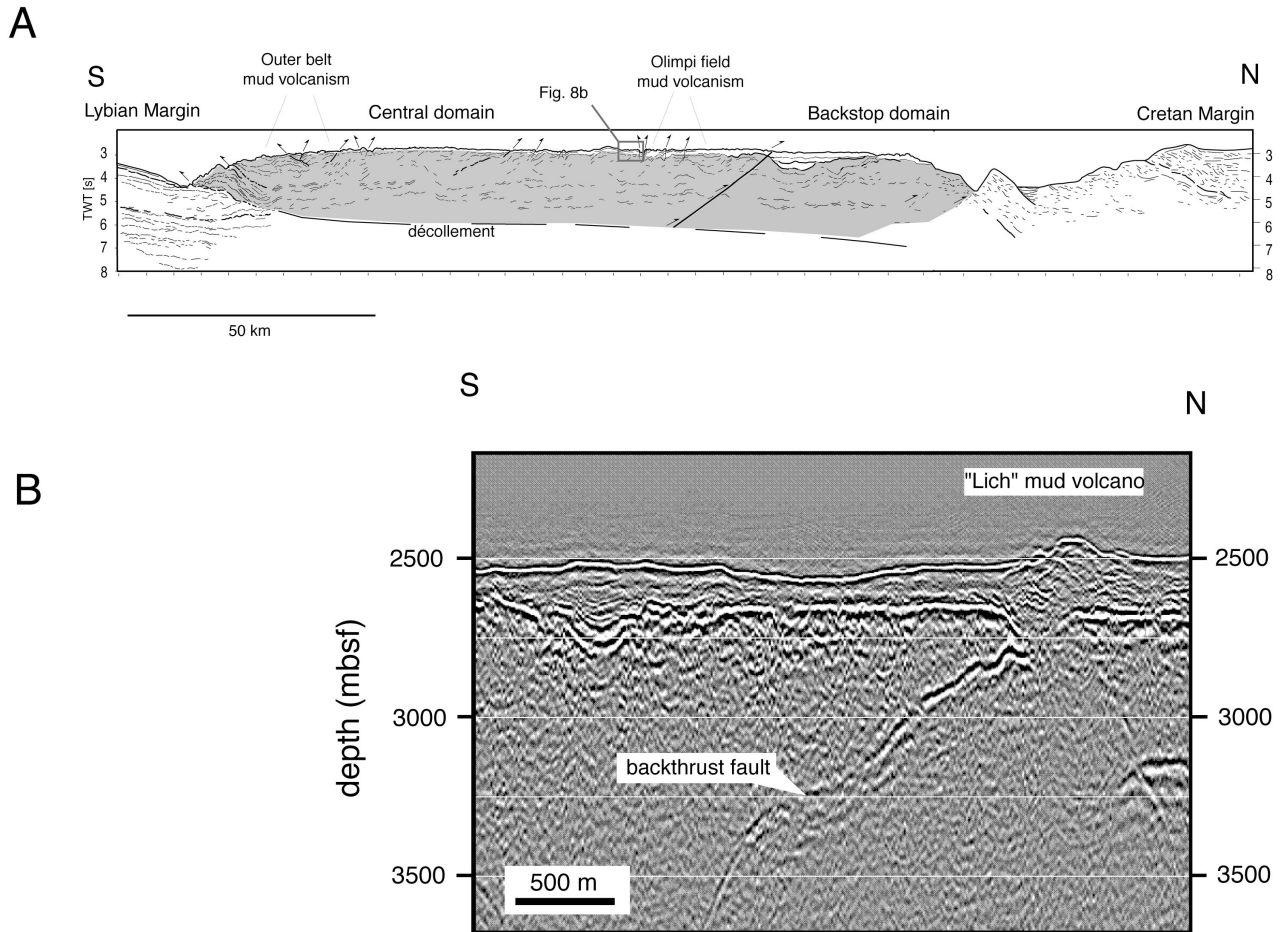
**Figure 7.** Structural map of the central branch of the Mediterranean Ridge accretionary wedge south of Crete, Greece, with an overview bathymetric chart (inset) for orientation. Note the small, outer belt MVs, the larger inner belt MVs, and the large mud pies farther east. Line indicates the location of the seismic cross section shown in Figure 8a. Figure is modified after Kopf *et al.* [2001]. Reprinted from Kopf *et al.* [2001] with permission from Elsevier Science.

the majority of the rheometers are designed for small samples. Consequently, a mud slurry often cannot be measured reliably before alteration effects (e.g., dryness due to high clay contents during shear) become operative. A recent series of experiments using a parallel disk rheometer yielded values of  $10^6$  Pa s for MV muds at water contents of 65% (which, for those Mediterranean Ridge features, appears to be the syndepositional porosity [Kopf and Behrmann, 2000]) at low stress. On that accretionary prism, low viscosities are also inferred from pie-like mudflows over tens of kilometers, disregarding slope angles of  $<2^\circ$  (compare Prior and Coleman [1978] and section A22). For comparison, salt diapirs have viscosities ranging from  $10^{10}$  to  $10^{17}$  Pa s (depending on mineralogy [see Odé, 1968, Table 4]).

[32] If the mud viscosity results of  $10^6$  Pa s are trusted, basic viscous flow can be estimated through a cylinder (i.e., a pipe- or dyke-like conduit) or a slit (e.g., a fault or shear zone) on the basis of Poiseuille's and Stokes' laws (see Kopf and Behrmann [2000] for theoretical background). Using no other driving force than the density contrast between mud and clasts (surrounding accreted rock) from the Mediterranean Ridge, the ascent velocity ranges between  $6 \text{ m yr}^{-1}$  (10 cm conduit diameter) and

$38,000 \text{ km yr}^{-1}$  (10 m conduit diameter). The dramatic effect the diameter has on the mud discharge is obvious from these numbers, and one can imagine that an unconfined system with conduits in the kilometer range (as suggested previously; see above) are out of the question for the subsurface geometries of these conduits. Using the Mediterranean MVs for precise estimates, a rate of  $60\text{--}300 \text{ km yr}^{-1}$  (or up to almost 1 km per day) is obtained for their actual conduit width of 2–3 m [Kopf and Behrmann, 2000]. Such values may appear very high, but are nonetheless the same order of magnitude as, for example, hydrous felsic magmas (their viscosities are pretty similar as well [see Petford *et al.*, 1994]). Thus a certain amount of fluid added to the system would undoubtedly result in a vigorous, diatreme-type eruption. A high discharge is definitely helpful (if not essential) to explain the presence of voluminous blocks of exotic lithology from deep levels, as has been described for the Mediterranean, Sakhalin [Gorkun and Syrik, 1968], and many other areas (see Appendix A).

[33] The logical step to follow these first-order mud discharge rates is an estimate of how long lived MVism has been. With the mud volume and conduit geometry of an individual feature known, the duration of MV activity



**Figure 8.** (a) Interpretation of a north-south-oriented seismic profile across the Mediterranean Ridge accretionary wedge between Libya and Crete and (b) detail showing the mud volcano, Lich, juxtaposing an active back thrust fault some 150 km hinterlandward of the deformation front. Modified after Kopf *et al.* [2001] with permission from Elsevier Science.

is determined by modifying Poiseuille's law and, in the case of the studied Mediterranean MVs, yields 12–58 kyr [Kopf and Behrmann, 2000]. Such periods are very short compared to the age of MV initiation ( $>1$  Myr before present [Robertson and Kopf, 1998a]). On the one hand, episodicity of extrusive activity had been inferred from the intercalation of mudflow deposits with hemipelagic background sediments from drilling [Robertson and Kopf, 1998a]. On the other hand, the brevity of mud expulsion relative to the long periods of quiescence ( $\sim 95\%$  of the total MV life) are surprising, given that the bulk of the dome (including its base) is composed of mostly mud breccia.

[34] A minority of the Earth's MVs are studied in sufficient detail to date their eruptive cycles. Onlapping sequences and seismic stratigraphy estimated some MVs from the Barbados Ridge to have lasted over the previous 20 kyr to not more than 300 kyr, with a considerable error on that estimate and with no constraints on eruptive and quiescent periods [Langseth *et al.*, 1988]. Although dating is not always possible when interfingering of background sediments occurs, evidence is provided

for episodic changes in fluid supply. Features that were previously interpreted as diapiric bodies are now reevaluated as buried MVs [Van Rensbergen *et al.*, 1999, Figure 15]. The key to such a model has been “fingers” of country rock separating individual mudflow events (Figures 6b and 6c). Examples are known from seismic profiles off Brunei [Van Rensbergen *et al.*, 1999], transects of oil wells in Trinidad [Higgins and Saunders, 1974, Figures 13 and 14], the Japan Margin [Ujiie, 2000], or commercial drill holes in British Columbia [Slack *et al.*, 1998, Figure 1]. The fact that pebbly, *mélange*-type rocks from the MVs are connected with the interfingering patterns on each occasion implies that interfingering is somehow an indication of violent, nondiapiric emplacement.

[35] One physical property so far neglected is the temperature regime in which mud extrusion takes place. In general, mud and fluid temperatures are most often found to be slightly elevated relative to the surrounding strata. On the other hand, even the presently active features rarely show an increase of  $>1$ – $5^\circ\text{C}$  [e.g., Robertson *et al.*, 1996]. An exception to this rule is the Håkon Mosby MV at the Norwegian Margin [e.g., Eldholm *et*



*al.*, 1999], where high local heat flow causes the MV fluid to rise to 13°C while the seafloor water column ranges from ~1° to ~3°C [Eldholm *et al.*, 1999] (see section A16 for details). More spectacularly, waters from Sicilian MVs near Etna volcano show temperatures up to 46°C [Chiodini *et al.*, 1996]. Other work encountered mud of 16°–18°C, which could reach 46°–49°C when freshly extruded during paroxysmal phases [Cumin, 1954]. The composition of the gas and liquid phases suggests a hydrothermal reservoir at 100°–150°C, possibly related to the magmatic feeder channel of Mount Etna (see section A19). There are more examples in the regional sections (see Appendix A) (e.g., some Barbados MVs have muds of elevated temperature, while others do not), and reference is made to the sources in the literature. However, despite some general similarities, most MVs are geological peculiarities in the area where they occur. As density contrasts from processes other than pure heat transfer are envisaged as the main driving forces (see above), it is not surprising that the observed temperatures of MV products are highly variable although features of different areas are strikingly similar.

### 3.5. Fluid Discharge and Related Phenomena (Biosphere and Gas Emission)

[36] Many MVs have previously been shown to emit gases or fluids during both eruptions and intervals of quiescence. In onshore environments the discharge of fluids is usually limited to gas flux of predominantly methane [e.g., Jakubov *et al.*, 1971]. Depending on the area regarded and on local variations, methane ranges between 70 and >99 vol %. The remainder is usually CO<sub>2</sub> (especially when MVism is connected with igneous volcanism) and, less often, is higher hydrocarbons, H<sub>2</sub>S [e.g., Stamatakis *et al.*, 1987], or noble gases [e.g., Chiodini *et al.*, 1996; Lavrushin *et al.*, 1996]. However, MVs that are closely interrelated to magmatism may consist of CO<sub>2</sub> as the dominant gas phase [e.g., Sheppard *et al.*, 1992; Chiodini *et al.*, 1996]. In terrestrial MVs, seeping of liquids is an uncommon phenomenon, except in some petroleum fields where higher hydrocarbons coexist in the ascending muds [e.g., White, 1955; Humphrey, 1963]. In marine environments, both liquid fluids and gases vent in considerable amounts from MVs into the overlying water column. Liquids may originate from deep-seated faults and allow upward migration of hydrothermal waters [e.g., Slack *et al.*, 1998], but may also be brines [e.g., Robertson *et al.*, 1996], freshened waters from mineral dehydration reactions or gas hydrate dissociation [e.g., DeLange and Brumsack, 1998], and lateral meteoric water influx. The signature of the fluid often hints toward the origin of the water [e.g., Mottl, 1992; Martin *et al.*, 1996] but also to the mobilization depth of the mud feeding the MV (see section 4).

[37] The primary control over fluid flow is the permeability of the material, while the absolute amount of fluid supplied is of secondary importance [Kopf *et al.*, 1998]. In general, MV settings are characterized by a sufficient

presence of fluid, although these fluids may be trapped and do not always (and sometimes episodically) migrate to the surface. Low permeability of the crestal MV deposits, either due to high smectite contents (with permeability of those mud breccias 2 orders of magnitude lower than other deep sea clays [Kopf *et al.*, 1998]) or presence of massive gas hydrates [Reed *et al.*, 1990; Bouriak *et al.*, 2000], at times blocks the conduit completely. Such temporary inactivity allows excess pore fluid pressures to build up, which, at lithostatic pressure, results in a usually violent eruption and sudden release, as evidenced by hydrofractured clasts [Robertson and Kopf, 1998b]. This mechanism applies to diatrema-like features more than to diapiric ones, as *scaly fabrics* often evolve along mud diapirs, causing an increase in permeability due to widened shear zones, increased effective stresses, and failure to create fluid overpressures [Moore and Byrne, 1987]. High fluid flow velocities cause long mudflows, slumping, and pockmarks [e.g., Hovland and Judd, 1988; Limonov *et al.*, 1998]. Tectonic activity and earthquakes are other efficient mechanisms to facilitate rapid pressure release and vigorous MV activity [e.g., Siryk, 1962]. In 1922, MV emissions in the Caucasus caught fire, resulting in a 14-km-high flame visible over hundreds of kilometers [Kugler, 1939]. Similarly, self-igniting methane gas has been reported from the Caspian Sea region [Bagirov *et al.*, 1996a, 1996b]. For quantitative fluid discharge estimates, see section 5.

[38] Fluid venting is often associated with the evolution of very specialized faunal assemblages. Large clam communities have been found off Cascadia and in the Mediterranean (often *Acharax* and *Calyptogena* in methane-dominated systems and *Vesicomya* in brine-dominated systems [see Corselli and Basso, 1996; Suess *et al.*, 1999]), and large specimens of the sponge *Cladorhiza* (with extracellular symbiotic bacteria) have been reported off Barbados [Vacelet *et al.*, 1996; Olu *et al.*, 1997]. Fields of nonsymbiotic organisms, such as abundant filter-feeding polychaetes and high densities of meiofauna, are indicative of enhanced biological production in the sediments. Bacterial mats of different species can also be observed in marine environments and are often associated with the above macrofauna. Their discovery, together with that of the subseafloor life, is an outstanding aspect of biological sciences, most importantly because the extent and magnitude of the deep microbial biosphere [Parkes *et al.*, 1994] has been estimated to be equivalent to 10% of all surface life. MVs have been demonstrated to provide a unique number of different subseafloor habitats for microbes, and biogenic degradation of organic matter (i.e., methanogenesis) may have profound effects on MV dynamics. Brown [1990] showed that even small amounts of methane (1%) can cause expansion at depths above 1 km that leads to extreme buoyancy. Most convergent margin MVs surveyed have shown much higher methane flux, for instance, off Barbados [Henry *et al.*, 1990].

#### 4. ORIGIN OF GASEOUS, AQUEOUS, AND SOLID PHASES

[39] In this section, the gas, liquid, and solid components of MV deposits and emissions are treated separately for two main reasons. First, their origin as well as their role in driving or triggering MVism may differ considerably (with the fluid phases often originating from much deeper levels than the position of the parent bed). Second, characterizing the various phases and their depth of mobilization (or generation) varies as a function of the gas, liquid, or solid material itself.

##### 4.1. Origin of Mud

[40] In general, mud volcanoes are an important “tectonic window” into the underlying strata, because both a low-competence parent bed and some overlying rock fragments are transported to the surface. Often, the mud breccia matrix (i.e., the parent bed) in a study area can be easily related to the regional geology and to clay or shale-bearing lithologies at depth. Even in old reports, where the scientists relied on standard field geological techniques, the depth of potential parent beds to MVs could successfully be estimated or extrapolated. This is particularly true for onshore geological fieldwork. This difficulty is particularly experienced along many accretionary margins, where it may not be known what type of sediment enters the subduction zone (either due to inaccessible depths for sampling or to a lack of data altogether). Moreover, large parts of the accretionary wedge may comprise similar argillaceous deposits, which have been accumulated through time and whose tectono-stratigraphic position may be obscured by complex imbrication and deformation patterns. In such cases, marker particles indicating thermal maturation, diagenetic alteration, or dating may have to be sought to gain information about the parent bed.

[41] Mud origin is exemplified by the Mediterranean Ridge MVs, where a wealth of methods have been applied to identify the source materials and depths. With 19 Myr [Thomson *et al.*, 1998] over which accretion takes place together with incipient deformation of the prism through time, detailed investigation of the mud breccias is required to shed light on the origin of the mud parent bed. Also, the regional diversity of mud features suggests that different processes are interacting, in turn involving different clay-rich lithologies to host mud mobilization (Figure 7). In the frontal part of the accretionary prism, small clast-free domes are found in an irregularly formed belt (the so-called “outer belt”; see Figures 7 and 8). These features are believed to be largely driven by the high strain and dewatering rates usually encountered at the *toe* of an accretionary wedge [e.g., von Huene *et al.*, 1998]. As availability of water from compaction decreases exponentially with distance from the deformation front, some other mechanism has to drive MVism of the “inner belt” features (Figures 7 and 8). These domes are larger in number and are generally

bigger than near the toe, so that other processes have to account for the enormous fluid volumes involved [Kopf *et al.*, 2001]. Their size and age (see section A22 for details) as well as their high acoustic reflectivity suggest considerable amounts of lithified clasts in the mud breccia, which also hinders rapid erosion. Such clasts are interpreted to represent fault breccia having been collected by the extruding mud mass during ascent, because many of the inner belt features juxtapose out-of-sequence thrusts [Kopf *et al.*, 2001] (Figure 8b). While both the outer belt and inner belt MVs occur in an area of pure compression, even larger mud features have been observed where collision is oblique (see Figure 7). These giant mud pies reach diameters of tens of kilometers and supposedly originate when small pull-apart structures in the prism give way to ascent of undercompacted mud [Kopf *et al.*, 2001]. Like the frontal small cones, the mud pies are apparently free of lithified clasts. For details on the eastern Mediterranean MVs, see section A22.

[42] Determining the origin of the solid components of a MV involves the investigation of the mud matrix as well as of the clasts. The latter may have been either collected during upward migration (hence representing loose wall rock) or part of the parent bed (likeolistostromes or mélanges; see Appendix A). After the discovery of MVs on the Mediterranean Ridge accretionary complex, the classical approach to identify the parent bed has been to relate the mud breccias of the Olimpi field (Figure 7) to the regional geology [Cita *et al.*, 1981]. This is a difficult task, because in the immediate vicinity (e.g., the island of Crete as the forearc high), no matching deposits exist. Owing to the similarity to mélange deposits in the Appennines in northern Italy, the “argille scagliose” shale units (or some analogue) of Upper Cretaceous age were proposed to compose the matrix of the MV deposits. The age constraints by a later microfossil study seemed to support such an interpretation, because Cretaceous taxa could be identified from gravity cores of very limited penetration [Staffini *et al.*, 1993]. No clear evidence has been provided for the potential depth of such Cretaceous deposits, although seismic surveys in the area led researchers to believe that the mud may be trapped beneath a seal of massive evaporites of Messinian (uppermost Miocene) age [Camerlenghi *et al.*, 1995]. Some doubt naturally remains because of the ~60 Myr between the Cretaceous and Messinian, during which one would be left to explain the underconsolidated state of the mud/shale. Another seismic survey in the central part of the Mediterranean Ridge between Libya and Crete (Figure 8a) revealed that the accretionary prism suffers maximum deformation and that incipient collision had already caused uplift of the area [Chaumillon and Mascle, 1997]. Consequently, only a little salt was deposited during desiccation of the Mediterranean Sea to serve potentially as an evaporite seal. Only recent deep drilling of the Milano and Napoli domes allowed a fuller understanding of MVism near the backstop to the large accretionary

**Table 3. Chemistry of Muds and Mud Breccia Pore Fluids From Selected Areas<sup>a</sup>**

	Seawater	Hydrothermal Experiments		Costa Rica Fluid	Barbados Fluid	Taiwan Fluid
		Low T Fluid	High T Fluid			
Alkalinity <sup>b</sup>	2.3	3–56	-	4–35	3–24	1–245
Cl <sup>b</sup>	560	450–590	-	555	200–550	13–347
Mg <sup>b</sup>	53	17–53	-	46–54	1–54	0.3–2.2
K <sup>b</sup>	10.2	0.9–12	-	-	2–11.8	-
B <sup>b</sup>	0.42	0.12	2.04	-	0.41–5.17	0.2–10
Li <sup>b</sup>	$2.6 \times 10^{-5}$	0.001–0.008	3.08	-	0.05–0.6	0.007–0.82
Br <sup>b</sup>	0.84	0.93–1.52	-	-	0.5–0.84	-
$\delta^{13}\text{C}^c$	0	-	-	-	-60 to -113 (G)	-38 (G)
$\delta^{18}\text{O}^c$	0	-	-	-	-0.3 to +1.5 (IW)	-
$\delta^{11}\text{B}^c$	39.5	25.5	2	-	-	22–65
Depth of mobilization, km	-	-	-	<<1	<1	1–3
References	<i>Sadiq</i> [1992]	<i>You et al.</i> [1996]	<i>You et al.</i> [1996]	<i>Zuleger et al.</i> [1996]	<i>Martin et al.</i> [1996]	<i>Gieskes et al.</i> [1992]
	<i>Deyhle</i> [2000]	<i>Taira et al.</i> [1991]	<i>Dia et al.</i> [1995]			

<sup>a</sup>For comparison, the believed mobilization depth of the MV products is given. References concerning the data shown can be found in section 4 and in the given regional sections in Appendix A. Dash denotes data not analyzed or not reported, G denotes gas, IW denotes interstitial water, and question marks denote data not known.

<sup>b</sup>Values are given in millimoles.

<sup>c</sup>Values are given in per mil.

prism [Robertson *et al.*, 1996]. Clast petrography and provenance of components of redeposited sandstones from nine drill holes provided the basis for a reevaluation of the origin of the mud breccia [Robertson and Kopf, 1998b]. Despite the presence of Cretaceous microfossils in the matrix and in some sandstone clasts (both of which are products of reworking), the oldest clast has been related to Miocene (Burdigalian). Its position within the accretionary prism may well have been above underthrust Messinian muds, which apparently form the matrix of the mud breccias. The latter conclusion was drawn from striking similarities in the physical properties, color, and composition of the mud breccia matrix and Messinian deposits in the Tyrrhenian Sea nearby [Kastens *et al.*, 1987; Kopf *et al.*, 1998]. A Messinian age was also inferred by the Lopatin method [e.g., Waples, 1980] for maturation of organic matter to muds from Napoli MV [Schulz *et al.*, 1997]. In their model, organic-rich mud has hypothetically traveled along the *décollement* to depths of up to >7 km below the seafloor before ascending and being extruded as MV (without having undergone compaction). Reevaluation of such a model using the same approach based on clasts and matrix from the adjacent Milano MV is in favor of a shallower origin of both clasts and matrix [Kopf *et al.*, 2000b]. The low vitrinite reflectance measured makes it unlikely that the solid component has experienced elevated temperatures or deep burial. These results are supported by another, more theoretical approach based on quasistatic modeling of the ascent of mud [Cherskiy, 1961; Kopf and Behrmann, 2000]. The latter estimate of a mud mobilization depth of 1.7 km is bracketed by the less well constrained 1–2 km depth of burial from the maturity data [Kopf *et al.*, 2000b]. In conclusion, the multidisci-

plinary investigation has successfully limited the possible parent bed (or reservoir) location within the highly deformed accreted strata of the central Mediterranean Ridge to a certain depth interval. Although not identified in seismic profiles, the source of the mud may well be located at a moderate depth, possibly within slices of Messinian evaporites and older argillaceous material.

#### 4.2. Origin of Aqueous Fluid

[43] Aqueous fluids may contribute to MV systems from various sources and by different mechanisms and reactions (Figure 2). Brown [1990] pointed out that especially in diatremes, the liquid may have been transported from elsewhere at high rates prior to facilitating liquefaction of a potential MV parent bed. Such lateral or vertical fluid advection is known in many compressional settings, where stresses usually increase both toward the hinterland and with increasing burial depth [e.g., Moore and Vrolijk, 1992]. It is beyond the scope of this summary to introduce the complex chemical interactions through which a fluid receives a signature diagnostic of certain conditions. However, such characteristic signatures inherited at subbottom depth are powerful tracers for the environment of the fluid origin [Kastner *et al.*, 1991]. They help to understand processes inaccessible to in situ sampling, with the MVs acting as a “window.”

[44] After deposition, pore fluid immediately starts to interact with the sediment particles, and numerous elements are exchanged during diagenetic and early metamorphic reactions [Guangzhi, 1996]. The two most profound diagenetic processes in MVs are (1) the successive dewatering of smectite (both thermally and compactionally [see Fitts and Brown, 1999]), which loosens its inter-

<i>Trinidad</i>	<i>Mediterranean Ridge</i>		<i>Caucasus</i>		<i>Håkon Mosby</i>	<i>Marianas</i>
<i>Fluid</i>	<i>Fluid</i>	<i>Mud</i>	<i>Fluid</i>	<i>Mud</i>	<i>Fluid</i>	<i>Fluid</i>
5–68	1–90	-	1–189	-	2.9–20.6	0.3–63
20–385	61–5300	-	3–145	-	82–561	310–560
0.5–6.2	0.6–500	-	1.2–12.3	-	2.5–54.3	0.1–50
0.2–2.2	0.3–94	-	0.12–3.3	-	2.8–14.1	5.9–15.2
0.3–12	1.7–9.7	7.9–18.5	1.85–84.7	13–50	-	1.85–3.9
0.01–0.71	0.01–0.23	-	0.06–0.67	-	-	0.01–0.14
<0.01–1.74	-	-	-	-	-	-
-	-	-8 to 0	-10 to +11 (G)	-20 to +13 (G)	-	-
1.6–7.5	-	-1 to +2.5	-	-	-0.15 to +4.6	-
-	25–40	-3 to +7	22–40	-8 to +13	-	-
1–4 (plus meteoric)	>5???	1–2	3–10 (plus mantle gas)	2–4	???	???( $>150^{\circ}\text{C}$ )
<i>Dia et al.</i> [1999]	<i>Deyhle</i> [2000]	<i>Deyhle</i> [2000]	<i>Deyhle</i> [2000]	<i>Deyhle</i> [2000]	<i>Ginsburg et al.</i> [1999]	<i>Mottl</i> [1992]
	<i>Emeis et al.</i> [1996]		<i>Lagunova</i> [1976]			

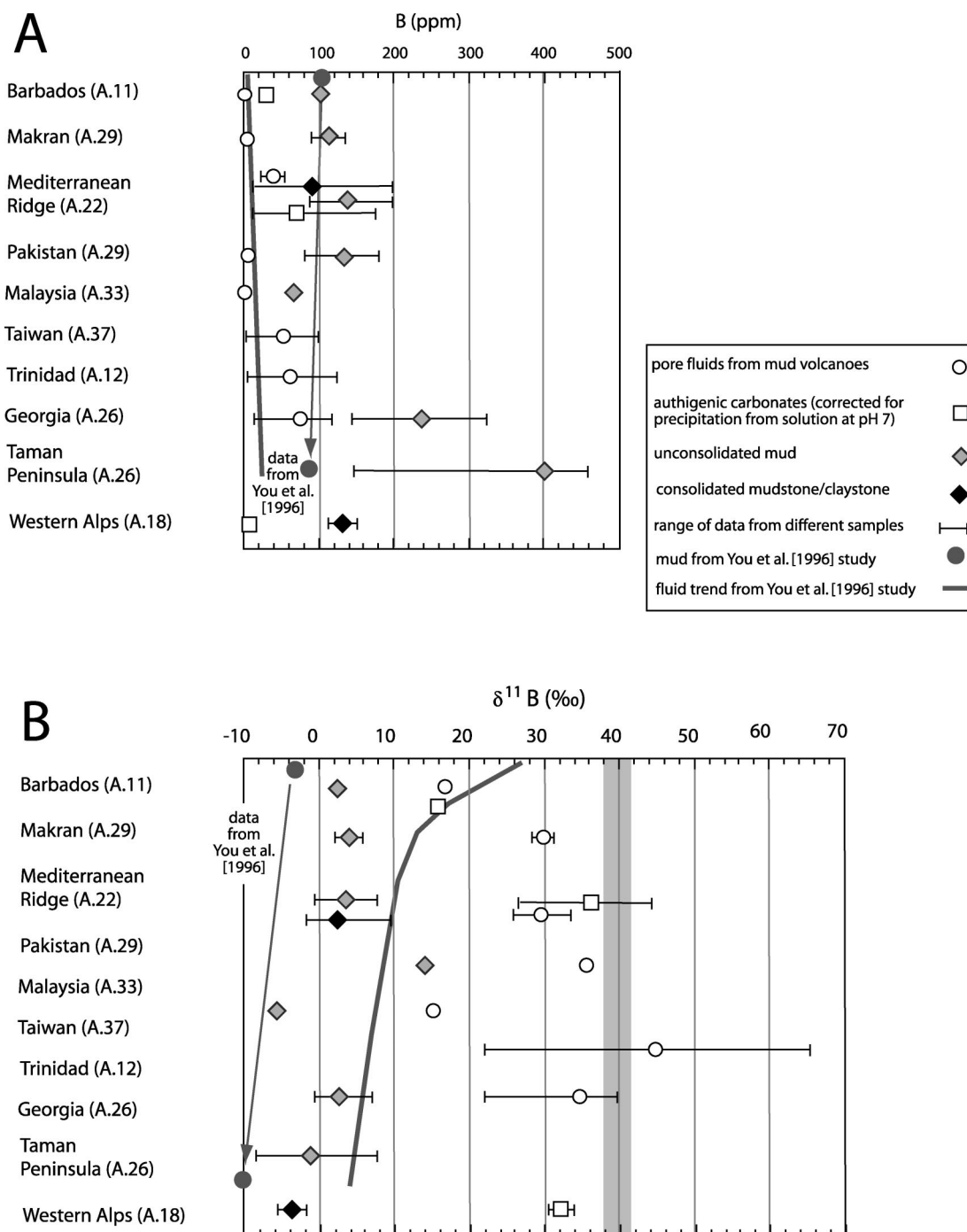
layer water together with soluble volatile elements adsorbed to the mineral (see below and Table 3), and (2) the possible enrichment of the fluid as well as part of the solid phase in MV deposits, the first of which often causes formation of authigenic minerals (e.g., carbonate cementation, as has been found on numerous active MVs; see sections A22, A29, etc.).

[45] On a clay-rich sediment from the Nankai accretionary prism, off Japan (see section A38), a systematic study has been conducted to identify geochemical water-rock interaction at temperatures of  $25^{\circ}$ – $350^{\circ}\text{C}$  at constant pressure in an autoclave system [You *et al.*, 1996]. With increasing temperature during the test, volatile elements such as B, N, Cs, Ba, Sb, and U were enriched in the pore fluid. Complementary depletion patterns in the sediment were observed. The first devolatilization at relatively low temperatures (still below  $100^{\circ}\text{C}$ ) was associated with release of elements formerly adsorbed to the clay minerals. Evidence for this interpretation has been provided by, for example, isotope ratios of boron of both fluid and sediment, which show characteristic excursions toward values typical for exchangeable B [You *et al.*, 1996]. At higher temperatures, less mobile elements (e.g., As, Li, and Be; see Table 3) are enriched in the fluid and, conversely, are removed from the sediment. Unfortunately, the laboratory equipment was limited to  $T = 350^{\circ}\text{C}$ , and there had still been lively exchange between the solid and fluid phase at this upper range. However, one can extrapolate trends when looking at subduction zone processes and especially at the part that escapes both metamorphism and arc or mantle recycling. High-temperature hydrothermal alteration and low-grade metamorphism/metasomatism create characteristic fluid isotope signatures (high  $\delta^{11}\text{B}$ , high  $\delta^{13}\text{C}$ , and

high  $\delta^{15}\text{N}$  [cf. *Bebout*, 1995]), which may be acquired through venting conduits and deep-seated faults or when intrusion and MVism affect the forearc [Fryer and Mottl, 1992]. As a consequence, the  $\delta^{11}\text{B}$  isotopes become more negative in the mud (see trend in Figure 9b).

[46] If the in vitro results by You *et al.* [1996] are compared to MV samples taken from several prominent convergent margins (such as Barbados, Costa Rica, Taiwan, Trinidad, the Mediterranean Ridge, and the Mariana forearc), a major discrepancy becomes obvious (Figure 9). While the fluid enrichment patterns with increasing temperature measured by You *et al.* [1996] match those from MVs triggered by deep-seated fluids [e.g., *Deyhle and Kopf*, 2001], MV muds are also enriched in volatiles when compared to marine sediments. For example, muds from Caucasian MVs have been demonstrated to have up to 80 mM B [Deyhle, 2000], which is about  $8\times$  higher than regular marine clays [Ishikawa and Nakamura, 1993]. Given that these muds experienced subduction and incorporation into the Caucasian orogenic wedge, this is unexpected, because the clay stones should have undergone desorption. Elevated B, Ba, Sr, and Li contents have been interpreted as secondary enrichment, probably because clay dehydration was partly reversed during liquefaction and mud mobilization. Other examples of enriched muds include the Mediterranean Ridge MVs [Deyhle and Kopf, 2001], Trinidad [Dia *et al.*, 1999], and the serpentine domes in the Marianas [Mottl, 1992]. In addition, the muds of these MVs are enriched in the same elements. Guangzhi [1996] also showed that many muds are enriched in light rare Earth elements (REEs) and are depleted in heavy REEs after diagenesis, with the major fraction bound by the clay-size particles. This observation leads to the conclusion that the hydrothermal experiments





**Figure 9.** (a) Boron content versus proposed depth of mud and fluid mobilization based on regional geology and B data from the literature; (b)  $\delta^{11}\text{B}$  versus proposed depth of mud and fluid mobilization based on regional geology and B data from the literature. Note that the numbers behind the sampling localities correspond to those in Figure 1 and Appendix A. Symbols in the plots represent mean average, while bars show the range of results. The underlying shading trends are fluid data approximated from the hydrothermal experiments by *You et al.* [1996]; the starting point is 25°C and the graph terminates at 300°C, which would also be the temperature at 10 km depth in the Caucasus (Taman Peninsula). Solid circles are initial and terminal mud composition from *You et al.* [1996]. For depths of mobilization for solid and fluid components of the mud breccias from the different regions, refer to Appendix A.

in a “closed system” only partly (i.e., for the fluid component) resemble natural processes. However, despite these shortcomings, the fluid enrichment can be used to tie in the source depths of MV fluids.

[47] Among the major subduction margins a systematic increase in deformation is seen from the frontal part of accretionary prisms (Nankai, Barbados, and Costa Rica), over the central and backstop domains of such

wedges (Taiwan, Barbados, and Mediterranean Ridge) and the deep forearc (Marianas), to the orogenic wedges (Great Caucasus; see Figure 10b). In general, a weak but systematic pattern in the altered fluid chemistry in the different MV areas along such margins with respect to the estimated source depth is inferred (Table 3). First, a basic trend of enrichment of the fluid phase in various elements with increasing burial and temperature exists. This includes some of the abovementioned elements, like Ba, Na, K, B, Sr, Cs, I, As, Rb, or Sb, which are usually enriched in mature MV waters [Dia *et al.*, 1995, 1999; Deyhle, 2000]. These basic trends may be blurred by dilution effects owing to mineral dehydration reactions, influx of gas hydrate cage water, or meteoric water from elsewhere. Regardless of the latter disturbances of the MV system, volatile elements seem to be more concentrated in fluids mobilized from considerable depth. For instance, maximum boron contents in accretionary prisms are low seaward or near the deformation front, increase in the central and landward prism [Deyhle and Kopf, 2001], and may be up to 20× higher than seawater when expelled from a highly deformed orogenic wedge, like the Great Caucasus [Lagunova, 1976]. This quasisystematic behavior is illustrated in Figure 9 and is shown for various elements in Table 3.

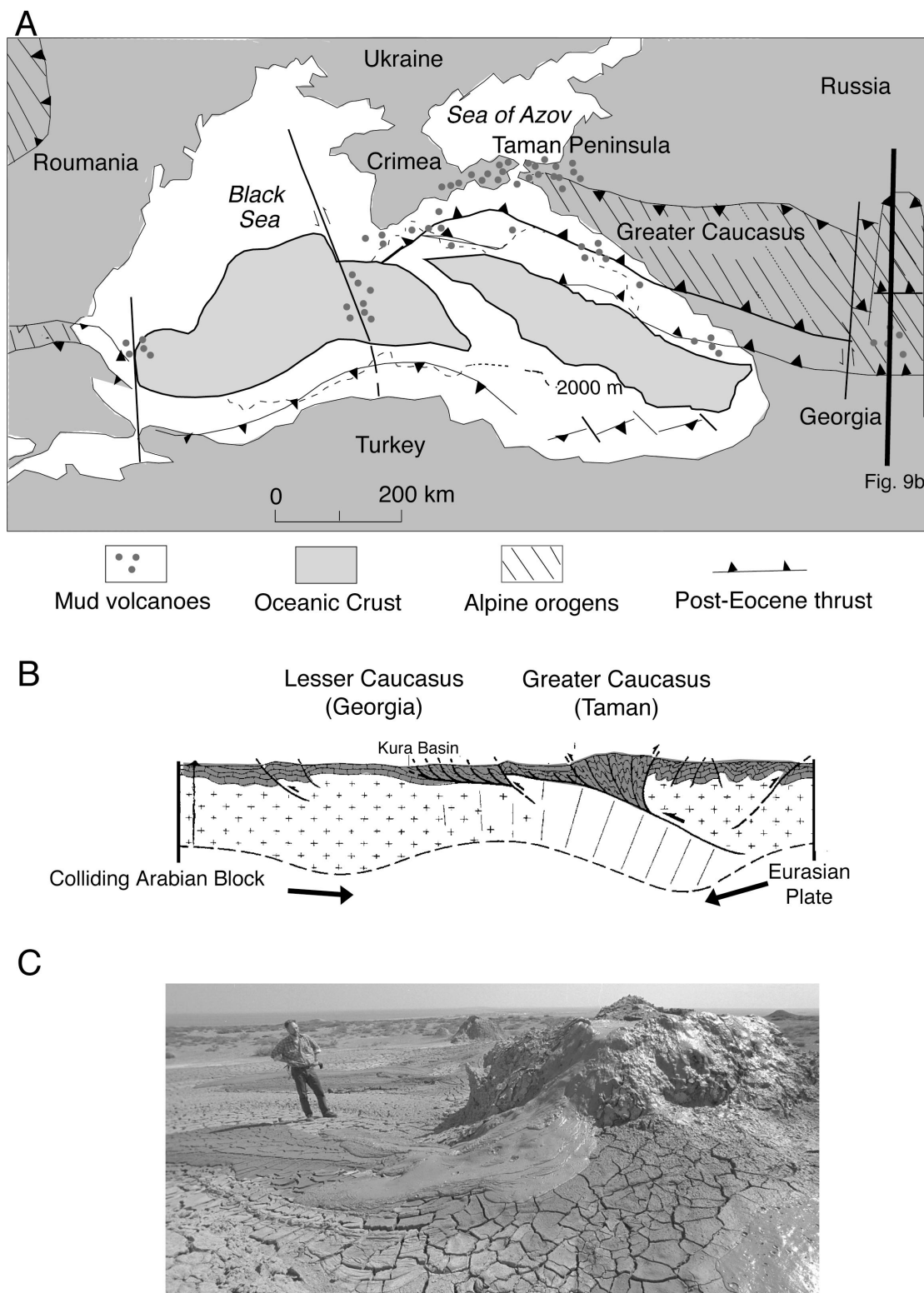
[48] The B enrichment is accompanied by preferential release of adsorbed (i.e., exchangeable)  $^{11}\text{B}$ , resulting in isotope ratios as low as  $-3\text{‰}$  (Mediterranean Ridge mud breccia) and even lower in Caucasian muds ( $-8\text{‰}$  [see Deyhle, 2000]). Similar trends are reported for other collisional margins (e.g., Barbados or Nankai accretionary complexes [You *et al.*, 1993]) and for a variety of elements and isotope systems (e.g., C, O, and He in Caucasian MVs [Lavrushin *et al.*, 1996]). In addition, it has been demonstrated that enrichment of fluids in volatile elements is regularly accompanied by strongly enriched muds [Deyhle, 2000]. For B, Li, Cs, As, and Rb, MVs represent important sinks in collisional environments and hence play an important role in geochemical cycling. Despite regional effects (like mobilization of gas hydrate waters, mineral waters, or brines), MV fluids as well as their authigenic phases are heavily mineralized. This applies to MVs on accretionary complexes compared with the surrounding accumulated strata [e.g., Deyhle, 2000] and to serpentinite MVs relative to upper mantle composition [e.g., Mottl, 1992], as well as to onshore MVs in fault zones when compared to their adjacent country rock [e.g., Deyhle, 2000]. As a consequence, mud volcanism has to be envisaged as an important back flux mechanism of waters and solubles from the lithosphere to the hydrosphere (and atmosphere).

### 4.3. Origin of Gas

[49] In the majority of MVism areas, liquid and gaseous fluids do not originate from the same source or depth. Also, despite thermocatalytic methane being the most abundant gas phase involved in MVism, there are

other areas where shallow methane from dominantly biogenic processes is involved in mud extrusion. There are many such regions known on Earth [e.g., Heggland, 1997; Wallmann *et al.*, 1997; Croker and O'Loughlin, 1998], where shallow gas is a trigger, but is not the driving force of mud extrusion. The Mediterranean Ridge MVs may serve once again as an example to illustrate this point. De Lange and Brumsack [1998] as well as Aloisi *et al.* [2000a, 2000b] proposed from pronounced pore fluid “freshening” (i.e., decrease in dissolved ions and, specifically, low chlorinity) in the uppermost pore fluid profiles that biogenic methane had been released from gas hydrate processes, and they conclusively made gas hydrate dissociation a driving force for MVism. If the authors are correct about the hydrate having caused low chlorinity, such hydrates would be stable only at depths not exceeding a few tens of meters. Consequently, the overwhelming evidence for a deep mud source in many MV provinces (see section 4.1) is in conflict with shallow gas being a major driving force for extrusion. Such shallow gas more likely assists the final stages of mud ascent and extrusion [Kopf *et al.*, 1998].

[50] For a gas driving force at deep levels of mud mobilization, several scenarios can be envisaged: (1) mantle degassing, (2) (igneous) volcanic degassing, and (3) hydrocarbon generation. As can be seen in Appendix A, mantle gas plays a rather marginal role as driving force. Even in the prominent MV regions near the Black and Caspian Seas with deep-seated faulting during the Caucasian orogeny (Figure 10b), the fraction of gas mobilized at crustal depth appears negligible ( $\ll 1\text{ vol } \%$ ) compared with the entire volume [Lavrushin *et al.*, 1996]. No active gas expulsion has been reported from the obvious candidates of mantle-derived degassing, the serpentinite MVs in the Marianas. The composition of the gaseous fluid collected with pore waters (and then sampled from the headspace of the core liner) shows  $\text{CO}_2$ , methane, S, higher hydrocarbons, and noble gases to be the main components. Given the lack of pristine sampling methods, no quantitative estimate exists of the amount of these gases. However, from pore fluid chemistry and fluid-rock interaction, it is suggested that deep aqueous fluids are released at mantle depth and then serpentinize the overlying forearc wedge [Mottl, 1992]. These fluids, rather than mantle gas, are available in considerable quantities from the sediment cover of the downgoing slab and are believed to drive MVism here. As for the second setting, the vicinity of large igneous volcanoes, deep gas ( $\text{CO}_2$  and  $\text{N}_2$ ) in conjunction with hydrothermal waters drive extrusion of MVs [e.g., White, 1955; Sheppard *et al.*, 1992; Chiodini *et al.*, 1996]. No deep fluid sampling has yet been undertaken in such a scenario of elevated geothermal gradients. Regarding the third aspect (hydrocarbons), an intimate connection with mud volcanism has long been acknowledged (see references made throughout Appendix A). The profound effect of hydrocarbon gas generation, its signifi-



**Figure 10.** (a) Map of the Black Sea area, also showing MV areas in Romania, on the Crimea and Taman Peninsulas, and in Georgia and Azerbaijan. Map is modified after *Slack et al.* [1998]. (b) Schematic cross section through the orogenic wedge; see Figure 10a for location. (c) Photograph of Dashgil MV, Azerbaijan. Photograph is courtesy of Martin Hovland, who also provides the scale.

cance for overpressuring, and its general relevance in driving MVs and shale diapirs are neatly reviewed by *Hedberg* [1974]. Together with enhanced fluid pressures generated from trapped pore water or released mineral water, methane is the most powerful agent for overpressuring, liquefaction, and extrusion (see Appendix A), especially in the Great Caucasus [e.g., *Jakubov et al.*, 1971] and Trinidad [*Higgins and Saunders*, 1974]. In the Caucasus it has been proposed that methane originates from depths where it is aqueous ( $\sim 10\text{--}12$  km according to industry seismic reflection data [*Cooper*, 2001]) before upward migration and expansion trigger vigorous eruptions and mud extrusion.

## 5. QUANTITATIVE ASPECTS: SIGNIFICANCE OF MUD VOLCANISM

[51] Despite the wealth of case studies (see Appendix A), the role of MVs in mass and volatile transfer remains difficult to assess. Usually, detailed evidence exists for only a minority of the features, and even within the same regional context it seems unsafe to extrapolate this knowledge. Arguably, the subduction zones with most abundant MV features are the Barbados and Mediterranean accretionary complexes (for references, see sections A11 and A22). In terms of area covered by mud extrusions, the Barbados Ridge MVs cover  $\sim 700$  km<sup>2</sup> [*Brown and Westbrook*, 1988], while  $>1500$  km<sup>2</sup> has been estimated for the Mediterranean [*Kopf et al.*, 2001]. In the latter case, deep drilling sets age constraints that are now a prerequisite to characterize MV evolution in space and time (see above and *Kopf* [1999]). All other areas where extensive work has been carried out (e.g., the Caucasus region, Taiwan, or Trinidad) lack some crucial information to allow reliable first-order budget estimates to be carried out. Indeed, data on fluid and gas venting apply to individual cones, but fail to be representative. For instance, *Olu et al.* [1997] used the density of clam population on two diatrema-like MVs (Atalante and Cyclope) on the Barbados Ridge to estimate fluid discharge velocities to  $\sim 10$  cm s<sup>-1</sup>, but without having tied such expulsion into the overall fluid budget of the accretionary wedge with its more than 450 MVs. Using heat flow data, *Henry et al.* [1996] estimated a minimum fluid supply of  $1.5 \times 10^5$  m<sup>3</sup> yr<sup>-1</sup> for the Atalante MV seaward of the Barbados accretionary complex. It is difficult to relate this rate from near the deformation front to the wide accretionary complex; however, it appears unlikely that the high fluid flux or dense clam communities are representative for the majority of the Barbados features. As stated in section A11, *Henry et al.*'s [1996] estimate is influenced by lateral fluid accumulation and by gas hydrate processes.

[52] Gas hydrate dissociation related to mud extrusive activity is known from elsewhere [*Milkov*, 2000]. On the basis of the geometry of MVs and the appearance of bottom-simulating reflectors (BSRs) on seismic profiles,

potential flux rates of methane have been estimated. The dissociation of all gas hydrate around Håkon Mosby mud volcano offshore Norway (see section A16) would result in  $3\text{--}4 \times 10^8$  m<sup>3</sup> methane (under atmospheric P [*Milkov*, 2000]) and, similarly,  $3 \times 10^8$  m<sup>3</sup> methane for Buzdag MV in the Caspian Sea [*Ginsburg and Soloviev*, 1998]. *Milkov* [2000] further extrapolates this to a global estimate; however, no estimate of error is provided. His study has a series of other shortcomings, such as the simplification that all dissolved gas hydrate may result in free methane release into the atmosphere. In fact, it has been shown previously that methane plumes may be stable in the water column for long periods of time [*Suess et al.*, 1999] or that methane may reprecipitate to gas hydrate when suitable pressure-temperature conditions are met. Also, the methane may be oxidized to CO and CO<sub>2</sub> in the water column or may be precipitated to authigenic carbonate crusts on the seafloor [e.g., *Aloisi et al.*, 2000a; *Deyhle and Kopf*, 2001]. No in situ flux rates from gas hydrate dissociation or other processes are reported by *Milkov* [2000].

[53] It has long been established that many subaerial mud volcanoes release enormous amounts of methane into the atmosphere [*Higgins and Saunders*, 1974; *Hedberg*, 1980]; however, very little is known about the volumes emanating from them. Gas emission has been measured for one of the most prominent Caucasian features, Dashgil MV, ranging from 800 m<sup>3</sup> yr<sup>-1</sup> [*Hovland et al.*, 1997] to  $15 \times 10^6$  m<sup>3</sup> yr<sup>-1</sup> [*Jakubov et al.*, 1971]; the gas flux can be highly variable through time. Similarly, *Etioppe et al.*, [2002] found MVs in Sicily/Italy to emit between 0.67 m<sup>3</sup> yr<sup>-1</sup> and 23,012 m<sup>3</sup> yr<sup>-1</sup>, i.e., a range over more than 5 orders of magnitude. Neither study stated whether such rates are applicable to the more than 220 features known in the surrounding area (see also section A26); however, it seems appropriate to distinguish between extrusive events and background emission of gas. The only extensive study on land has been carried out by *Guliev* [1992]. In his report, catastrophic extrusions have been distinguished from background gas emanation [see *Guliev*, 1992, Table 8]. For four prominent eruptions between 1902 and 1961, the amount of gas expelled during the first few hours ranged from 22.5 to 495 million m<sup>3</sup> [*Guliev*, 1992, p. 17]. The most vigorous outbursts on land uproot trees, ignite methane, and release up to 50,000 m<sup>3</sup> mud and  $5 \times 10^8$  m<sup>3</sup> gas [*Jevanshir*, 2002]. Reliable constraints concerning episodicity in mud eruptions come from historic records of the Caucasus region and show that during the past 2 decades, three to five violent eruptions occurred each year. Relating the average four annual eruptions to the total 220 domes, each feature erupts every  $\sim 50$  years. By contrast, the annual background flux of 20 MV features was monitored and yielded between 1.3 and 731 m<sup>3</sup> yr<sup>-1</sup> [*Guliev*, 1992, Table 8], with an average of 89.5 m<sup>3</sup> yr<sup>-1</sup>.

[54] In the marine realm the only semiquantitative case study exists for the Eastern Mediterranean Ridge, an accretionary prism where deformation and dewater-



ing are accentuated due to the proximity of the colliding African Shelf (Figures 7 and 8). This work may serve here as an example of how important MVism may become for fluid budgets in the subduction factory. Volumetric estimates of extruded mud were based on prestack depth-migrated seismic profiles across the entire >150-km-wide prism. When the volume of MVs in the main collision zone south of Crete is related to the sediment input from the incoming African Plate (derived from plate kinematic rates and sediment thickness), it can be seen that a maximum 4.3% of the total input volume is extruded as MVs on the prism [Kopf, 1999]. Although such a percentage may appear of minor significance in an overall mass balance, the generally undercompacted muds become of major interest when considering the fluid budget. When the volume of mud from seismic data is combined with age constraints from drilling of Milano and Napoli MVs [Robertson *et al.*, 1996], rates of mud extrusion can be obtained. Subtracting the solid rock mass using porosity data from physical property measurements and downhole logging, fluid flux as a function of mud volcanism has been calculated to reach up to 15 km<sup>3</sup> fluid per kilometer of trench every million years [see Kopf *et al.*, 2001]. Very little of this fluid discharge relates to compaction-driven dewatering in the frontal part of the prism; the majority is expelled some 50–150 km behind the deformation front and exceeds estimates from toes elsewhere (where undoubtedly the majority of the interstitial fluid is lost due to compaction [cf. von Huene *et al.*, 1998]). Such fluids near the backstop of the wedge are likely to result predominantly from mineral dehydration and diagenetic reactions at depth and consequently provide a window to understand processes along the deep décollement. More importantly, the enormous rates (up to 15 km<sup>3</sup> per kilometer of trench and per 1 Myr [Kopf *et al.*, 2001]) with which such fluids escape along the out-of-sequence faults make MVism an important back flux mechanism in hydrospheric budgets. Indeed, previous fluid flow modeling and budget calculations in subduction zones assumed the basal detachment fault (or décollement) to be the most efficient drainage system, where permeabilities are several orders of magnitude higher than in the surrounding rock [e.g., Screatton *et al.*, 1990; Saffer and Bekins, 1998]. Given that it has repeatedly been demonstrated that out-of-sequence faults provide similarly effective means for fluids to escape the deep prism (see Figure 8b) [see, e.g., Kopf *et al.*, 2001; Deyhle and Kopf, 2002], future models need to accommodate that tapping process. In any convergent margin setting, where much of the Earth's low-temperature biogeochemical exchange is concentrated, the present-day fluid flux through landward mud volcanoes may equal that of the toe of the wedge and may have done so earlier in Earth's history. Although the discharge rates are hard to constrain, they have been shown to be high for numerous presently active features.

[55] Gas flux on the Mediterranean Ridge MVs has

been estimated based on the emanation rates suggested for Azerbaijan and Barbados (see above and Kopf [1999] for details). For the Olimpi field (Figure 7) a conservatively estimated  $1.68 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$  to  $2.85 \times 10^7 \text{ m}^3 \text{ yr}^{-1}$  of gas may have been expelled with the extruding overpressured muds (volumetric values under atmospheric pressure [Kopf, 1999]). If extrapolated to the two broad corridors studied by Kopf *et al.* [2001] by simply taking the extruded volumes into account, this would result in  $8.72 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$  to  $1.48 \times 10^8 \text{ m}^3 \text{ yr}^{-1}$  (volumetric values under atmospheric pressure). If such a number is further taken for a global estimate of all active features, the emission from the known features on Earth would be  $\sim 1.14 \times 10^8 \text{ m}^3 \text{ yr}^{-1}$  to  $\sim 1.94 \times 10^9 \text{ m}^3 \text{ yr}^{-1}$  (volumetric values under atmospheric pressure). Such contribution of MVs to the emission of greenhouse gases appears to be negligible; however, given that MVs may have existed on Earth over long periods during the evolution of the planet, MVism may well have had an impact on the evolution of the Earth's atmosphere.

## 6. SUMMARY AND CONCLUSIONS

[56] Despite the variability in appearance, deep-seated mud volcanoes have a number of features in common: (1) a connection with rapidly deposited, overpressured, thick argillaceous sequences of mostly Tertiary age as parent beds; (2) the incorporated fragments of underlying rocks and other structural associations; (3) a relationship to regional tectonics and seismicity or to petroleum reservoirs; and (4) the presence or influx of gaseous and liquid fluids to facilitate diapiric intrusion and extrusion.

[57] Mud volcanoes act as “windows” to depths otherwise inaccessible to sampling, as gas, liquid, and solid particles from up to several kilometers are transported to the Earth's surface. There is a steadily increasing number of new discoveries of mud volcanoes from improved geophysical exploration techniques. As plate convergence and fluid cyclicity have been two fundamental processes throughout Earth's evolution, one can safely assume that mud extrusion may have played a prominent role over long periods. However, fossil evidence is scarce, as most of the MVs have been eroded, with only a few cemented examples preserved [Wilson, 1975; Cavagna *et al.*, 1998].

[58] The growing importance of mud volcanism as an efficient dewatering mechanism in active convergent margin scenarios has been acknowledged in recent work [Kopf *et al.*, 2001]. At least on a regional scale, these researchers have shown that fluid flux by MVism may exceed that from compaction. Moreover, such MV fluids are typically enriched in volatile and (some) trace elements, so that high back flux rates of these elements into the hydrosphere have an impact on geochemical cycling [Deyhle and Kopf, 2001]. Hence the significance of mass transfer through mud intrusion and extrusion will influ-

ence future fluid budget estimates. From the small number of gas flux estimates through mud volcanoes, it can be estimated that the annual amount of methane globally emanated through MVs is  $\sim 10^8$  to  $2 \times 10^9$  m<sup>3</sup>. Although this number appears small when compared to other sources of gas emission, it may be a conservative estimate of their contribution over wide periods during Earth's evolution. Regardless of the small number of fossil examples preserved, MVs are likely to have been common dewatering and devolatilization features with a significant overall contribution to the earlier Earth's atmosphere.

[59] Continued seafloor mapping will undoubtedly identify more MVs, even if the study is not dedicated to these features. Given the present-day knowledge and technology, side-scan surveys for clasts and carbonate crusts or pockmark depressions on the seafloor, heat flow studies, or methane composition in the water column will also add to the discovery of new mud volcanoes. Some of these observations may even hint toward regions rich in hydrocarbons, either to exploit them for fossil fuel or to prevent hazards.

[60] Future mud volcano studies should focus on refined strategies of long-term observatories of the fluid discharge through features onshore and offshore. Sampling techniques to collect pristine waters and gases are of particular importance. As it is clearly impossible to cover wide MV areas with long-term observatories, suitable targets for well-defined case studies have to be identified to assess global budgets. For drilling of transects and installation of long-term observatories, the Mediterranean Ridge/Black Sea/Caucasus region or the Barbados Ridge would be good choices. With the type of examples carefully chosen, the assessment of the role of mud volcanoes in global budget estimates may improve significantly.

## GLOSSARY

**Accretionary prism/accretionary wedge:** Body of fluid-rich sediment being accumulated at the leading edge of the overriding plate in a subduction zone; its base is a highly permeable fault called the décollement.

**Argillokinetic:** Caused by the mobility of clay-rich sediment.

**Avalanche:** Landslide on continental forearcs and slopes, often triggered by rapid fluid flow and/or gas-charged sediments.

**Backstop:** Mechanical abutment of the overriding continental plate to allow an accretionary wedge to build up; often the leading edge of the continental crust or older accreted rock of high strength.

**BSR:** Bottom-simulating reflector; a characteristic reflection in seismic data with reversed polarity relative to the seafloor reflection. It usually follows the seafloor topography at a certain depth, which is defined by the thermal gradient of the area. The cause of the reflection is free gas beneath the zone of gas hydrate stability.

**Cauldron:** Subsided crater area, often used as a synonym for crater.

**Chemoherm:** Seafloor feature of variable geometry, which is mostly composed of authigenic carbonate from inorganic precipitation.

**Chimney:** Precipitates of more or less cylindrical shape around the wall of a conduit.

**Conduit:** Cylindrical or odd-shaped feeder channel through which mud ascends.

**Conglomerate:** Here, like mud breccia, but with rounded rather than angular clasts and rock fragments.

**Crater:** Depression in the crestal area of cone-shaped MVs.

**Décollement:** Plate boundary fault in subduction zones that represents the main detachment in which many thrust faults root.

**Diapir:** Clay- and fluid-rich intrusion.

**Diapirism:** Intrusion of a sedimentary body into its overburden without reaching the surface.

**Diatreme:** Type of mud extrusive feature that evolved from a violent eruption of overpressured mud, cross-cutting the overlying strata like a dyke.

**Eruption:** Extrusive outflow of mud and fluids that may be quiescent (mostly degassing) or vigorous (see diatreme).

**Ejecta:** Material extruded during violent eruptions.

**Extrusiva:** All extruded material.

**Fumarole:** Product of volcanic devolatilization, sometimes in conjunction with precipitation of, for example, sulfur.

**Gryphon:** Small cones or mud craters off the crest, or at the flank of the mud volcano.

**Hydrofracturation:** Brittle failure of rock due to enhanced pore fluid pressures; a common phenomenon in overpressured strata of, for example, accretionary wedges.

**Liquefaction:** Process of rehydrating a partly compacted claystone or shale, in which the internal friction is zero as all stress is taken up by the fluid.

**Mélange:** Deformed mixture of usually clay-bearing lithologies, often found in tectonic fault zones and accretionary prisms.

**Mud breccia:** Type of sediment that is characterized by a clay mineral-rich matrix in which various amounts of (firmer) rock fragments and clasts (usually of the overburden rock through which the mud ascended) are embedded.

**Mud diapir:** Intrusive body of shale or clay that does not reach the surface.

**Mud lump:** Small mud volcano (a few meters in size and height).

**Mud mound:** Accumulation of mud debris, biogenic detritus, etc., that is usually cemented by carbonate precipitated by organisms. In contrast to mud diapirs or volcanoes, mud mounds do not necessarily involve the movement of a mud body and hence are excluded from this summary. Owing to the carbonate cementation, they

are often preserved over long periods of time (i.e., since the Precambrian).

**Mud pie:** Flat (slope angle  $<5^\circ$ ) mud extrusive feature (see Figure 2b).

**Mud pool:** Soupy mud accumulation in the *crater* (or, more generally speaking, central) area of a mud volcano or diatreme; a synonym is *tassik*.

**Mud pot:** Small mud mound.

**Mud ridge:** Elongated mud extrusive feature, supposedly related to faulting or folding.

**Mud volcano:** Surface expression of mud that originated from depth. Depending on the geometry of the conduit and the physical properties of the extrusiva, the feature may be a dome (cone; see Figure 2a) or a pie with low topographic relief.

**Olistolith:** Rock carried by an olistostrome.

**Olistostrome:** Deposit of a fluid-rich mudflow, often containing debris that was accumulated during emplacement.

**Overpressured:** Here, sediment with porosities higher than predicted from compaction law under a certain lithostatic pressure, i.e., undercompacted sediment.

**Parent bed:** Stratigraphic horizon that provides the bulk of material that ascends and extrudes; often undercompacted and rich in clay or fluids.

**Pingo:** Synonym for crater.

**Plasticity:** Difference between the water content of a material at its liquid and plastic limit, given in wt%  $H_2O$ .

**Pockmark:** Seafloor expression of high fluid discharge (venting) through a conduit, often resulting in a depression relative to the surrounding seafloor.

**Scaly fabrics:** Texture of clays and claystones having been dewatered and sheared, often with striations.

**Seepage:** See vent.

**Tassik:** See mud pool.

**Toe:** Frontal tip of an accretionary wedge.

**Vent:** Location (on the seafloor) at which fluids escape.

## APPENDIX A: GLOBAL MUD DOME OCCURRENCES

### A1. Aleutian/Alaskan Margin

[61] In the Copper River Basin in Alaska, mud volcanism has been reported to be associated with the occurrence of hot springs [Allen, 1887; Nichols and Yehle, 1961]. The MVs of the Klawasi group in the west and the Tolsona group in the east are triggered by different fluids. The Tolsona mud cones are made of mud with sand and pebbles of the underlying formations; the water has been related to connate waters expelled from Upper Cretaceous marine sediment [Grantz *et al.*, 1962]. Gas analyses show methane and nitrogen as the predominant phases. In contrast, the Klawasi MVs emanate largely  $CO_2$  and also have authigenic carbonate crusts and cements at their surfaces. The fluids are proposed to

be either volcanic or fossil interstitial waters of marine origin [Nichols and Yehle, 1961]. They are characterized by high salinities and enhanced contents of mobile elements and resemble oilfield brines. The clasts within the mud reflect unmetamorphosed source rocks of the Wrangell Mountains area [Grantz *et al.*, 1962]. Despite a series of geophysical surveys and bottom sampling, no evidence for offshore MVism has been found to date in the Aleutian subduction zone of the Alaskan forearc [e.g., Wallmann *et al.*, 1997]. This is particularly surprising because diffuse as well as conductive fluid expulsion with rapid flux rates have been demonstrated for the toe of the accretionary prism [von Huene *et al.*, 1998]. However, deep ocean mud diapirs have been inferred from seaward dipping thrusts through overpressured shale [Seely, 1977].

### A2. British Columbia

[62] The Mount Sullivan hydrothermal Cu/Zn/Pb deposit in southeastern British Columbia, Canada, has been proposed to have evolved from a mud volcano complex [Slack *et al.*, 1998]. Both pebble-bearing mud volcano deposits and massive sulfide bodies are interbedded with Mesoproterozoic clastic rocks and seem connected with the Kimberley fault. The preserved MV deposits have been traced by drill holes along a 5-km-long transect, showing an average thickness of 300–400 m. In cross section [Slack *et al.*, 1998, Figure 1] the conduits to the mud-clast breccias are often related to steep normal faults and contain sulfides, tourmalinites, pyrrhotite, and sedex-type Pb-Zn ores. Such ancient seafloor tourmalinites resemble modern analogues such as the hydrothermal mud volcano fields in the Black Sea area [Shnyukov *et al.*, 1986]. The model of MV evolution in a hydrothermal setting under anoxic conditions, as proposed by Slack *et al.* [1998, Figure 3], is discussed in section 3.3 (see also Figure 6d).

### A3. Cascadia Margin/Oregon, Washington

[63] Along the Oregon Margin, there is only weak evidence for MVism. Although fluid venting and gas hydrate processes are well documented, the seismically opaque mounts and ridges on seismic profiles were only initially interpreted as mud volcanoes [MacKay *et al.*, 1992]. A more detailed study, however, suggests that tectonic shortening causes the formation of plunging anticlines along which fluid venting and carbonate precipitation occurs [e.g., Suess *et al.*, 1999]. Reevaluation of seismic lines together with new swath bathymetry lead Trehu *et al.* [1999] to the hypothesis that three dome-shaped features on the flanks of Hydrate Ridge on the Cascadia accretionary prism, off Oregon, may be vent sites and MVs. Recent submersible evidence, however, identified at least one of the structures as a massive carbonate *chemoherm* [Brown *et al.*, 1999]. Evidence from three-dimensional seismic data across southern Hydrate ridge suggests that buried MVs exist (J. Chevallier, personal communication, 2002). The features



reach up to 3 km in width, show incoherent seismic signatures (compared to clear reflectors in their surrounding), and probably relate to enhanced fluid flow in the past.

[64] Onshore in the Hoh accretionary complex on the Olympic Peninsula, diapiric mélanges have been mapped and described by *Orange* [1990]. They represent the onshore continuation of the Cascadia accretionary prism off Washington, exhibiting rocks of Miocene age. The mélanges result both from shear movements and from diapiric ascent of mud breccia due to buoyancy [*Orange*, 1990, Figure 16]. Similar mud ridges of diapiric origin have been inferred from seismic images across the offshore portion of the Washington margin [*Silver*, 1972; *Barnard*, 1978]. However, only one active mud volcano, the Garfield gas mound, has been mapped adjacent to the onshore outcrop of the Duck Creek mélange zone [*Orange*, 1990]. The feature is <20 m high, is several tens of meters across, and is presently belching methane. Fluid is expelled as a result of burial and tectonic stress.

[65] A different type of mud deposit has recently been described by *Vallance and Scott* [1997]. The occurrence of mudflows from hydrothermal activity and, specifically, phreatomagmatic eruptions was reported from the western flank of Mount Rainier, Washington. A total of 3.8 km<sup>3</sup> of mud started as a water-saturated *avalanche* and covered some 200 km<sup>2</sup> in the Osceola region. One peculiarity of the mudflow deposit is the downstream decrease in clay, most likely resulting from incipient incorporation of surrounding altered rocks of sand and gravel size [*Vallance and Scott*, 1997].

#### A4. California/Nevada/Wyoming

[66] Other examples of thermal activity triggering MVism are the Lake City hot springs, northeastern California [*White*, 1955], and Yellowstone, Wyoming [*Pitt and Hutchinson*, 1982; *Sheppard et al.*, 1992]. The latter features emit gases of largely volcanic origin, which consist of CO<sub>2</sub>, N<sub>2</sub>, and generally <5% CH<sub>4</sub> [*Sheppard et al.*, 1992]. He isotopes indicate minor contributions of a mantle source. The mud volcano domain is a system of mud cauldrons, *fumaroles*, warm springs, and cold seeps and has previously been related to earthquake activity [*Pitt and Hutchinson*, 1982]. As a result, widened fracture networks at depth facilitate upward migration of hydrothermal fluids, which liquefy mudstones. Other small subaerial mud mounds (*mud pots*) in the Salton Sea area seem to be unrelated to the hot brines in the area [*Sturz et al.*, 1992].

[67] In Monterey Bay, offshore of California, abundant cold fluid seeps and mud volcanoes are connected with the transform fault separating the Pacific and North America Plates [*Orange et al.*, 1999]. Often, small (tens of meters across) mounds are covered with authigenic carbonate crusts, which originate from bacterial oxidation of the methane-rich fluids. Such mud volcanoes are circular to irregular surface expressions of diapiric mélanges, and the locally restricted fluid discharge and

cementation of mud and talus allows formation of durable topographic highs [*Orange et al.*, 1999, Figure 9]. Similar to accretionary wedges, fluid is augmented due to tectonic compaction between the San Gregorio fault zone, thus imparting overpressures and a buoyancy force in the sediment. A field of small MVs has also been observed in the nearby Santa Barbara Basin during acoustic imaging of the seafloor (P. Eichhubl, personal communication, 2001).

[68] The Diablo mountain range, Franciscan Belt, is one of the southern coast ranges in California where serpentine extrusions have been found [*Oakeshott*, 1968]. The serpentine represents an old marine layer, which got incorporated into subduction and orogenic processes. Low bulk densities made the serpentinized rocks a lubricant in thrusting and folding before some serpentine, which had been sheared into fold hinges, pierced the overlying strata. The extreme mobility of this mass allowed it to diapirically rise upward, with the erosion of some of its overburden aiding this movement. The upheaved domes reach diameters of ~8 km and are currently mined for short-fiber chrysotile asbestos [*Oakeshott*, 1968].

[69] A different scenario in which mud extrusion has been observed is Pyramid Lake, Nevada [*Miffin*, 1970]. Here sediment *mud lumps* result from the rapid progradation of sediment over undercompacted offshore muds in the lake. The proposed mechanism of intrusion is excess pore pressure relative to the lithostatic load of the overburden [*Miffin*, 1970] (see also sections 3.3 and 3.4).

#### A5. Mexico

[70] In Mexico the active El Cocuite mud volcano, near Veracruz, has been described by *Humphrey* [1963]. It is 25 m wide, ~6 m high, and of dome-shaped geometry. Its activity has been related to the viscosity of the mud that is mobilized from different stratigraphic levels within an anticlinal structure of kilometers-thick sediments. Its microfossil content and the presence of gas and heavier liquid hydrocarbons suggest an origin from Oligocene strata at several kilometers depth [*Humphrey*, 1963].

#### A6. Texas, Louisiana, and Mississippi/Gulf of Mexico

[71] A series of fossil mud volcanoes is preserved along an Oligocene-Miocene succession in south Texas [*Freeman*, 1968]. The circular hills are ~500 m across and up to 40 m high and cover some 110 km along strike. The source is very likely related to Eocene clayey tuff deposits of the Frio formation, which diapirically extrude along fault planes into the younger Gueydan sedimentary rocks at the surface. Because of igneous boulders of inferred greater depth related to the mud extrusions, *Freeman* [1968] inferred violent, gas-assisted eruptions and rise over enormous vertical distances. Also, individual blocks of up to 150 m<sup>3</sup> among the ejecta support a forceful mechanism. Shale diapirism has thinned and penetrated several hundred meters to form



the North LaWard diapir at the lower Texas Gulf Coast [Brooner, 1967]. No violent eruptions, venting, or tectonic relations are described, so that the phenomenon is attributed entirely to buoyancy of deep-water shales at depth.

[72] Offshore of Louisiana, oil slicks over the site of an active mud volcano were recorded from space [MacDonald et al., 1993]. The seepage generalized for the entire area is estimated to be on the order of  $20,000 \text{ m}^3 \text{ yr}^{-1}$ . In the immediate vicinity, one active and two dormant MVs have been identified on the upper continental slope [Neurauter and Roberts, 1994]. Small intermittent eruptions of gas- and oil-rich muds cause spillover and growth of the feature in the crater area as well as on its flanks. Authigenic carbonate crusts were observed on the dormant MV [Neurauter and Roberts, 1994]. One of the mounds, Bush Hill MV, has been subject to an earlier study [Neurauter and Bryant, 1990], which revealed an irregular cone-shaped geometry of up to 1000 m diameter and 40 m height. From seismic images, mud extrusion seems to be related to steep normal faulting.

[73] Literature spanning several decades has been published on mud mounds in the Mississippi delta, Texas Gulf Coast. The features are described as small anticlines in fine-grained, rapidly deposited sediments in the distributaries of the Mississippi River [e.g., Morgan, 1961; Morgan et al., 1968]. The island-type topographic highs have been related to diapiric ascent of overpressured clays, with vertical displacements on the order of 100–200 m. Cone-shaped mud vents are also known, some of which occur along fault lines [Morgan, 1961]. Prior and Coleman [1978] have shown that mudflows in the area occur at slope angles of as little as  $1^\circ$ , suggesting a very low viscosity of the mud (see section 3.4).

#### A7. Lake Michigan

[74] When Colman et al. [1992] studied the stratigraphy of deposits in southern Lake Michigan, a variety of features that disrupt the otherwise smooth, muddy surface of sediments were found. Next to circular depressions, which have been interpreted as pockmarks, a number of small slumps as well as low, irregular, subcircular mounds, possibly small mud volcanoes, were mapped. Their nature and origin remain unclear, although migrating gas may be the driving force for mud extrusion.

#### A8. Costa Rica

[75] MVs on the upper forearc off Costa Rica have been investigated during numerous geophysical surveys [Shipley et al., 1990; Stoffa et al., 1991; von Huene et al., 2000]. As has been shown recently by deep-sea drilling, the frontal wedge of the overriding plate is of nonaccretionary origin, so that the mud volcanoes on the sediment apron overlying the igneous forearc wedge either are dewatering products or relate to deep-seated faults [Kimura et al., 1997]. The mud domes are numerous,

generally cone-shaped, of less than 1 km diameter, and do not contain clasts of underlying strata (on the basis of the evidence from low backscatter on side-scan sonar maps [von Huene et al., 2000]). Pore water studies show signatures close to seawater [Zuleger et al., 1996], so that mixing of deep fluids, gas hydrate water, and pore water is inferred [Kopf et al., 2000a]. Recent bottom sampling attests that the MVs are massive carbonate-cemented highs, similar to the chemohierms in Cascadia (see section A3).

#### A9. Northern Colombia and Panama

[76] In northern Colombia the Sinu and San Jacinto fold belts form an accretionary wedge of sediment from the Caribbean Plate, which was scraped off by a rigid buttress comprising South American basement. On the 12-km-thick imbricated sequence, folding, sediment overpressuring, and abundant mud volcanism have been reported [Toto and Kellogg, 1992]. Mud extrusion is related to undercompaction of the thick sedimentary pile as well as to tectonic shortening. The most detailed information exists for the area between the Gulf of Uraba and northeastward to Cartagena, where shield-shaped MVs have been described by Gansser [1960]. They occur in several groups within Tertiary clay-rich folded strata, emitting methane and, rarely, oil. The most prominent features, the Turbaco group, comprise various domes of several tens of meters in diameter, with soupy muds flowing into the surrounding jungle.

[77] It has been suggested that the small El Totuma mud volcano farther east is genetically connected to the marine features. It reaches 12 m height, is located onshore, and appears to be dormant at present [Humphrey, 1963]. Apart from El Totuma, a large number of similar features are located along the Cordillera Occidental of northern Colombia. Most likely, the onshore features are older remnants of convergent tectonics, accretion, and accumulation of thick sedimentary successions along this margin. However, some activity of mud and methane bubbling has been reported in places [Humphrey, 1963].

[78] More recently, Vernet et al. [1992] reported mud diapirs off the Caribbean coast of Colombia in the Magdalena delta. The authors propose tectonic stress as well as undercompaction of the delta sediments to be the driving forces for extrusion. The features observed on seismic reflection profiles are up to 2.5 km in diameter and a few hundred meters high. Samples indicate the predominance of smectite and kaolinite. The 3.5-kHz profiling provided evidence for abundant gas seepage in the MV area. A total of 24 domes has been identified during this survey [Vernet et al., 1992, Figure 13].

[79] Offshore of north Panama, where the Caribbean Plate is subducted beneath Middle America, Reed et al. [1990] have reported the occurrence of more than 40 MVs. The features are between 0.4 and 2 km wide, <100 m high, and usually occur at the lower slope of a seaward vergent thrust belt. They pierce the crestal part of folded

ridges that have been accumulated from two depocenters with undercompacted sediments. Seismic evidence is provided for strong BSRs and thus for gas hydrate formation. A majority of the MVs are directly connected with fold and fault traces visible on the seafloor, both thrusts and strike-slip faults [Reed *et al.*, 1990, Figure 3]. Sediment overpressure as the main driving force for mud extrusion is facilitated by high sedimentation rates, tectonic shortening, and gas hydrate processes (see section 3 and Figure 6a).

#### A10. Ecuador

[80] A few occurrences of MVs have been reported by Sheppard [1937] in southwestern Ecuador, where Tertiary sediments and olistostromes dominate the complex geology. Although the rocks (i.e., olistoliths) carried with the mudflows are described in detail [e.g., Marchant and Black, 1960], no information regarding the depth of mud mobilization or mechanism of extrusion exists.

#### A11. Barbados

[81] An extensive literature exists on MVs onshore and offshore of Barbados, Lesser Antilles. The island of Barbados represents the apex and backstop of an extremely broad accretionary prism, comparable to the Mediterranean Ridge accretionary complex in many respects (see sections 4.1 and A22). Here sediment is scraped off the Atlantic Plate and accumulated to the imbricate wedge during subduction beneath the Caribbean Plate. Senn [1940] considered the olistostrome-like Joes River formation on the island as a product of sedimentary volcanism. While Kugler [1961] argued that these deposits result from slumping or mudflows from Paleocene parent beds, Speed and Larue [1982] more recently demonstrated that the Neogene uplift and Pleistocene arching of the island can be partly attributed to clay diapirism. The upwelled mass contains the mud debris flow suite, which is bounded by younger faulting in the north, and probably migrated upward as a rigid plug [Speed and Larue, 1982].

[82] Offshore of the island, MVs have been mapped on the toe of the accretionary prism during geophysical surveys [e.g., Stride *et al.*, 1982]. A number of early studies have examined the occurrence of mud volcanoes seaward of the Barbados accretionary prism [Brown and Westbrook, 1988; Langseth *et al.*, 1988; Henry *et al.*, 1990, 1996; Martin *et al.*, 1996], where their morphological variability is well exposed. More than 450 MVs have been observed on top of the southern part of the Barbados Ridge, where they cover an area of  $>700 \text{ km}^2$  [Brown and Westbrook, 1988]. The features are circular to oval, with edifice diameters ranging from 200 m to 6 km and with a height of up to 200–300 m above the surrounding seafloor. Many, but not all of the MVs show a rough surface owing to boulders and seem to be aligned to fault lineaments. Although no seismic data were available, an origin from diapirism at depth has

been inferred [Brown and Westbrook, 1988]. Regarding their size and distribution, the MVs are similar to a MV field farther south, that is, toward Trinidad [Masclé *et al.*, 1979]. More recent studies in the latter area relate fluid venting and MVism to the complex pattern of the surface traces of faults, folds, and networks of conjugate fractures [e.g., Gribouillard *et al.*, 1998]. Both argillokinetic diapirism and mud volcanoes are found [Gribouillard *et al.*, 1998, Figures 6 and 10]. The MVs are up to  $>6 \text{ km}$  wide, and their conduits are estimated to reach 2 km in diameter. The majority of the clayey diapiric material originates from Miocene beds [Faugères *et al.*, 1997]. The vertical migration of clays was partly initiated by tectonic deformation and was guided by major faults before it appears as ridges and cones on the seafloor [Faugères *et al.*, 1997].

[83] In MV fields off the deformation front (i.e., on the incoming Demerara abyssal plain), extensive geophysical and submersible studies revealed another mechanism for MVism [Henry *et al.*, 1996; Sumner and Westbrook, 2001]. Between  $13.5^\circ\text{N}$  and  $14.2^\circ\text{N}$  along the Mercurus fracture zone, the fluids involved in mud extrusion originate from clay dehydration at depth as well as from lateral flux [Martin *et al.*, 1996] and are transported beneath the décollement of the accretionary wedge by diffusive flow [Westbrook and Smith, 1983, Figure 5]. Recently, the reorganization of the fluid flow regime in the oceanic crust has been suggested to have allowed for outward migration of waters [Sumner and Westbrook, 2001]. Secondary processes triggering mud volcanism are gas hydrate dissociation or degradation of organic matter. In the small corridor mapped during the expedition, 23 mud features (domes and diatremes) have been observed. In these MVs, free methane flux triggers mud convection and ascent due to lowered density and viscosity [Henry *et al.*, 1996]. The amount of gas expelled from the biggest feature, Atalante diatreme, has been estimated from heat flow data. Gas flux ranges are on the order of  $1800\text{--}11,000 \text{ m}^3 \text{ d}^{-1}$  [Henry *et al.*, 1996], although this value does not seem representative for the average Barbados MV. On these MVs, benthic communities are sustained by massive methane-rich fluid expulsion [Olu *et al.*, 1997]. Chimneys and authigenic carbonate crusts are common, with salinity-driven fluid convection as main motor. On the basis of nannofossil occurrences, the oldest MVs were dated 750 ka or younger [Lance *et al.*, 1998]. Different stages of activity have been deduced from the submersible observations, reaching from collapse to growth by mud extrusion. Mud temperatures may be as high as  $21^\circ\text{C}$ . The geometry of the feeder has been related to the material sampled and to the physical properties of the mud. Postcruise analog modeling confirmed that plastic mud allows the retention of conical mounds, while soupy mud and wide conduits lead to pie-like MVs [Lance *et al.*, 1998]; see also section 5.

## A12. Venezuela and Trinidad

[84] The southwestward continuation of the deformation front of the Southern Barbados Ridge terminates in a system of thrust and strike-slip faults and, most prominently, in the El Pilar fault zone, a right-lateral wrench fault. The earliest studies of MVism date back to *Ferguson* [1823]. Numerous small MVs have later been described by *Gansser* [1960] and *Arnold et al.* [1960] and have been related to Neogene sediments. The mud is mobilized from marine clays of the diapiric mass in the Pedernales anticline, which collected various rocks of overlying strata during ascent. Apart from many small cones, there are a few big domes (e.g., the flat-topped, 100 m-high Morne Diablo), which consist of Oligo/Miocene oil-bearing clays [*Gansser*, 1960].

[85] Farther east, on the island of Trinidad, a similar setting is met, where faults separate the anticlines. MVs also occur offshore, and their description dates back to *Kugler* [1939]. Other key references, from which the following summary is collated, include *Kugler* [1953], *Gansser* [1960], *Higgins and Saunders* [1974], *Carr-Brown and Frampton* [1979], and *Yassir* [1989]. Among the 26 active and four fossil MVs described by *Higgins and Saunders* [1974], the majority are found in the Southern Range deposits. They relate to thick mid-Tertiary clay sequences, specifically, the Navira-, Karamat-, and lower Cruse-Lengua Formations, which are characterized by low  $p$  wave velocities hinting toward sediment overpressuring [*Yassir*, 1989]. In these lithologies, sedimentary and tectonic mélanges have been described [*Yassir*, 1989]. An early study by *Birchwood* [1965] estimated the depth of mud mobilization to be at least 3 km. The “mixed fauna clays” are of proposed diapiric origin and, according to wells onshore, originate from parent beds at depths between 1.2 and 1.8 km [*Higgins and Saunders*, 1974]. Onshore features can be divided into four types of MVs: (1) mud pools, ranging from a few tens of centimeters to hundreds of meters, forming shields or pies; (2) cones, reaching 60 m (Anglais Point) and more, with boulders of up to 42 m<sup>3</sup> of Eocene or Cretaceous blocks and flows >250 m long [*Higgins and Saunders*, 1974]; (3) big tassiks, extending over up to 175 × 110 m (Lagon Bouffe), with several conduits; and (4) fossil MVs, like Moruga Bouffe, which may reach over 1200 m in diameter and include more than 600 extinct individual cones [*Higgins and Saunders*, 1974]. The subsurface structure of many of the MVs is well constrained by commercial well information and often resembles a diapiric main body with interfingering patterns from ancient mudflows (similar to the models in Figures 6b and 6c). For detailed descriptions of the MVs, reference is made to *Higgins and Saunders* [1974], *Yassir* [1989], and *Dia et al.* [1999].

[86] Several historic reports of island formation due to mud volcanic extrusion exist from the Trinidad coast. Violent eruptions accompanied the rise of small islands off Chatham, Erin Bay, in 1911 [*Arnold and MacReady*, 1956], 1928 [*Weeks*, 1929], and 1964 [*Higgins and Saunders*, 1967]. Striated muds and absence of salt water

imply that the source beds had undergone considerable tectonic loading prior to extrusion. Fresh fluid, probably from clay mineral dehydration within the lower Cruse-Lengua clays, caused overpressures and explosive eruption [*Higgins and Saunders*, 1967]. The size of such islands varies between tens and hundreds of meters in diameter; their geometry is usually a flat shield or cone that rarely reaches more than 10 m above sea level. Given the tidal variation in the area, they are short-lived structures and suffer rapid erosion (8 months in case of the 1964 Chatham Island [*Higgins and Saunders*, 1967]).

[87] Recently, extensive studies on the physical properties of the Trinidad muds [*Yassir*, 1989] and the fluid history and origin [*Dia et al.*, 1999] were conducted. The muds generally have clay contents between 40 and 70%, corresponding to plasticity indices (i.e., range of Atterberg limits) of 15% and almost 80% [*Yassir*, 1989]. Shear strength is found to be a function of plasticity and clay content; weak, clay-rich muds also show the strongest pore pressure response [*Yassir*, 1989]. The fluid chemistry is indicative of two reservoirs separated by the major Los Bajos wrench fault. Chemical signatures inherited from high  $T$  (>150°C [*Dia et al.*, 1999]) water-rock interaction suggest mixing of deep-generated fluids with meteoric water. This influx is believed to recharge the expulsion system with fluid. The gas phase expelled with the mud is mostly methane, with minor contributions of CO<sub>2</sub> [*Dia et al.*, 1999].

## A13. Greenland and Northern Atlantic

[88] An arctic mud volcano, or pingo, situated in Svartenhuk, northwest Greenland, was subject to a phytoplankton study. The feature is apparently dormant, with a crater pond filled with meteoric water/ice [*Kristiansen et al.*, 1995].

[89] In the Norwegian-Greenland Sea, side-scan sonar mapping discovered several fields of pockmarks within soft, stratified silty clays [*Vogt et al.*, 1999]. Gas venting appears vigorous in places and has caused large-scale slope failure in the case of the Storegga slide. Tiny mounds (several to tens of meters across and only a few meters high) have also been observed [*Vogt et al.*, 1999]. On acoustic profiles these features show an opaque, patchy signature, possibly illustrating the gas-charged conduit. Both bulk sediment density and heat flow are low [*Vogt et al.*, 1999]. Some of the mounds can clearly be related to regional faulting.

[90] In the Porcupine Basin, northeastern Atlantic, along the eastern Irish continental margin, numerous MVs have been imaged during commercial [*Croker and O'Loughlin*, 1998] and scientific [*Henriet et al.*, 1998] seismic surveys. The features, termed mud mounds, are of small to moderate size (200–600 m wide and 40–60 m high) and pierce the well-stratified sediments, as evidenced by their characteristic opaque signature. Four provinces, the Magellan, Hovland, Belgica, and Connemara fields, consist of pockmarks, shallow gas traps, and more than 120 mounds within the sedimentary succes-



sion. Some of them are buried (and overlain by contourites), while others are domes of ejecta surrounded by a moat, the latter possibly from collapse after gas venting ceased. Here onlapping sediments allow dating of the MVs. Preservation of the features relies on abundant microbial activity precipitating methane to authigenic carbonate cements.

#### A14. Morocco

[91] Complex interactions between the Iberian and African Plates since the Triassic create a complex structural pattern between the Gulf of Cadiz, Alboran Sea, and adjacent Moroccan continental margin. *Gardner* [1999] described several seafloor structures to be gas hydrate related MVs. In the west of the study area, several sinuous ridges of proposed diapiric origin have been mapped and sampled, while farther east, at least six circular MVs and four more ridges have been sampled. Methane hydrates were recovered by gravity coring on one MV. The two biggest domes are 4 km across [*Gardner*, 1999].

#### A15. Spain

[92] Onshore MVism in Spain is known in the Cantabrian Mountains, where diapiric clays deform the overlying carbonates [*Stel*, 1976]. The driving force for the ascent of the Lower Emsian La Vid Shales is believed to be undercompaction and enhanced pore fluid pressures from mineral dehydration reactions [*Stel*, 1976].

[93] MV formation was also observed in fluvial mid-Pleistocene deposits of the southwest Madrid Basin, Spain [*Silva et al.*, 1997]. The features vary in size (decimeters to tens of meters) and appearance from small domes and wavy ridges to hummocky surfaces of ancient flood plains. Although their origin was related to sediment loading, mud extrusion may have been triggered by earthquake activity.

[94] In the NE Gulf of Cadiz at the Iberian Margin, N-S oriented diapiric ridges have been described by *Maldonado et al.* [1999]. They comprise early-middle Miocene blue marls and mud breccia and seem related to slope instability and tectonic movements of the deformed sediment wedge. Recent oceanographic cruises discovered a total of eight circular to oval-shaped mud volcanoes, which consist largely of gas-saturated breccias with a strong H<sub>2</sub>S smell and tube worm fauna [*Fernandez-Puga et al.*, 2002]. The domes show slope angles between 2° and 9° but locally reach up to 25°. The parent bed may be Eocene olistostrome deposits. Fluid and gas mobilization is related to convergent tectonics between Africa and Eurasia.

#### A16. North Sea, Barents Sea, and Baltic Sea

[95] In the North Sea several MV occurrences have been described in some detail. Among the most prominent features is Håkon Mosby mud volcano near the Norwegian-Barents-Svalbard continental margin [*Vogt et al.*, 1997]. The dome is one of two 1-km-wide features

next to each other, which supposedly results from fluid expulsion owing to gas hydrate processes and liquids trapped in mass wasting deposits. Heat flow data exceeding 1000 mW m<sup>-2</sup> are among the highest in ocean basins (excluding hotspots and plate boundaries), and active venting creates warm water plumes above the MV [*Eldholm et al.*, 1999]. A relatively limited biological community, dominated by tubeworms and demersal fish, exists on Håkon Mosby [*Milkov et al.*, 1999]. White mats on the seafloor are believed to represent both bacterial mats and massive gas hydrates, the latter being  $\sim 1.8\text{--}2.5 \times 10^6$  m<sup>3</sup> in volume [*Ginsburg et al.*, 1999].

[96] In the area of the Sleipner gas reservoirs [*Heggland*, 1997], buried mounds are believed to be mud volcanoes generated during mid-Miocene time. Their locations seem to be associated with minor faults and fractures. Their conduits, seismic chimneys, indicate migration of gas from below this level through the faults and fractures and up to the seabed. In addition to the seepage, shallow gas accumulations found recently in late Pliocene sands above the MVs may be a result of such gas migration.

[97] Three fields of what has been termed “seafloor piercing diapiric structures,” the Vema, Vigrid, and Vivian fields, exist on the marginal Vøring Plateau [*Hjelstuen et al.*, 1997]. These MVs rise 150 m above the surrounding seafloor and overlie well-stratified basin sequences. From seismic profiles and scientific drill holes, Eocene-Miocene biosiliceous oozes and muds have been identified as parent beds. The ooze mobilization started in late Pliocene and was induced by differential loading and bulk density contrasts within the succession [*Hjelstuen et al.*, 1997]. *Bouriaud et al.* [2000] have also reported geophysical evidence for MVism on the Vøring Plateau. A seal of massive gas hydrates allows enhanced fluid pressures at depth, with mud extruding when sliding creates zones of weakness in this barrier.

[98] The Crater field, located several hundred kilometers north of Norway in the Barents Sea, shows an accumulation of  $\sim 20$  seafloor depressions and occasional mounds [*Long et al.*, 1998]. The features reach only tens of meters in diameter and seem related to gas hydrate instability. In the subsurface the BSR is interrupted by a seismically opaque conduit to the feature. The proposed evolution relates to gas hydrate dissociation due to postglacial uplift. The pockmark-type depressions most likely reflect rapid gas dissipation, which is still ongoing, as evidenced by frequent dense colonization in the crater area (small hydrozoans, sponges, actinians, and soft cold water corals [*Long et al.*, 1998]).

[99] In the northern Stockholm Archipelago, Baltic Sea, small domes associated with gas seepage have been reported [*Söderberg and Flodén*, 1992]. The features are only 30 cm high and a few meters in diameter, which is mostly a function of the thin sedimentary cover ( $\sim 10$  m in thickness) on the shelf. The gas emanating along tectonic lineaments through the crystalline bedrock has



a thermogenic origin, indicating a deep trigger of sediment disturbance and mud extrusion.

#### A17. Alboran Sea

[100] In the western Alboran Sea, Mediterranean, diapiric ridges and, to a lesser extent, subcircular MVs are abundant phenomena in geophysical records [*Perez-Belzuz et al.*, 1997]. Although one would suspect that intrusion and extrusion result from extensional tectonics in the narrow rift basin, there is no straightforward pattern of the ridges relative to kinematic constraints. In fact, only a few ridges align with the southwest-northeast trend of the Alboran Ridge spreading axis, while many others are associated with north-south trending thrust or do not correspond to any known tectonic lineaments. The flat-topped nature of all features (sometimes the mud diapir does not pierce the seafloor sediments at all [*Perez-Belzuz et al.*, 1997, Figures 4b–4e]) suggests that ascent of parts of the Miocene shales at depth (some diapirs are Aquitanian-Langhian and others are Seravallian-Tortonian) has occurred some time ago. The MVs form small cones (~1 km across) and are fed by seismically well imaged, vertical conduits that root in upper Miocene sediments (upper Tortonian-Messinian [*Perez-Belzuz et al.*, 1997]). The parent bed depth has been inferred to be between 10 and 12 km from industry seismic records (A. C. Weinzapfel, personal communication, 2001).

#### A18. Western Alps and Apennines/Italy

[101] In the Maritime Alps and Northern Apennines, reports of olistostromes, chaotic facies rocks, and diapiric mélanges of the argille scagliose date back as far as the late nineteenth century [*Ferreti*, 1878]. More recent studies imply that the strata involved in MVism dates back as far as Upper Cretaceous [*Abbate et al.*, 1970]. These deposits are part of a prealpine accretionary wedge that was thrust beneath the Eurasian Plate during orogenesis [*Di Giulio*, 1992]. Because of undercompaction and flow of mud along detachment surfaces, mélanges and mud volcanoes formed [*Di Giulio*, 1992]. In the Apennine foredeep thrust belt, chemosynthetic communities of inferred Miocene age attest paleo-dewatering and seepage. In fact, detailed field analyses allow us to distinguish between periods of concentrated flow and diffuse background flux in the system (P. Vannucchi, personal communication, 2001).

[102] For most of the MVs in the western Alps, intense postdepositional deformation hinders the reliable reconstruction of the in situ geometry. However, in places, cemented conduits and gryphons were preserved. The authigenic carbonate cements together with analyses of boulders within the shales allow us to identify, for example, the Verrua MV near Monferrato, northwest Italy, as a former cold seep marine mud dome [*Cavagna et al.*, 1998]. Carbon and oxygen isotope geochemistry are in favor of gas hydrate processes having been involved in carbonate formation [*Cavagna et al.*, 1998].

The two best-known areas of MVism in the Apennines are near the villages of Regnato and Maranello. Either MV field is characterized by an area of several hundred meters squared, each containing numerous domes and mud pools of several meters in diameter. Mudflows may stretch over tens of meters downhill, with mostly methane bubbling in the craters and pools [*Martinelli*, 1999]. The diameter of inactive central conduits varies from 10 to 30 cm (A. Kopf, unpublished data, 2002). Several generations of mudflows with variable contents of mostly angular claystone and carbonate clasts of variable abundance overlie each other. While the mud of the Regnato region originates from Cretaceous strata, the mud domes near Maranello are fed by Miocene deposits at depth of the faulted belt.

[103] Certain MVs in the Po plain, in the southeastward prolongation of the ancient MV occurrences, have recently emitted gas and liquids during local seismic activity [*Martinelli and Ferrari*, 1991; *Martinelli et al.*, 1995]. More recently, *Conti et al.* [2000] concluded from their chemical data on fluids that brine-type compositions indicate deep-seated tectonic features allowing upward migration. The ejected material typically shows two different compositions. Normally, the emissions show thermal reequilibration with the surrounding rock in the faulted Apennine mountains. However, during less frequent violent eruptions, when explosions of mud, brackish waters, petroleum, and gas occur, chemically anomalous waters and gases have been found [*Martinelli and Ferrari*, 1991]. In the eastern part of the Po plain, these researchers find active fluid and gas venting a useful precursor for earthquakes, with the water increasing in temperature relative to background values. In the less active western part, cemented chimneys document former MV activity [*Martinelli and Ferrari*, 1991].

#### A19. Sicily

[104] MVs in the vicinity of Paterno at the base of Mount Etna volcano, Sicily, were described already by *von Gumbel* [1879] and *Deeke* [1897]. Recent investigations of three MVs at the southwest flank of Mount Etna, at the contact between the volcanics and overlapping sediments, have reported discharge of cold brines as well as large quantities of CO<sub>2</sub> [*Chiodini et al.*, 1996]. The composition of the gas and liquid phases hints toward a hydrothermal reservoir at 100°–150°C, which can be explained by groundwaters from the central part of Etna feeding the MVs through lateral flux. Farther west, three active MV areas have been recently investigated by *Etioppe et al.* [2002]. The biggest field, Maccalube near Atagona, spreads over 1.4 km<sup>2</sup> and has numerous small domes of less than 1 m height. Salty waters as well as gas are discharged at considerable rates (see section 5).

#### A20. Adriatic Sea and Greece

[105] Gas seepage and possible MV occurrences have been reported from the Adriatic Sea, east of Italy. Seismic reflection data are characterized by abundant highly

reflective patches, which have been interpreted as gas-charged diapiric structures [Hovland and Curzi, 1989]. Often, they show updoming of the seafloor, forming small domes of several tens of meters up to  $\sim 300$  m in diameter [Hovland and Curzi, 1989, Figure 4]. The features are only a few meters higher than the surrounding seafloor and have not been sampled. However, “acoustic fountains” of gas seeping out of the seafloor indicate active fluid escape.

[106] One MV example is known from the Katakolo Peninsula, western Peloponnesus, Greece [Stamatakis *et al.*, 1987]. The small dome has a conduit of 30 cm diameter that emits hydrogen sulfide and gaseous hydrocarbons. On the walls of the conduit as well as in the crestal area, native S, halotrichite, gypsum, and other sulfide minerals are found. While most of the peninsula’s geology is dominated by clay stones, marlstones, and other sediments of Pliocene age, Triassic anhydrites from depth are believed to intrude as diapirs before piercing the Pliocene cover [Stamatakis *et al.*, 1987]. Similar structures of updoming and MVism have been observed offshore (northwest of the peninsula) in the Ionian Sea. Papatheodorou *et al.* [1993] mapped active gas seeps, MVs of a few meters in height, and pockmark-type depressions on the seafloor near the westernmost prolongation of the Hellenic Arc.

#### A21. Aegean Sea

[107] The Aegean Sea is surrounded by mainland Greece and is the fast-spreading back arc basin to the eastern Mediterranean Sea (see Figure 7, inset). Gas-charged sediments, pockmarks, and small MVs and ridges were identified during high-resolution geophysical profiling on the Sporades Shelf [Papatheodorou *et al.*, 1993]. MVism is fed by Quaternary fine-grained deltaic deposits of two river systems. The sediment’s overpressure triggers normal faulting and gas seepage. Mud volcanic ridges (100 m in length [Papatheodorou *et al.*, 1993, Figure 8]) evolve along the seafloor outcrops of such faults.

#### A22. Eastern Mediterranean Sea

[108] As already mentioned in sections 3 and 4, the eastern Mediterranean Sea (Figure 7) is arguably the region with the highest abundance of MVs and diapirs on Earth. Several hundred features of variable age, geometry, and origin have been discovered during the previous 2 decades of geophysical surveys. Thereafter, a wealth of data and samples have been collected by coring, deep drilling, and submersible studies, so that the region of convergence between Africa and Eurasia is well understood.

[109] The Mediterranean Ridge accretionary complex (MedRidge) is an arcuate structure of  $>1500$  km length and up to 250 km width [Fusi and Kenyon, 1996], which is suffering incipient tectonic deformation and uplift. Accretion has started as a result of the exhumation of thrust nappes on Crete after subduction of the Pindos

Ocean [Thomson *et al.*, 1998]. Crete, as an outer arc high, acted as a backstop to offscraping Neotethyan sediments and presently represents the northern border at the apex of the accretionary prism (Figures 7 and 8). Although northeastward subduction of the African Plate is relatively slow ( $1\text{--}2$  mm yr $^{-1}$ ), half the Aegean spreading rate in the back arc sums up to a net rate of  $\sim 5\text{--}6$  mm yr $^{-1}$  [Le Pichon *et al.*, 1995]. Morphologically, there are two distinct areas forming the accretionary prism: the actual thrust wedge and the so-called Inner Ridge, which is believed to represent the paleo-MedRidge and which presently acts as a backstop to the modern wedge [Kopf *et al.*, 2000b]. In the western part of the MedRidge, subduction of the Ionian abyssal sediment occurs orthogonally to the grain of the prism, while east of Crete the Herodotus abyssal plain is obliquely thrust beneath the accretionary complex. This bears consequences for the geometry of the prism’s and forearc’s morphological elements and has tectonic repercussions regarding the nature of mud extrusions on the wedge. While dome-shaped, small MVs dominate the western and central branch of the MedRidge, the prism southeast of Crete is covered by mud pies of up to several tens of kilometers in diameter [Masclé *et al.*, 1999]. When following the MedRidge to its easternmost prolongation, right where the Hellenic Trench system joins the Cyprean Arc, cone-shaped MVs are found again in the Anaximander Mountains and Florence Rise areas [Woodside *et al.*, 1998; Aloisi *et al.*, 2000a, 2000b]. The first to discover MVism on the MedRidge were Cita *et al.* [1981] in one of the densest MV fields south of Crete, the Olimpi region (Figure 7). Gravity coring of some of the domes recovered a potpourri of polymictic clasts in a clayey matrix, termed mud breccia [Cita *et al.*, 1981]. Later on, the difference in geometry between the settings on the MedRidge was related to the nature of the tectonic features that they are associated with, which operate as conduits. While the domes in the western and central part of the prism relate to reverse and back thrust faulting (Figure 8b), the mud pies correspond with extensional or transtensional forces when oblique subduction takes place [Kopf *et al.*, 2001]. Hence, in the first case, mud breccia domes result from mud and fault breccia having been mixed during upward migration and emplacement [Kopf *et al.*, 1998]. By contrast, pull-apart forces allow overpressured mud to extrude, so that (according to low backscatter intensities [Volgin and Woodside, 1996]) clast-free pies form over wide areas (Figure 7). This is in good agreement with results from analogue modeling of MV geometry as a function of material properties and width of the conduit (see Lance *et al.* [1998] and section 4). In the Anaximander Mountains in the northeast Mediterranean, MVism is related to strike-slip faulting and gas hydrate processes [Woodside *et al.*, 1998]. Domes of generally hundreds of meters width carry rock fragments from the regional framework (mostly known from mainland Turkey) with them. Toward Cyprus on the Florence Rise, MVism is less pro-

nounced and may result from thrusting and shortening that causes the offscraped Herodotus Basin sediments to expel their pore fluids.

[110] It has been widely accepted that the main driving force of MVism in the area is generally related to incipient compression [Camerlenghi *et al.*, 1992, 1995]; however, a variety of hypotheses have been put forward concerning the nature and origin of the muds and fluids. As the variety of methods in MV research used to characterize the origin of the gaseous, liquid, and solid phases are described in section 4, only the key aspects are briefly stated here.

[111] One of the biggest steps forward in MV investigation was drilling two transects of deep holes into submarine MVs south of Crete [Robertson *et al.*, 1996]. The main findings from the cores recovered included their long-lived, though episodic nature (>1-Myr-old mudflows intercalated with hemipelagics) and their eruptive (rather than diapiric) origin. The mud breccia shows variable lithologies and ages of clasts in a clayey matrix, some of which can be biostratigraphically dated back to the Cretaceous [Staffini *et al.*, 1993]. However, some concerns have risen that reworking of accreted strata, or even accretion of reworked material, may have led to such estimates, because several arguments hint toward a Messinian age of the mud matrix (see review given by Kopf *et al.* [2000b]). Indirect evidence is provided by brine pools on the MedRidge [Westbrook *et al.*, 1995], saline pore waters on some MVs [DeLange and Brumsack, 1998], characteristic vent organisms [Corselli and Basso, 1996], and physical properties of Messinian muds drilled elsewhere [Kastens *et al.*, 1987]. Also, the difficulty of having to explain noncompaction of fine-grained sediments since Cretaceous time would not arise when the mud was deposited only 5 Myr ago. In fact, if evaporites were precipitated above the mud, this seal may have trapped pore fluids until recent extrusion [Zabanbark *et al.*, 1998].

[112] Apart from brines, freshened pore waters as well as hydrogen sulfide, methane, and traces of higher hydrocarbon gases emanate from some of the MedRidge MVs [e.g., DeLange and Brumsack, 1998; Robertson *et al.*, 1996]. Although it had been proposed that diluted pore waters relate to gas hydrate dissociation [DeLange and Brumsack, 1998], the lack of BSRs, the relatively high temperatures of Mediterranean bottom waters, and the amount of water discharge through MVism in the area (see sections 4 and 5) make this hypothesis an unlikely one. Other sources of fresh water, like mineral dehydration reactions due to stress, seem a more likely explanation in a scenario with deep-seated faults near the apex of an intensely deformed prism [Kopf *et al.*, 2001]. Massive gas hydrates, however, have been sampled in the Anaximander Mountains at deep-water MVs [Woodside *et al.*, 1998]. Gas hydrate occurrence at the edge of its stability field may explain large slides (a single event of 550 km<sup>3</sup> [Woodside *et al.*, 1998]) and abundant

gas vents and could act as trigger mechanism for MV evolution.

[113] Within this overview of worldwide MV distribution, no more detailed descriptions can be given about MVism in the eastern Mediterranean. However, because the MedRidge is an example of a large accretionary complex undergoing intense deformation and dewatering (and is arguably the region with the largest number of submarine MVs on Earth), certain aspects of mud extrusion have been highlighted in earlier sections. They include mechanism and rates of extrusion, physical properties of the phases involved (both covered in section 4), and quantitative estimates of mass transfer owing to MVism (section 5).

### A23. Roumania

[114] Many dozens of MVs occur along the easternmost units of the Carpathians where the mountain chain abuts the thick Neogene sediments to the east. The description of the domes by an engineer in 1924 [Higgins and Saunders, 1974] mentions huge blocks weighing several tons scattered among the mudflows, the latter of which originate from Miocene parent beds. The fault trace along which the sediment is thrust over the Carpathian orogenic wedge is shown in Figure 10a (upper left).

### A24. Tanzania/East Africa

[115] Mud volcanoes near the coast of Moa, south of Mombasa, have been reported by Richard [1945]. Mud extrusion and gas discharge seem to be connected to regional tectonics (i.e., along a fault separating the Mesozoic Karroo series from younger units), but are unrelated to the enhanced dewatering of deltaic deposits in the Pemba Channel.

### A25. Black Sea/Crimea and Kerch Peninsulas (Ukraine)

[116] Extensive literature exists describing MVism on the Crimea Peninsula bordering the north Black Sea [Kulschin, 1845; Ansted, 1866; Borisyak, 1907]. At its southeastern tip, Crimea extends into the Kerch Peninsula between the Sea of Azov and the Black Sea (Figure 10a). Here MVs and their relationship to petroleum fields in the area were the subjects of early investigations [e.g., Ansted, 1866; Morosevitch, 1888]. Recent reconnaissance studies distinguished between episodically active, violent MVs (up to 400-m-long mudflows from 60-m-high crests) and continuously bubbling mud pools and pies [Akhmetjanov *et al.*, 1996].

[117] Recently, numerous studies were directed to examine submarine mud volcanoes in the Black Sea [Limmonov *et al.*, 1994, 1995, 1997]. Nine large MVs are found adjacent to the west Crimea fault, which divides the western and eastern Black Sea basins (Figure 10a). While rifting in the western part lasted until the Miocene, the eastward part rotated, resulting in compression along the Greater Caucasus (see section A26). MVism



at the junction of the two basins was facilitated by transtensional tectonic forces, while gas hydrate processes act as a trigger (although found in only some of the domes [Limonov *et al.*, 1997]). Apart from massive gas hydrates, bacterial mats indicative of gas hydrates and authigenic carbonate crusts of oxidized methane from gas hydrate dissociation were sampled in the Sorokin Trough, south of Crimea [Ivanov *et al.*, 1998]. The methane is of proposed thermogenic origin. The features can be divided into midsize (2.5 km across, 100–150 m height above the surrounding seafloor) domes with collapsed crater-type conduits and smaller, actively venting domes of presumed younger age. Multiple overlapping mudflows of >1 km in length as well as pockmarks have been identified on high-resolution sonographs. Seismic data suggest the conduits to be as wide as 1.5–3.5 km (at depth), extending to 7–9 km depth into the 13–14 km of Tertiary and Quaternary sediments [Limonov *et al.*, 1997]. Apart from the features on the seafloor, seven buried MVs have been identified during seismic surveys [Meisner *et al.*, 1996]. MVism is related to the 5-km-thick Maykopian shales of Miocene age.

[118] Geochemistry indicates high hydrocarbon and CO<sub>2</sub> fluxes and odd fluid signatures. Both chlorine and boron contents in the pore fluids (the latter up to 915 ppm B [Lagunova, 1976]) give evidence of hydrothermal interaction at depth. Muds contain fragments of the overlying succession, but also contain authigenic sulfates such as barite and anhydrite [Shnyukov *et al.*, 1986]. On the basis of the geochemical signatures, Slack *et al.* [1998] proposed a model in which hydrothermal mud volcanism causes tourmaline alteration and “black-smoker”-type deposits when hot metal-bearing brines are expelled in an anoxic environment (Figure 6d). Such deposits would be strikingly similar to Pb-Zn tourmalinite deposits, like the Sullivan ore body [Slack *et al.*, 1998] (see also section A2). In oxic environments, volatile-bearing geothermal waters would produce borate minerals due to lower temperature and alkaline pH [Palmer, 1991]. In other areas (i.e., the Fedosia region), mud volcanoes with active gas vents have been observed. Some features exceed 1 km in diameter and are related to gas hydrate processes [Soloviev and Ginsburg, 1994]. The released methane shows characteristic  $\delta^{13}\text{C}$  ratios of biogenic origin, which coincides with results from the Taman Peninsula [Soloviev and Ginsburg, 1994] (see section A26).

## A26. Caucasus (Taman Peninsula, Georgia, and Azerbaijan)

[119] The Greater Caucasus is the eastward prolongation of the Taman Peninsula all the way through Georgia and Azerbaijan to the western border of the Caspian Sea (Figures 10a and 10b). MVism has long been recognized in the area, and detailed reports are given on violent eruptions accompanied by gas dissipation (e.g., Abriutski [1853] during that very year). It was noted that earthquake activity preceded such eruptions [Abich, 1865,

1869] and that there is a clear relationship between petroleum and MVism [e.g., Redwood, 1913a; Jakubov *et al.*, 1971]. The most comprehensive studies on MVs in the Caucasus area have been conducted by Jakubov *et al.* [1971] and Lavrushin *et al.* [1996], and a summary has been provided by Jevanshir [2002].

[120] In a first systematic study on the Taman Peninsula, 35 prominent MVs have been located along the saddle of anticlines in the Greater Caucasus [Shardanov and Znamenskiy, 1965] (e.g., see Dashgil MV in Figure 10c). The Maykop Formation wildflysch deposits, possibly a chaotic reminiscent of submarine postdepositional slumping, are the presumed parent bed to the domes [Lavrushin *et al.*, 1996]. However, some authors argue that the presence of Cretaceous boulders within the MV deposits indicate a Cretaceous origin of the parent bed [Jakubov *et al.*, 1971]. These undercompacted sediments were squeezed out at the crests of the folds when the Neogene sequence suffered deformation, with variable intensity of activity of the more than 30 features [e.g., Basov and Meisner, 1996]. Previously, vigorous eruptions had caused circular rims and deep craters of blocky mud breccia [Basov and Meisner, 1996], while during the most recent past, gas bubbling of fluid-saturated muds and mud breccias has been reported. Chemical instability of the fluids suggests either mobilization from different reservoirs or in situ alteration owing to the inhomogeneous parent beds [Lavrushin *et al.*, 1996; Rudakov *et al.*, 1998].

[121] Farther southeast of the Taman Peninsula, MVism remains a common phenomenon in Georgia, with early descriptions dating back more than a century (e.g., Melikov [1896] on Achtala MVs near Tiflis). Also, a dozen MVs have been reported farther east, near the border with Azerbaijan [Lavrushin *et al.*, 1996]. Chemical analyses of gas, pore waters, and muds from the domes point to a mobilization from 3 to 5 km depth. Only occasionally, low  $\delta^{13}\text{C}_{\text{CH}_4}$  and  $\delta^{11}\text{B}$  signatures favor fluid reservoirs as deep as 8–10 km [Lavrushin *et al.*, 1996; Deyhle, 2000] (see also Figure 10). The mud and embedded rock fragments predominantly originate from the Maykop Formation, which is found at a depth of 2.5–6 km in the area.

[122] Still farther southeast, Azerbaijan is probably the area with the world’s densest onshore MV population. The pioneers of MVism already noted activity over considerable periods of time and described some of the features in greater detail [e.g., Abich, 1863]. A major eruption occurred at Lok Botan, Aspheron Peninsula, in January 1887 [Sjogren, 1887], which was apparently related to an almost 2-year-long phase of violent eruptions from 1885 to 1887 [Sjogren, 1888]. In follow-on studies [e.g., Goubkin, 1934] the MVs were described as steep, up to 500-m-high cones made of mud with clasts (3–8 vol %). What was then termed “intensely crumpled plastic mud” most likely refers to scaly fabrics and mélange formation during intrusion and emplacement. In a major effort a total of more than 200 domes have been de-



scribed in much detail by *Jakubov et al.* [1971]. The size of the MVs is variable (up to 600 m height and 10 km<sup>2</sup> area; see Figure 10c) and so are the occurrence of gryphons (~20), salses (30–75 m across), sinter mounds (aligned near the crest), and the ejection of oil or water or the emission of gas. Although most of the work is purely descriptive and lacks some comparison with similar phenomena in other areas on Earth, valuable information can be extracted. Many of the more impressive MVs have been proposed to be younger; conversely, areas with neighboring small domes are believed to be a product of incipient erosion. One of the most prominent features, Dashgil MV (Figure 10c), is known to have been active every 6 to 32 years in historic time. At present, it has been tentatively estimated to release  $\sim 15 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$  of radiative gases into the atmosphere [*Jakubov et al.*, 1971]. A more recent evaluation of gas flux conservatively suggests an annual emission of 800 m<sup>3</sup> (predominantly methane) during quiescent intervals [*Hovland et al.*, 1997]. Similar to Taman and Georgia, the material having formed the bulk of the dome is assumed to be of the Oligocene/Miocene Maykop Formation (and, specifically, the wildflysch deposits therein [*Higgins and Saunders*, 1974]). The clayey matrix comprises polymictic clasts, from within both the Maykop Formation and the overlying country rock. From historical records and by studying 220 MVs, *Bagirov et al.* [1996a] compiled an impressive database. They show that over the past 100 years, four new MVs evolved, which are only small in size and are no hazard to mankind. Among these MVs, three to five eruptions per year occur on average [*Jevanshir*, 2002]. Next to the establishment of previously acquired data on gas composition, mud breccia, and geometry, estimates are given for gas emission during a (presently very unlikely) violent eruption. The amount of  $6 \times 10^8 \text{ m}^3$  equals 750 kyr of quiescent background flux [*Bagirov et al.*, 1996a]. During eruptions, self-ignition of the methane (CO<sub>2</sub>, H<sub>2</sub>S, and higher hydrocarbons contribute little to the overall gas discharge) can cause >100-m-high flames. The reader is referred to the wealth of statistical estimates that *Bagirov et al.* [1996a] put forward for likelihood of MV-related phenomena in the area.

#### A27. Caspian Sea

[123] The entire Caspian region has long been known to be rich in MVs (see section A26 on Azerbaijan). Marine MVs may have been an equally common phenomenon, but investigators had to await the development of geophysical acquisition techniques. On occasion, however, submarine MV eruptions were so powerful that such small islands appeared above sea level [*Schweder*, 1893]. As in Azerbaijan, flame eruptions are known offshore, which may cause heating hazards when occurring too close to shore (or near an oil exploration site [*Bagirov and Lerche*, 1998]). Offshore MVism, especially in the Chirag area, has been investigated by *Bagirov et al.* [1996a, 1996b], who suggest that MV ac-

tivity is very low at present and may be connected to local earthquakes. On the other hand, gas hydrate processes are connected with MVism [*Soloviev and Ginsburg*, 1994], possibly acting as a separate trigger. More than 60 MVs floor the southwestern Caspian Sea [*Soloviev and Ginsburg*, 1994, Figure 4]. Mud breccias sampled at two of those MVs, Buzdag and Elm domes, contained up to 35 vol % massive gas hydrate. Given that massive gas hydrate is less dense than water, such large volumes have a profound impact on the buoyancy of the bulk mud and on its behavior during ascent [*Soloviev and Ginsburg*, 1994].

#### A28. Turkmenistan and Iran

[124] Active degassing and variable gas composition in MVs of southwest Turkmenistan have also been related to local tectonic activity [e.g., *Voitov et al.*, 1991]. The ten features described border the western coast along the Caspian Sea and are generally domes of a few hundred meters width and tens of meters in height (for location, see *Lavrushin et al.* [1996, Figure 1d]). Gases emanating from these domes are reported to have distinct thermogenic  $\delta^{13}\text{C}_{\text{CH}_4}$  signatures; their He isotope ratios suggest minor contribution of mantle gas, possibly owing to deep faulting during the Caucasian orogenesis [*Lavrushin et al.*, 1996].

[125] *Gansser* [1960] discusses the Gorgan Steppes, a series of wide MVs with caldera-type craters owing to subsidence and internal collapse after the main extrusion event, having created the 6-m high crater rim. The relationship to the regional geology is poorly known, but the fluidized, oil-bearing nature of the mud hints of a deep origin. Cone-shaped domes (like Napag MV, Belutchistan, Iran) of up to 20 m height and ~80 m across have also been found [*Gansser*, 1960, Figure 11]. Abundant MVs have been reported in an early study by *Stiffe* [1874] as being located along the Persian Gulf coast of Iran. Diapirism in the area has also been mentioned by *Heim* [1958]. Domes are usually cone shaped (40° flanks) and of heights of meter to decimeter scale. Formation of the MVs was apparently unrelated to the convergent tectonics having created the Makran Arc farther east (see section A29). Recent reevaluation of the colored mélanges shows that these chaotic rocks pierced through the gently folded Neogene pelagic and flysch cover, forming randomly distributed, isolated domes [*Stöcklin*, 1990]. The clasts and blocks within the shaly matrix are proposed to be derived entirely from deeper levels, with no gravitational gliding (olistostromes) involved.

#### A29. Makran and Pakistan

[126] An early survey following the entire coast from the Persian Gulf to Karachi, Pakistan, over hundreds of kilometers revealed abundant MVs [*Stiffe*, 1874]. On an expedition through Pakistan, *Hart* [1840] described the Chandragup MV as a 100-m-high dome with two craters of >10 m diameter. *Snead* [1964] compiled systematic differences between the MVs close to the coast com-

pared with those farther inland in the Hala and Haro mountains. While the first are usually cones, the latter are ridges of up to 30 km along strike, with mudflows extending over several kilometers in length along their flanks. The gray-blue extrusive clays carry angular clasts and fragments (up to 1 m across) of the rocks overlying the Miocene parent beds. Both the sediment and tectonic loading were discussed as driving forces, with water and gas acting as a lubricant for upward migration [Snead, 1964]. More recently, some of the features were studied in greater detail, like the Chandragup or Jebel-u-Garab [Delisle *et al.*, 2002]. Mud discharge varied between 0 and  $1.4 \text{ m}^3 \text{ h}^{-1}$ , while gas emission ranged from negligible amounts to  $1 \text{ m}^3 \text{ s}^{-1}$  [Delisle *et al.*, 2002]. The activity of some Makran MVs was correlated with earthquakes in the area [e.g., Skrine, 1936; Harrison, 1944]. In fact, after a major earthquake (Ms 8.25) on the Makran coast in November 1945, island formation resulting from mud ejection was reported some hundreds of meters off the coast [Sondhi, 1947]. Similarly, Malan Island formed in March 1999 as a result of a vigorous extrusion of  $160,000 \text{ m}^3$  of soft mud [Delisle *et al.*, 2002]. Although not triggered by seismicity, overpressured mud and gas ascended some 2–3 km from folded Pliocene/Pleistocene sediments (Hjinglaj Formation). The island reached only  $100 \text{ m}^2$  in size and was destroyed by tidal activity during the monsoon season in November 1999 [Delisle *et al.*, 2002].

[127] During recent cruises in the Arabian Sea along the Makran convergent margin, a number of small MVs ( $>1 \text{ km}$  in diameter) were found during seismic profiling [White and Loudon, 1982; Wiedicke *et al.*, 2001] and bathymetric mapping [Flueh *et al.*, 1997]. Some of these features are only tens of meters high and are characterized by gas plumes in the overlying water column. Their occurrence offshore as well as onshore is closely related to the location of thrust and strike-slip faults [Flueh *et al.*, 1997]. Fluid venting and authigenic carbonate precipitation accompanies MVism [von Rad *et al.*, 2000]. Apart from seven of the small domes, recent 4-kHz sediment echo sounding has identified two larger mud domes adjacent to the deformation front of the Makran accretionary complex [Wiedicke *et al.*, 2001]. They reach 1.5–2 km in diameter and heights of 36–65 m. Sediments from the MVs are methane charged ( $\sim 40 \text{ ppm}$ ), which explains the seismically transparent root of the structures. Pore fluids from the features reveal enrichment of volatile elements (e.g., boron) relative to seawater (Figure 9). One buried mound, similar to the seafloor piercements, has also been identified [Wiedicke *et al.*, 2001]. This led the researchers to suggest tectonically induced fluid expulsion as being the driving force for these features seaward of the décollement (in analogy to Barbados; see section A11 and Henry *et al.* [1996]).

[128] Within the Indus fan sediments on Murray Ridge, Gulf of Oman, MVs occur as piercement features and as buried domes almost regularly spaced [Collier and White, 1990]. The features originate from a seismically

opaque parent layer at  $\sim 500 \text{ m}$  depth below the seafloor and apparently rise at low to moderate rates. Although methane is known in the area (and could account for the bright patches on seismic profiles), no vigorous eruptions or disrupted chaotic strata have been observed [Collier and White, 1990]. Hence rapid sedimentation and fluid overpressure are believed to control diapirism.

### A30. India

[129] MVism is long known from the Arakan coast of India and Burma [e.g., Mallet, 1878, 1879, 1880, 1881, 1885, 1907]. Frequent mud eruptions forming domes as well as shield-shaped islands have occurred in historic time, for example, in 1843, 1879, and 1907. Among the explanations of activity, both gas expansion [Mallet, 1880] and the influx of large amounts of meteoric water during the monsoon season [Mallet, 1885] have been suggested. On Baratang Island, Andaman, an area of  $\sim 40 \text{ km}^2$ , is peppered with MVs in the South of the island around Wafer's Creek [Poddar, 1954]. MV ejecta contain microfossils of Cretaceous and mid-Eocene age that hint toward parent beds of considerable age and depth [e.g., Badve *et al.*, 1984; Ling *et al.*, 1995]. In the Jarawa Creek MV deposits on Baratang Island, Achyuthan and Eastoe [1999] found volcanic glass, brines, and sulfide nodules in addition to the dominant illite and kaolinite. Methane is the dominant gas emitted. Sulfur isotope composition of the mud, brines, and nodules also indicates large influx of groundwater into the system [Achyuthan and Eastoe, 1999]. Tassik areas are up to 50 m wide, with pebbles of several centimeters floating in them [Poddar, 1954]. Domes are generally less than 10 m wide, have dried and fresh mudflows, and are aligned to fault traces [Poddar, 1954]. Eruptive activity is linked to local earthquakes [Jhingran, 1953].

[130] Banks of extruding terrigenous mud have been reported from the coast near Kerala in southwest India [Nair, 1976]. Their shallow water occurrence (only tens of meters) has been related to oxygen-deficient waters and gases from degradation of abundant organic matter in the fine silts. The banks are  $\sim 4 \text{ km}$  long, parallel the coastline, and consist of porous (60–80%) mud with clay contents between 45 and 90%. Active extrusion of soapy blue muds as well as gas bubbling has been reported from the nineteenth century and apparently caused fish to die in these coastal waters [Bristow, 1938].

### A31. Burma

[131] Apart from the descriptions in the nineteenth century (see section A30), Pascoe [1912] describes two MV areas along the eastern and western borders of Yarakon Yoma. Along the Burmese coast the discovered features vary between a few to almost 50 m in height, while the eastern MVs are smaller ( $<30 \text{ m}$  high). Both types are cone shaped, and in the west, violent eruptions with mud breccias containing angular clasts are more frequent. Over a distance of almost 1000 km, being sourced by a trough filled with thick Miocene/

Pliocene sediments of the Pegu Series, occasional MVs occur. However, the parent bed may be located somewhere in the Oligocene deposits. Estimates of the pipes and veins acting as conduits range around 1.5 m [Pascoe, 1912], which Dudley Stamp [1934] related to tectonic fracturing along a fault scarp.

### A32. Java and Sumatra

[132] Goad [1816] describes one flat dome on Java on the plains of Grobogan, where mud is ejected in the center of the crest. From the description, it appears as if both brines and gas were set free with the mud. The eruptive products of a MV near Poerwodadi have been studied by Ehrenberg [1855]. Hofer [1909] revisited the same and some other MVs near Poerwodadi and Semarang, as well as on Madura island, and related ejection of fluidized mud to the occurrence of hot springs.

[133] In Sumatra, mud breccias with large boulders have been mentioned north of Langsa [Blumer, 1922]. Regarding both Java and Sumatra, the information given relies on the earlier MV compilation by Higgins and Saunders [1974].

### A33. Brunei/Borneo and Sabah

[134] On and around Borneo, shale diapirism and MVism have been known for many years from the Klias Peninsula [e.g., Blumer, 1922], where extrusion is restricted to anticlines. Resurgence of activity correlates with local earthquakes. Recently, two geophysical studies have shown MVism onshore [Morley et al., 1998] and offshore of Brunei [Van Rensbergen et al., 1999]. Regarding the first, multiphase intrusion of shale, indicated from dyke formation patterns, affected mid-Miocene anticlinal sediments [Morley et al., 1998]. Transpressive tectonics with small-scale normal faults allowed the shale to move, but then relatively high normal stresses exceeded fluid pressures. More recently, subsequent erosion and uplift remobilized the shale bodies and gave way to MV formation in the Jerudong anticline [Morley et al., 1998]. In the Ampa and Egret areas offshore in the Baram delta, the situation is more complex, with an intrusive phase followed by MVism, which in turn got buried, before migrating gas and water may have helped a renewal of ascent and extrusion [Van Rensbergen et al., 1999]. High-resolution seismic data across the structures suggest an interfingering of shales (showing a chaotic texture with incorporated country rock) and the wall rock (well stratified sediment). From the seismic signature, it was estimated that only 7% of the total 35 km<sup>3</sup> of the Ampa feature represent parent bed shale, while the remainder is overburden having been incorporated during intrusion. It is hypothesized that during dyke formation along preexisting faults, the material reached the former seafloor and formed domes from multiphase mudflows (Figure 6c). Such MVs got either eroded or buried, leaving an irregularity in the cylindrical dyke, which in the future may act as a trap for fluids (the latter possibly triggering the next eruptive phase). Dating of

the stratigraphic position of the Setap Shale parent bed (early to middle Miocene) and of the MV extrusion (latest Pliocene) allows the duration of inactivity of the undercompacted sediment to be dated as 9 Myr [Van Rensbergen et al., 1999].

[135] On Sabah, both west of Sandakan and on the Dent Peninsula at the junction of the Sulu and Celebes Seas, Reinhard and Wenk [1951] mentioned MVs made of “giant breccias.” The lithic fragments are of pre-Tertiary and younger age, with the oldest rocks being metamorphosed. However, the interpretation of a deep-seated parent bed within such units [Reinhard and Wenk, 1951] supposedly lacks consideration that olistostromes of the Danau Formation of Upper Cretaceous age comprise those very components as well. The clay/shale component within these olistostromes may cause intrusion and MVism as a result of low bulk densities relative to their overburden. The first to suggest that parts of the mélanges of Sabah have a diapiric origin were Haile and Wong [1965]. Several hypotheses regarding the fractured, hardened clays have been put forward, the most convincing explanation being very local soft sediment deformation of the mud matrix during emplacement [Clennell, 1992]. There is no clear coevolution between the ~24 flat mud domes (none of them exceeding 200 m width) and the massive outcrops of the East Sabah Mélange over several hundred square kilometers. In fact, evidence suggests that the mélanges rose only tens of meters while the MV ejecta entrained a thick cover of coherent rocks. Some of the MVs, for example, Pulau Batu Hairan MV in the north, near Banghi Island, source in the mélanges, hence ejecting enigmatic polymictic rocks [Clennell, 1992]. Other features, like Jeroco MV, are only a few meters in diameter and are free of clasts (Figure 4a). In general, both onshore and offshore of Sabah, a variety of MVs have been mapped. Commercial drill holes into the offshore area yielded anomalously high formation pressures associated with muddy sediment. Fluid comprises biogenic and thermocatalytic methane and water, sometimes accompanied by small amounts of CO<sub>2</sub> and higher hydrocarbons [Wilford, 1967]. Water influx is most likely from near-surface groundwaters [Haile and Wong, 1965].

### A34. Nigeria

[136] Offshore of Nigeria in the Niger delta, numerous circular features have been reported from the upper continental slope [Graue, 2000]. The domes are both active and dormant, are usually 1–2 km in diameter, and have chaotic seismic signatures. Some features overlie a rolling anticline, whereas others juxtapose a diapir. Seabed coring revealed oil, gas, and clasts of shale and sandstone in the mud. Occasional carbonate nodules have also been found. The age of the material is Pliocene and Pleistocene, with the dormant features being older than the active ones [Graue, 2000]. Evidence from geophysical investigation and coring suggests that the parent bed to the MVs consists of an overpressured



shale, which is overlain by low-integrity sediment. While some of the shale intrudes the overburden diapirically in a nonviolent manner (forming mud domes in the process), other features evolved from high fluid discharge from an underlying sediment wedge and appear as circular depressions in the surrounding seafloor. Buried MVs with ancient flows have been recently mapped using three-dimensional seismic acquisition [Heggland *et al.*, 2001]. The features occur predominantly in large-scale anticlines (compressional folds) and are often underlain by strong BSRs.

### A35. Timor-Ceram Arc

[137] Both in the east and west of Indonesian Timor, MVism and diapiric mélanges are abundant (Figure 4b). Despite some debate, the majority (or even all features) are fed by the Bobonaro clays, which cover some 4000 km<sup>2</sup> of outcrop [Audley-Charles, 1968] and formed during the Permian-Triassic. The MVs are dome shaped with relatively steep flanks (of ~50°) and show well-developed tassiks at their crest. The mud breccias show flow structures and carry clasts of >1 m and have been related to regional formations and explosive eruption [*t* Hoen and van Es, 1928]. Mud volcanism is also known from islands like Samau (6 MVs), Roti (2 MVs), Tanimbar [cf. Heim, 1940], and Kambing, the last of which is a 2-km-wide MV representing the island itself [Higgins and Saunders, 1974]. On the island of Sumba, up to 18-km-long mud ridges pierce the overlying strata [Clenell, 1992]. Initially, Heim [1940] related the diapiric muds to the overall orogenic movements in the southwest Moluccas. The Tanimbar mud breccia was studied in great detail by Yassir [1989], revealing its very fine grain size (no particles >0.4 mm) and high kaolinite and illite contents (up to 99.4% of the entire sample). A detailed study of 21 MVs in western Timor revealed that the mud originates from diapiric rise of the Bobonaro clays [Tjokrosapoetro, 1978]. Ascent is allowed along a sinistral, southwest-northeast-striking wrench fault, with oil and gas acting as lubricants (see model given by Barber *et al.* [1986, Figure 5]). Also, the occurrence of 80% illite but only 20% smectite in the extruded clays suggests that mineral dehydration supplied water as an additional driving force for ascent [Barber *et al.*, 1986]. In contrast to earlier interpretations, the scaly clays forming the Timor MVs have been interpreted as diapiric mélanges due to their shape and crosscutting relationship to the surrounding strata. Unlike olistostromes (where the blocks travel far and mostly horizontally), the mélanges of Timor show exotic, angular blocks of broken material [Barber *et al.*, 1986, Figure 6].

[138] Offshore geophysical surveys revealed MVism near the island of Sumba [Breen *et al.*, 1986] as well as along the Flores thrust zone [e.g., Silver *et al.*, 1986] in the Sunda forearc and back arc, respectively. In the forearc wedge as well as on the abyssal plane off the Timor Trough, MVs and mud ridges are observed [Breen *et al.*, 1986]. The domes in the forearc reach only a few

hundred meters in diameter; however, the elongated ridges parallel to strike are several kilometers long. The outward migration of the long décollement with near-lithostatic fluid pressures probably causes mud extrusion in the protodeformation front region of the downgoing Australian Plate [Breen *et al.*, 1986]. None of the material was sampled. Compared to the scale of deformation in the Timor Trough, the back arc thrusting is minor. However, along the Flores thrust zone the Flores and Bali Basins are overridden by the island arc, forming what has been termed a back arc accretionary wedge [Silver *et al.*, 1986]. Scattered MVs and ridges occur over a length of 150–200 km along strike and correspond with the grain of the Flores thrust (i.e., the basal detachment to the back arc wedge). The biggest mud ridge reaches a length of 10 km and occurs some 5 km behind the “frontal” thrust (i.e., south of it). Fluid overpressuring has been the inferred driving force [Silver *et al.*, 1986].

### A36. Irian Raya/Indonesia and Papua New Guinea

[139] Shale diapirism and mélange formation has been reported for wide parts of Irian Raya and western Papua New Guinea [Williams *et al.*, 1984]. MVism is concentrated in fields covering several tens to a few hundred square kilometers, which are bound to east-west-striking fault lineaments. The individual domes range from 3 m to 2.5 km width and reach maximum heights of 110 m [Williams *et al.*, 1984]. The source rocks of the mud breccias are the Miocene Makats and Mamberano turbidites, into which limestones and serpentinites from deeper stratigraphic levels got incorporated during folding and faulting prior to ascent.

### A37. Taiwan

[140] Taiwan is located at the boundary between the Philippine Sea Plate and the Eurasian Plate, where the Luzon Arc collides with eastern Taiwan. In the old Taiwanese literature (e.g., Fukutome [1928] as cited by Shih [1967, pp. 259–260]), there are records of mud volcanic eruptivity dating back as far as 1723, when “firelight lit up the sky. Two holes burst in the ground with black colored mud and water flowing out. The vegetation around was all baked into ashes . . . dark mud gushes out night and day. The mud can be ignited. This is certainly a wonder.” On Taiwan mainland, eruptive MV centers are known from 17 areas in South Taiwan, with altogether 64 active and several extinct features [Shih, 1967]. The majority of the MVs are located in the southeast and southwest of the island, and incipient arc-continent collision and tectonic shortening are believed to account for extrusion. The ejecta have been associated with parent beds of the Lichi Formation (Pliocene/Pleistocene) and the mélange-bearing Gutinkeng Formation (Pliocene), respectively. All southwestern domes occur along fault traces and anticlines, which seem to be the onshore continuation of the trace of the marine deformation front [Lee *et al.*, 1992]. Two diapiric domes are known from gravimetric mapping



[Hsieh, 1972]. If the mud density is compared between the areas in the southwest and southeast, it is obvious that the southwestern domes are more consolidated and are presumably older [Hsieh, 1972]. The activity has somehow shifted to the east through time. The geometry of the MVs is highly variable, with domes of only several meters across and a few meters in height, but also with wider features with 150-m-wide tassiks. The conduit width, where visible, has been estimated to be only ~10 cm [Yassir, 1989]. Two mud basins have also been found, which show continuous gas bubbling in the center of their 6-m-wide pond. Low-viscosity mudflows over their rims extend over tens of meters. A variety of physical properties have been measured [Yassir, 1989] and are compared to data from other areas of MVism in section 3.4.

[141] A comparative geochemical study on MV fluids from the southeast and southwest Taiwan MVs reveals similarities in the thermogenic  $\delta^{13}\text{C}_{\text{CH}_4}$  gas composition, suggesting a deep source [Gieskes *et al.*, 1992]. In contrast, the MV pore waters of the different areas differ considerably (Table 3). The southwest samples apparently source from a deeper reservoir, as indicated by much higher B, but lower Ca, Mg, and Na. Chlorinity is highly variable, but is always well below seawater (even for the southwest features adjacent to the deformation front), so that dilution from deep mineral dehydration within the large accretionary prism is suggested [Gieskes *et al.*, 1992].

[142] Offshore of Taiwan, seismic surveys located numerous MVs connected with the occurrence of gas hydrates [Chi *et al.*, 1998]. BSRs are located in the crest of anticlines and mud volcanoes, having been sourced from offscraped sediments derived from the Taiwan orogen and from the Chinese continental margin. Gas seepage (mostly methane) is a result of biogenic degradation of organic matter in the sediments accreted from the Manila Trench [Chi *et al.*, 1998]. Farther to the north, Liu *et al.* [1997] investigate a complex pattern of MVs, faults, and sedimentary features. The mud domes are only ~100 m wide, have cone-shaped geometries, and show gas plumes in the overlying water column. The MVs lie structurally above subsurface shale diapirs of much larger extent. While some diapirs pierce the seafloor sediments, others have stopped ascending hundreds of meters below the seafloor. Diapiric movement is facilitated along steep normal faults in a scenario of abundant horst-and-graben structures along the upbreking Chinese continental margin, but is also facilitated along thrusts in the Taiwan accretionary wedge [Liu *et al.*, 1997].

[143] A special type of trigger mechanism has been inferred for a dozen MVs near Lichelieu Island, southwest of Taiwan. While most of the features are <200 m wide and are only a few meters high, Lichelieu MV extends over >1 km in diameter and is bound by fault scarps [Chow *et al.*, 2001, Figure 3]. The diapiric root of the feature can be traced on seismic data, which

also show abundant steep normal faults and gas craters. The source of MVism here is strongly connected to the sediment supply from the nearby Kaopingshi River in the north. The rapidly deposited material in the Kaoping submarine canyon is fine-grained, trapped gas, and it developed overpressures sufficient to allow the material to extrude [Chow *et al.*, 2001]. Subsequent diapiric movement of the undercompacted material later caused the uppermost part of Lichelieu MV to rise above the seafloor, hence forming the island of the same name.

### A38. Ryukyu Trench, Nankai Trough, Japan Trench, and Japan

[144] At the convergent margin off Japan, several MV occurrences are known both on the subducting and overriding plates. A small mud ridge of ~1.2 km length and 130 m height is found on the incoming Philippine Sea plate at >5 km water depth in the Japan Trench area [Ogawa and Kobayashi, 1993]. Extrusion of fluidized sediment follows northeast-southwest-trending normal faults, which are believed to be caused by downward flexure of the oceanic plate. Frequent seismic activity of the area may have triggered MVism as well.

[145] In the Kumano Basin, offshore of Kii Peninsula (southern Honshu), several dozen MVs have been discovered during a recent geophysical survey (J.-O. Park, personal communication, 2001). The domes are ~100 m high, are usually <1 km wide, and contain clasts of the older part of the accretionary prism (i.e., Shimanto Belt). Gas emanated is mostly methane of thermogenic origin, which indicates that the material may be rehydrated Shimanto clay stones. A few smaller features have been observed farther east (S. Lallemand, personal communication, 2001), but have not been sampled.

[146] To the south, in the eastern portion of the Nankai Trough accretionary prism, Kobayashi *et al.* [1992] discovered three MVs with diameters of several hundred meters and heights of several tens of meters during bathymetric mapping. Submersible studies revealed cold seep vents and biological communities.

[147] Even farther south, in the Ryukyu forearc, side-scan sonar imaging and piston coring characterized MVism in accreted sediments [Ujiie, 2000]. A total of >24 domes are observed. The example shown is related to a thrust along which overpressured material migrated upward. Microfossils of Eocene to present are found in mud-supported breccia, which is interlayered with background sediments and ash layers from the arc volcanoes. Piston core evidence suggests interfingering of mud breccia and hemipelagic sediments during the late Pliocene and Pleistocene [Ujiie, 2000].

[148] Ancient chaotic breccias and mélanges were identified in the accretionary prism of the Shimanto belt and have been interpreted as extinct diapirs or MVs [Shimizu, 1985]. However, these accreted deposits from the pre-Eocene wedge now overlying the modern accretionary prism may equally originate from already disturbed parent beds with cataclastic material, like the

former décollement zone. More recently, *Lewis and Byrne* [1996] have described the ancient Tako mud diapir as a chaotic, pebble-bearing shale body within coherent rocks of the Kogawa Formation. The blocks are angular and range between centimeters and tens of meters, the smaller fragments being separated from larger units by hydrofracturing during ascent [*Lewis and Byrne*, 1996, Figure 3; *Behrmann*, 1991; *Brown et al.*, 1994]. Diapiric rise, as well as hydrofracturing, is believed to be associated with underconsolidated shales.

### A39. Sakhalin

[149] MVism on the island of Sakhalin, Sea of Ochotsk, has been known throughout historic time and seems to be related to the regional oil and gas fields [*Siryk*, 1962]. Eruptions seem to occur frequently (and sometimes explosively), for example, in March 1959 and September 1961 [*Gorkun and Siryk*, 1968]. In 1959 the Yuzhno-Sakhalinskiy MV ejected 150,000–200,000 m<sup>3</sup> of mud, covering 60,000 m<sup>2</sup>, with the mud, rock fragments, and trees being propelled up to ~100 m into the air. Similarly, the mud discharge for the Pugachevskiy MV in 1961 has been estimated to cover 8000 m<sup>2</sup> of ground with some 7200 m<sup>3</sup> of mud, which was thrown some 40–50 m into the air above the crater [*Gorkun and Siryk*, 1968]. The diameters of the conduits are reported to be 30–200 cm. A total of five active MVs are identified on Sakhalin, and the average emission of predominantly methane gas per vigorous eruption has been calculated to be ~14,400 m<sup>3</sup> [*Gorkun and Siryk*, 1968]. The equations used for the gas flux estimates are further used to estimate the mobilization depth of the ejecta, which again bears some errors (see discussion and equations of *Kopf and Behrmann* [2000]). Although detailed fieldwork in the exhumed accretionary complex on the island of Sakhalin revealed shaly and olistostromal series [*Kimura et al.*, 1992], no close relationship between these beds and the ejecta has been established. From what is known about the regional geology, however, it may be assumed that the parent bed of the mud breccias lies within argillites of the Bykovskaya Series at ~2.3–3 km depth.

[150] A recent Ms 7.2 earthquake affecting northern Sakhalin in May 1995 was immediately followed by various secondary phenomena such as landslides, falls, soil liquefaction, and mud volcano eruptions [*Ivashchenko et al.*, 1997]. However, this MV activity triggered by aftershocks and related to fault movement along the preexisting Upper Piltun strike-slip fault is an exception here. Usually, buoyancy (and gas-assisted lift) of shales and clay-rich sediments is the main driving force that mobilizes material from a few kilometers depth.

### A40. Marianas

[151] A different form of diapirism and volcanism can be studied at some subduction zones where hydrothermally altered mantle wedge material (i.e., serpentinites) ascend from the deeper part of the plate interface. In the

Mariana and Izu-Bonin forearc, two serpentinite seamounts were drilled during Ocean Drilling Program Legs 125 [*Fryer and Mottl*, 1992] and 195 (M. Salisbury et al., Leg 195 scientific prospectus: Mariana convergent margin/West Philippine Sea seismic observatory, available at <http://www-odp.tamu.edu/publications>). These seamounts form as MVs, composed of undercompacted serpentine mudflows, or as horst blocks of serpentinized ultramafics that diapirically intruded the leading edge of the overlying plate [*Maekawa et al.*, 1993]. As many as 100 up to 30-km-wide and 2-km-high features have been reported from the Mariana forearc as being 50–120 km behind the trench axis [*Fryer et al.*, 1985]. Their size varies, but it is generally an order of magnitude larger than for sedimentary MVs. For instance, the Conical and Torishima seamounts drilled are >10 km across and have an elevation of ~1 km relative to the surrounding seafloor [*Fryer and Mottl*, 1992]. Apart from flows, slumping and various soft sediment deformation can be found. The material recovered comprises serpentine with various amounts of clasts (both sedimentary and mafic rock types) underlain by serpentinized dunite, harzburgite, and metadiabase of various compositions at the base [*Fryer and Mottl*, 1992]. Hence an increase in alteration toward the seafloor can be inferred. However, fluid chemistry and authigenic phases are indicative of a fluid other than seawater having interacted with the mafic rock at depth (Table 3). Such fluids may be derived from mineral dehydration reactions. Although not sedimentary volcanism, the serpentine MVs play a similar role in mass transfer at active convergent margins as, for example, the MVs on the Mediterranean Ridge (see section A22). They occur in a similar location some tens of kilometers behind the deformation front and rheologically resemble their sedimentary counterparts [*Phipps and Ballotti*, 1992]. Also, there are numerous sedimentary serpentine deposits known from land in former convergent margin settings [e.g., *Oakeshott*, 1968; *Lockwood*, 1972].

### A41. Australia (Gosses Bluff)

[152] In central Australia a circular feature known as Gosses Bluff rises from a plain of Paleozoic sedimentary rocks. It is ~10 km in diameter (crater area ~3 km), with its core at the same topographic level as the surrounding rocks, but made of highly disturbed Cambrian and Ordovician rocks [*Ranneft*, 1970]. The elevated rim (180 m higher than the core area) of the feature comprises steep layers of Silurian to Carboniferous rocks, which may have been dragged upward if a diapiric mechanism of emplacement is inferred (either by sedimentary or salt intrusion and updoming and/or gas discharge, from depth). However, nothing similar is known from elsewhere.

### A42. New Zealand

[153] MVism on the northern island of New Zealand has been described for the Raukumura Peninsula by

*Ridd* [1970]. Two of three domes are dormant at present; however, historic records exist regarding their episodic, earthquake-shock-generated nature and activity. The parent beds are bentonitic clays of either the Arnold or Dannevirke Series. These Paleocene/Eocene rocks form many diapirs, with abundant clasts of Cretaceous and younger age. High formation pressures in the ~6-km-thick Tertiary sequence may play a crucial role in MVism [*Ridd*, 1970]. The MVs are small domes with crater mud lakes (in the case of the active Arakihi Road MV).

[154] Historic accounts of regional earthquakes mention bubbling of the shallow waters offshore of Raukumura Peninsula, which may have been submarine mud eruptions [*Ridd*, 1970]. Historic records link offshore MV eruptions at Open Bay and East Cape in 1877 with seismic tremor. It remains unclear, however, whether the mechanism is similar to the onshore features or whether processes along the active margin at the Australian-Pacific plate boundary caused submarine gas venting. More recently, *Nelson and Healy* [1984] reported pockmarks that may result from MVism on the Poverty Bay seafloor. However, no subseafloor evidence has been provided.

[155] On the northern island of New Zealand, the Waimata MV erupted in 1908 [*Adams*, 1908]. The feature ejected debris with blocks of up to 27 kg to a height of 150 m, scattering them over tens of meters distance relative to the central conduit of the mud spring. Fluid overpressure hauled ~100,000 tons of mud breccia within the first hour of the vigorous eruption [*Adams*, 1908]. Another 150,000 tons extruded during the similarly violent 1930 eruption [*Strong*, 1931]. Some 70% to almost pure methane escapes at high gas discharge rates with hissing sounds. The control of activity has been related to tectonic movements, with the rock fragments (up to 15 cm across) ejected being interpreted as removed fault breccia during upward migration of mud from a deeper reservoir (Cretaceous of younger [*Strong*, 1931]). The total volume of the underlying clay diapir, which rose vertically ~3 km along the transcurrent fault system, has been estimated to range around 30–35 km<sup>3</sup> [*Stoneley*, 1962]. Similarly, activity of Mangachu Stream MV farther west is controlled by tectonic movements along the complex Waimata-Mangachu fault system [*Ridd*, 1970, Figure 5].

[156] In the Hikurangi subduction zone many small mud pools have recently been described by *Lesedert et al.* [2001]. Their activity is related to petroleum occurrence and gas seeps onshore. Fossil examples are also found. The conduits range from centimeter to decimeter size and often contain authigenic carbonates and zeolites. The parent bed to the MVs is proposed to represent an offshore diapiric wall south of the subducting margin [*Lesedert et al.*, 2001].

#### A43. Egypt/Libyan Desert

[157] *Hume* [1929] discovered “asymmetrical elongated domes of the diaper-type, with dips of 5° to 10° on the NE-flanks” east of Cairo, Egypt. One of these clay diapirs from the folded and faulted Paleozoic rocks in the Giran el Ful-Gebel el Hiqaf anticline has been described in more detail. The feature is ~300 m in diameter and domes up near the intersection of a fault cutting the core of the anticline [*Omara*, 1964]. Also, clayey dykes have been observed in the area, possibly related to syntectonic injection of the plastic material into more indurated rock of Turonian age. Injection as well as diapirism have been interpreted to be tectonically rather than density driven [*Omara*, 1964], mostly because the less competent clays got accumulated locally during shear.

#### A44. Netherlands

[158] One peculiarity of sedimentary volcanism closes the compilation of global MVism: peat diapirs in Pleistocene sediments in Netherlands [*Paine*, 1968]. The features are <2 m high, are <3 m wide, and occur in the ~7-kyr-old Flevoland Lower Peat unit. Diapiric rise supposedly started 1–1.5 kyr ago and pierced the overlying clays and sands [*Paine*, 1968]. Some of the features have been related to normal faults, which allowed some features to crop out on the surface [*Paine*, 1968, Figure 2]. The peat is rich in plant debris, and these debris flow deposits on the Earth surface bear striking similarities to mud volcano flows elsewhere (compare to, e.g., *Paine's* [1968] Figure 4 and to *Martinelli and Ferrari's* [1991] Figure 1).

#### A45. Summary

[159] In summary, mud volcanism is most abundant in compressional scenarios (see compilation of selected areas in Table 1) and, to a lesser extent, in deltas of great rivers. As for the first, tectonic activity is an additional trigger to the buoyant driving mechanism. Fluid for MVism is supplied from various sources (see section 4.2 and Figures 2 and 9), including meteoric and volcanic waters, pore water expulsion, hot springs, mineral dehydration reactions, and gas hydrate destabilization. Gas may originate from as deep as the upper mantle (see section 4.3). Among the MV occurrences known to date, the Barbados Ridge, Caucasus, and Mediterranean Ridge are the areas with the most abundant and best-studied features (see sections 4 and 5).

[160] There are other areas of MVism known to the author; however, only sparse information exists. This is especially true for early publications in somewhat obscure journals (not all of which I was fortunate enough to get hold of). For an overview of several dozen such references, the reader is referred to volume III of *Redwood's* [1913b] bibliography. Another excellent collection of literature related to diapirism (not entirely of clays, shales, and muds, but also of salt, peat, and ice) has been compiled by *Braunstein and O'Brien* [1968].



[161] **ACKNOWLEDGMENTS.** The author is indebted to the input by numerous colleagues, many of whom cannot be listed by name. I particularly benefited from discussion with Jan Behrmann, Gerhard Bohrmann, Kevin Brown, Ben Clennell, Rachel Flecker, Pierre Henry, Dirk Klaeschen, Jean Mascle, Alastair Robertson, John Saunders, Liz Screaton, Paola Vannucchi, and Najwa Yassir. Special thanks go to John Saunders, who was of invaluable help tracking down old literature and rare volumes, and to Annette Deyhle for her enthusiastic efforts on an early draft of this summary. Three anonymous referees and Editor Thomas Torgersen helped improve the manuscript. I am also grateful that parts of my own research on mud volcanism were supported by Deutsche Forschungsgemeinschaft, the large-scale facility programme of the European Union, and by BASF AG, Germany.

[162] Thomas Torgersen was the Editor responsible for this paper. He thanks Liz Screaton and an anonymous reviewer for technical reviews and thanks an anonymous cross-disciplinary reviewer.

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