Buried Gas Hydrates in the Deepwater of the South Caspian Basin, Azerbaijan: Implications for Geo-Hazards

by

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BURIED GAS HYDRATES IN THE DEEPWATER OF THE SOUTH CASPIAN SEA, AZERBAIJAN: IMPLICATIONS FOR GEO-HAZARDS

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ABSTRACT

Two multi-channel seismic reflection profiles in the deepwater of the South Caspian Sea, offshore Azerbaijan, document one of the first examples of buried gas hydrates. Based on their geophysical signature, these clathrates are characterized by (1) a depth-restricted, lenticular body well beneath the seafloor, (2) the apparent accumulation of free gas within the underlying sediment, and (3) evidence of associated recent slope failure in the overlying strata. The interpreted thickness and depth of gas hydrates in the South Caspian Basin fall within the hydrate stability field predicted from thermobaric modelling of gas compositions identified from coring at the seafloor. Predicted minimum water depths (~150 m) and maximum thicknesses (1,300 m) for hydrate stability are much shallower and considerably thicker in the South Caspian Sea than for other known hydrate occurrences. Accumulation of these hydrates near the base of the continental rise appears to control a large region (> 200 km^2) of shallow deformation, here named the Absheron allochthon. Such attributes make these gas hydrates important, and perhaps previously underestimated, geo-hazards of the South Caspian region. Primary among these hazards are (1) uncontrolled release of free gas trapped beneath the hydrate seal, (2) disruption of the gas hydrate stability field leading to either explosive dissociation of the gas hydrate, or (3) reduction in sediment strength, slope instability, and mass sediment transport. Documentation of the presence and distribution of gas hydrates, especially when concealed at depth in the subsurface, is a clear pre-requisite for exploration activities in the deepwater region of the South Caspian Sea.

Key words: *gas hydrates, Caspian Sea, geo-hazards.*

1. INTRODUCTION

The South Caspian Sea of Central Eurasia (Figure 1) has been the focus of intense exploration activity for most of the past decade. While this region is without doubt one of the oldest commercially producing areas in the world (Devlin et al., 1999), the break-up of the Soviet Union in 1991 led to new and unprecedented access for global petroleum companies to participate in exploration and production activities in the

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newly established republics of the Caspian Sea region. To date, much of this activity has been centered on the republic of Azerbaijan and the adjacent offshore territorial waters. Through production sharing agreements with numerous national and international companies, industry activities have included 2-D and 3-D seismic acquisition, coring programs, exploration and production drilling, and platform and pipeline construction in the challenging offshore environment. While much of the industrial activity thus far has been focused in the vicinity of the Absheron ridge (Devlin et al., 1999), closest to known and producing fields in the offshore area of the South Caspian, the deepwater of the South Caspian is thought to hold the highest future potential for discovery of new petroleum reserves.

Gas hydrates are solid substances similar to ice, but consist of molecules of hydrocarbon gas (mostly methane) enclosed in cages of water molecules (Kvenvolden, 1993; 1995; Sloan, 1998). Recent estimations indicate that the largest accumulations of natural gas on Earth are in the form of gas hydrates (Kvenvolden, 1995; Sloan, 1998). Since the gas hydrates form under conditions of high pressure and low temperature, where there is a sufficient supply of gas and water (Kvenvolden, 1995), they occur either in marine sediments on continental slopes, or in polar regions in association with permafrost (Kvenvolden, 1993; Collett, 1994). Gas hydrates have been a central theme for both the scientific and economic communities due to three main aspects of their occurrences: (1) potential drilling hazard, (2) fuel resource potential, and (3) role in global climate change (Kvenvolden, 1993; 1995). This study of gas hydrate occurrences in the deepwater of the South Caspian Sea was driven mainly by concern for potential hazards posed by gas hydrates for petroleum exploration activities.

For the past two decades, scientists and engineers have attempted to understand gas hydrate systems in near-seafloor sediments and sedimentary processes. A particular focus has been placed on gas release and sediment mass transport (e.g. McIver, 1982), so that safe procedures for hydrocarbon production can be implemented. Both marine and permafrost related sediments have proven to cause problems during drilling and production of hydrocarbons, such as gas release during drilling, casing collapse, blowouts, or well site subsidence (Sloan, 1990; 1998). Most of these problems are generally caused by the dissociation of gas hydrates due to the heat generated by circulating drilling fluids, or by the production of hydrocarbon fluids. Mitigation of gas hydrate hazards as well as the need to develop techniques to avoid these types of problems is still ongoing research.

The South Caspian Sea of Central Eurasia is located between the Neogene age Caucasus Mountains to the west, and the Kopeh-Dagh strike-slip fold belt to the east (Zonenshain and Le Pichon, 1986; Zonenshain et al., 1990; Priestly et al., 1994). With seafloor depths in excess of 1,000 m, and with proven reserves of hydrocarbon gas (Gegelyantz et al., 1958; Zonenshain et al., 1990; Bagirov and Lerche, 1999), the South Caspian Sea was identified as a potential gas hydrate site as early as the 1970's (Yefremova and Zhizhcenko, 1974). The South Caspian Sea has been known for centuries to be affected by natural hazards, including explosive eruptions of mud volcanoes, as attested in historical documents (Bagirov and Lerche, 1997; 1999). Association of gas hydrates with mud volcanoes (Ginsburg et al, 1992; Ginsburg and

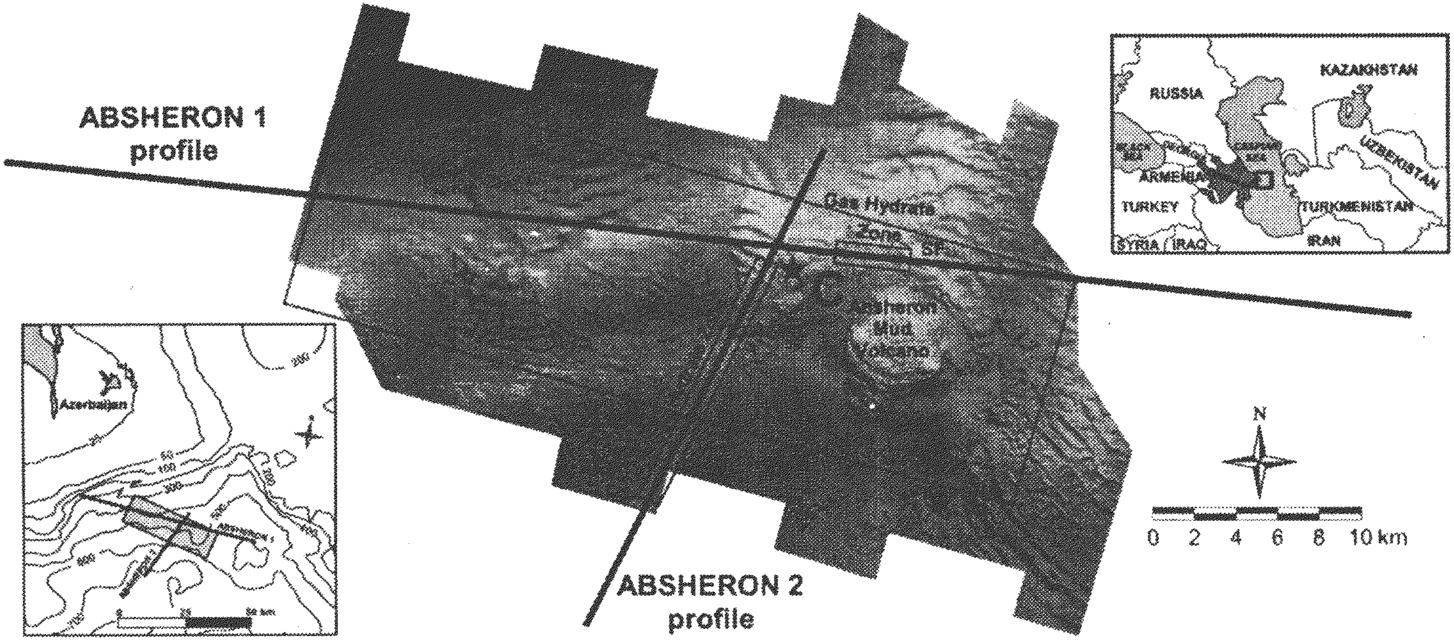

Figure 1. Location map of seismic profiles ABSHERON 1 and 2 within the South Caspian Sea, offshore Azerbaijan. Central is the bathymetry of the seafloor, generated from the 3-D survey, highlighting the transition from the shelf edge to deepwater. Star labelled C indicates location of coring for hydrocarbon gas geochemical analysis explained in the text. Inset in upper right corner shows the geographic setting of the Caspian Sea within Central Eurasia. Inset in the lower left corner displays a zoom out of the study area, and bathymetric contours in meters. SF stands for shallow faulting.

Soloviev, 1994) enhance the chances of offshore explosive eruptions, and slope failure on the continental slope.

Previous studies (Ginsburg et al., 1992; Ginsburg and Soloviev, 1994) attested to the presence of gas hydrates in the South Caspian Sea, offshore Azerbaijan, but in shallow water (up to 200 m), and developed in association with mud volcanoes. Based on two ~70-km long seismic reflection profiles acquired as part of Chevron's exploration program in the South Caspian Sea, offshore Azerbaijan (Figure 1), here we present the first documentation of gas hydrates in the deep water of the South Caspian Sea (~400-715 m). As suggested by these new (1998) reflection data, the gas hydrates of the South Caspian Sea, in the study area, occur in a well-defined, depth restricted layer ~200 km thick, well beneath the seafloor (300–400 m below the seafloor; mbsf). This is one of, if not the first documentation of buried gas hydrates in marine sediments. Based on this study, these gas hydrates are underlain by sediments filled with free gas, making them particularly dangerous hazards during the drilling process.

2. GAS HYDRATES IN THE SOUTH CASPIAN SEA

2.1. Thermobaric Modeling

Since gas hydrates form in sediments under specific thermobaric conditions which require high pressure, low temperature, present of water and natural gas (e.g. Kvenvolden et al., 1981; Bagirov and Lerche, 1997) their occurrence can be predicted with theoretical phase equilibrium calculations (Sloan, 1990; 1998). Here we used the three-phase equilibrium analysis based on statistical thermodynamics methods of Van der Waals and Platteeuw (1959) that predict the temperature and pressure at which hydrates form from a given gas composition and free water (Sloan, 1990).

Three theoretical gas hydrate phase equilibrium diagrams were analyzed for our study area (Figure 2), for systems formed by pure-water and (a) pure methane, (b) and (c) thermogenic gas as derived from a seismic environmental impact assessment coring (see location C in Figure 1; Moukhtarov, 1998). The hydrocarbon gas compositions specific to each diagram are listed in Figure 2. A hydrostatic pore-pressure gradient of 0.1 atm/m was assumed for the depth scale (Kvenvolden, 1993). The seafloor temperature considered in these diagrams is 5.85°C (Ginsburg et al., 1990; Schoellkopf and Dahl, 1995). The geothermal gradient in the study area varies between 11 and 17°C/km (Schoellkopf and Dahl, 1995; Bagirov and Lerche, 1997; Tagiyev et al., 1997). The phase diagrams were displayed for a seafloor depth of 475m, which corresponds to the up-dip termination of the gas hydrate occurrence observed on the seismic data. The intersection of the gas hydrate stability curves (shown in bold lines in Figure 2) with the seafloor isotherm of 5.85°C denotes the minimum water depth at which gas hydrates are stable given the specific hydrocarbon gas composition. The depth at which the geothermal gradient intersects the gas hydrate stability curve marks the bottom of the gas hydrate stability field (Kvenvolden et al., 1981; Kvenvolden, 1993). The area delimited by the gas hydrate stability curve, the water/sediment interface, and the geothermal gradient represents the gas hydrate stability field (Figure 2).

Based on the thermobaric modelling shown in Figure 2, gas hydrates are predicted to be a common occurrence of the deep water of the South Caspian Sea. Gas hydrates

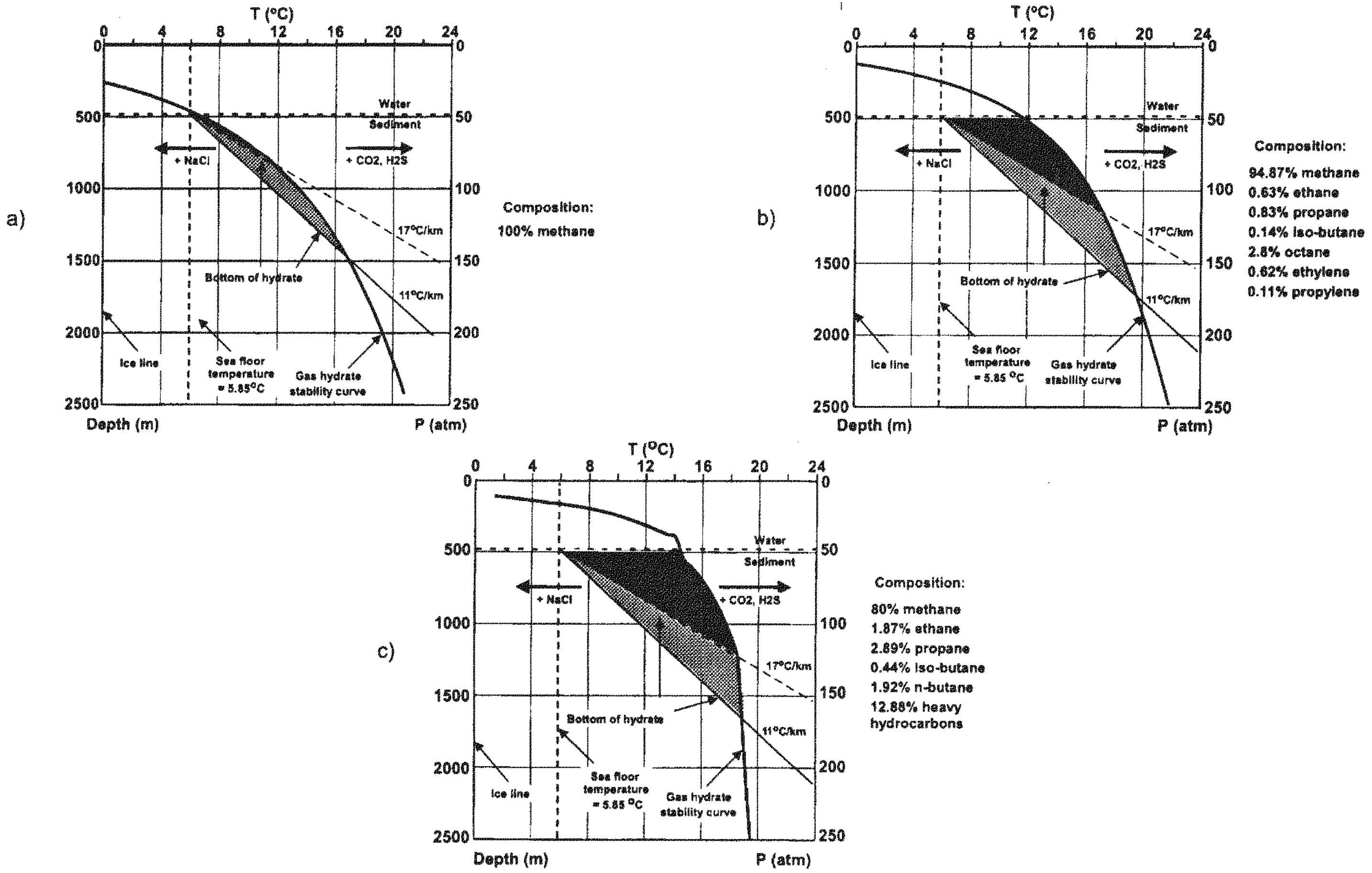

Figure 2. Theoretical phase equilibrium diagrams showing the inferred gas hydrate stability field in the study area for systems of pure water and (a) pure methane, (b) and (c) measured gas compositions from a coring displayed as C in Figure 1. The gas compositions in (b) and (c) correspond to the bottom and the top, respectively, of a 55 m core sample. Hydrate stability fields are calculated for geothermal gradients of 11°C/km (plain lines) and 17°C/km (dashed lines), for water depths of 475 m. The base of the gas hydrate stability field is positioned at the depth at which the geothermal gradient crosses the gas hydrate stability curves. The gas hydrate stability field corresponding to the geothermal gradient of 17°C/km is shown in dark gray. Depth scale assumes a pore-water hydrostatic pressure gradient of 0.1 atm/m. Arrows show direction toward which the gas hydrate stability curves move if NaCl (left) and/or CO_2 or H_2S (right) are added to the system.

may form in water as shallow as 150 m (Figure 2c) if the hydrocarbon gases have a thermogenic origin. In the case of biogenic gas (Figure 2a), the minimum water depth for gas hydrate formation is ~460 m. The maximum depth of the predicted gas hydrate stability field, as shown in Figs. 2b and c, is 1,700 m for the specified water depth of 475 m. The total predicted thickness of the gas hydrate stability field in the study area, given a seafloor depth of 475 m, varies between 0-1,225 m. These numbers increase with the increase in water depth as shown by Diaconescu et al. (in review, a). The heavier the hydrocarbon gases and the lower the geothermal gradients, the larger the gas hydrate stability field (Kvenvolden et al., 1981; Kvenvolden, 1993; 1995).

2.2. Seismic evidence of Absheron gas hydrates

Two multi-channel seismic reflection profiles, ABSHERON 1 and 2, were acquired in 1998 in the deepwater of the South Caspian Sea, offshore Azerbaijan (Figure 1). Processing of these profiles was focused on noise reduction and preservation of true amplitudes, necessary for accurate evaluation of elastic properties, including possible "blanking" (reduced acoustic impedance) effects, and detection of potential free gas accumulations beneath the hydrated layer. Principal processing steps included wavelet deconvolution, spherical divergence, bandpass filtering, surface consistent amplitude scaling, finite-difference migration, and depth conversion. The depth seismic sections of the two ABSHERON profiles are displayed to a maximum depth of 1,600 m in Figure 3. Line ABSHERON 1 is displayed in full length (~70 km; Figure 3b), whereas only a portion (~25 km) of the line ABSHERON 2 is shown, where the presence of gas hydrates was detected.

Seismic evidence for the presence of buried gas hydrates within the study area consists of a shallow zone of pronounced high velocity ($V_p \approx 2.1$ km/s, $V_s \approx 0.8$ km/s) as compared with the surrounding sediments ($V_p \approx 1.55$-1.60 km/s, $V_s \approx 0.36$ km/s). This zone appears on the seismic data as a depth-restricted layer (~200 m thick) well beneath the seafloor (~300-400 m), extending down the flanks of the buried Absheron anticline (Diaconescu et al., in review, a). The top of this velocity anomaly is marked by a strong, ($R_c \approx 0.123$), positive-polarity (same polarity as the seafloor ($R_c \approx 0.198$) reflector that is interpreted as the top of the gas hydrate layer (Top Absheron Hydrate; TAH in Figure 3). Similarly, a high-amplitude ($R_c \approx 0.11$), negative polarity reflector (reversed relative to the seafloor) coincides with the base of the high-velocity layer, and is interpreted as the base of the hydrate zone (Base Absheron Hydrate; BAH in Figure 3). Both the TAH and BAH reflectors approximately parallel the seafloor, and display a slight crosscutting geometry with the shallow stratigraphy (Figure 3), suggesting that these two reflectors are thermobaric and not stratigraphic interfaces. As in other gas hydrate examples identified worldwide, the shallow high-velocity anomaly zone is associated with blanking effects of the sedimentary section (Figure 3).

Previous seismic studies of gas hydrates (Shipley et al., 1979; Field and Kvenvolden, 1985; Hyndman and Spence, 1992; Dillon et al., 1994; Diaconescu et al., in review, a) suggested that the interface separating gas hydrate containing sediments from underlying hydrate-free strata is a high-amplitude, negative polarity reflector. For a better understanding of the seismic signature of the interpreted Absheron gas hydrates, representative common-mid point (CMP) gathers from both ABSHERON profiles are displayed in Figure 4. These CMP gathers emphasize the seafloor and the

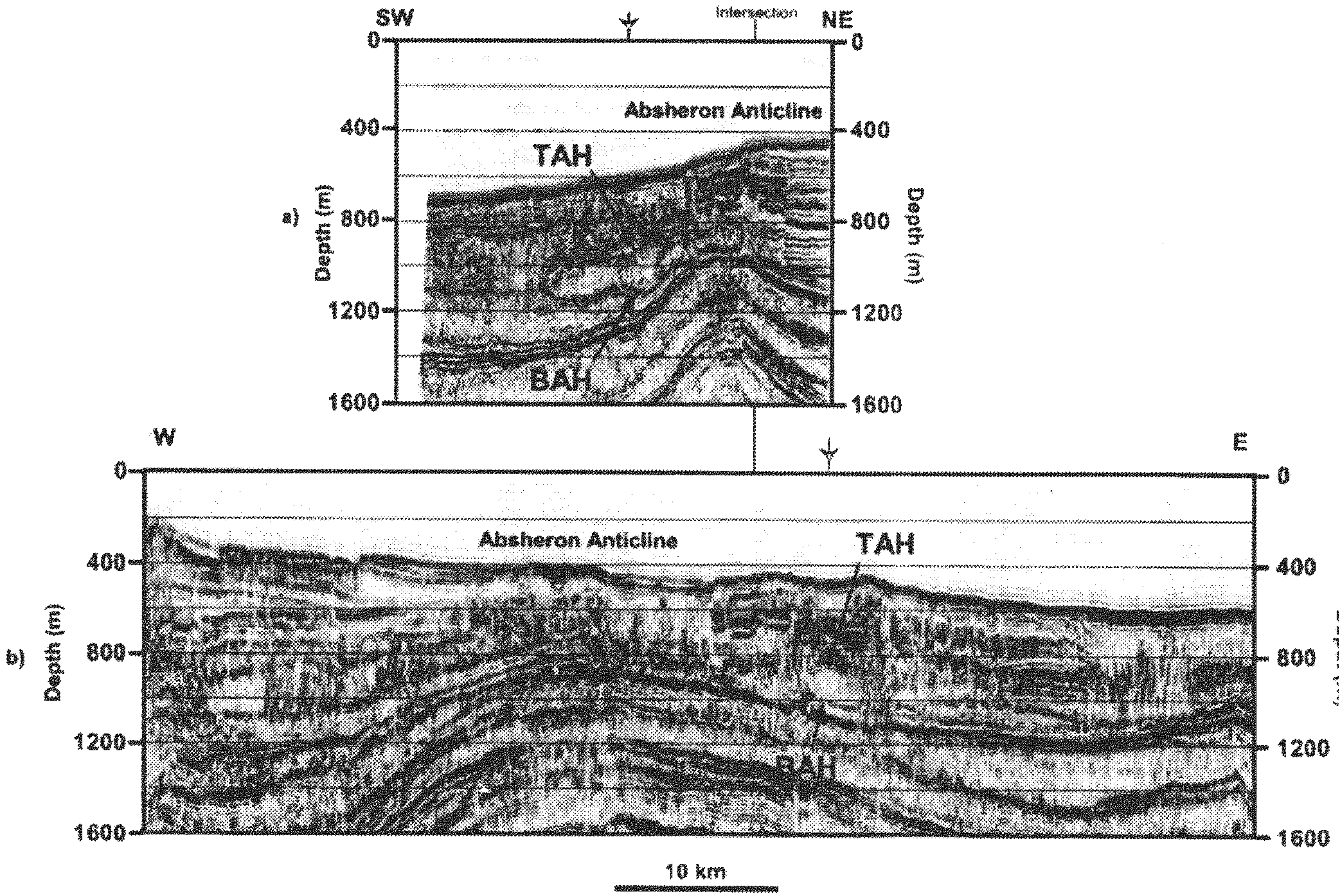

Figure 3. Composite display showing migrated CMP depth seismic sections of (a) line ABSHERON 2, and (b) line ABSHERON 1. The inferred top (TAH) and base (BAH) of the Absheron gas hydrate bound an ~100-200 m thick depth-restricted hydrate layer situated ~300 mbsf. Positive polarity (peak) reflections are shown in black (e.g. seafloor and TAH); negative polarity (trough) reflections are shown in white (e.g. BAH)

TAH wavelet as a positive (peak) polarity reflection, whereas the BAH wavelet appears as a negative (trough) polarity reflection. Interval velocity (V_p) curves (Figure 4a) illustrate the high V_p between the TAH and BAH reflections, where we interpret the occurrence of the gas hydrates on the ABSHERON profiles, and an ~20-25% decrease in V_p in the underlying layer. A similar velocity signature is observed in other marine gas hydrate occurrences worldwide (Singh et al., 1993; Ecker et al., 1998).

Although still a controversial issue, reflection polarity itself is not a sufficient seismic indication of the presence of free gas accumulation underneath the hydrated layer (Hyndman and Spence, 1992; Andreassen et al., 1997, etc.). Results from amplitude variation with offset (AVO) modelling on line ABSHERON 2 (Diaconescu et al., in review, a) suggest that (1) gas hydrate concentration in the sediments is ~20%, and (2) the BAH displays decreasing AVO, suggesting accumulation of free gas underneath the hydrated layer. Partial results from the AVO study on the Absheron gas hydrates are shown in Figure 4b, where the amplitude variation of the seafloor, TAH, and BAH reflections with the angle of incidence are displayed. As observed here, the seafloor and TAH reflections show similar AVO patterns of decreasing amplitude with offset (or angle of incidence), from more positive to less positive peaks. The BAH reflection shows also decreasing amplitude at larger offsets (or angle of incidence), but the wavelets (troughs) become less negative as they depart from the vertical (0°) incidence. This AVO behavior of the BAH reflection, with less negative wavelets at larger offsets, is also hinted in the CMP gathers in the Figure 4a.

Earlier studies of gas hydrates (e.g. Bangs et al., 1993; Andreassen et al., 1997; Ecker et al., 1998) suggested that increasing AVO at the base of the gas hydrate layer is indicative of the accumulation of free gas underneath the hydrated layer. In contrast, Diaconescu et al. (in review, a) concluded that this might not be the case, and in fact, decreasing AVO is more likely to indicate the presence of gas sands beneath the hydrated layers. This analysis was based on AVO crossploting (Castagna and Swan, 1997; Castagna et al., 1998; Simm et al., 2000) and suggested that due to decrease in both V_p and V_s at the base of the gas hydrate interface, gas hydrates could be considered similar in this regard with "tightly cemented sediments" (Castagna et al., 1998) overlaying gas sands, and which reveal decreasing AVO at the separating boundary.

2.3. Structural setting

Evidence for the presence of shallow, buried gas hydrates can be found on both ABSHERON 1 and 2 profiles (Figs. 3 and 5), and occurs within a relatively restricted depth range from ~800–1,200 m. On the ABSHERON 2 profile, the gas hydrate zone can be traced continuously for ~12 km, with as much as ~300 m of relief on both the top and base of the layer. In contrast, the area where hydrates are identified on the ABSHERON 1 profile is much more restricted in extent, with a small zone ~3 km in length characterized by seismic blanking, higher seismic velocities, and a positive-polarity top (TAH) and negative-polarity base (BAH) (Figs. 3 and 4). In both cases, the zone of gas hydrate development is situated on the flanks of the Absheron anticline, but is neither uniquely associated with the crest of the structure, nor symmetrically distributed on the flanks. While gas hydrate stability further to the west and north might be limited by shallowing water depths, thermobaric modelling of the

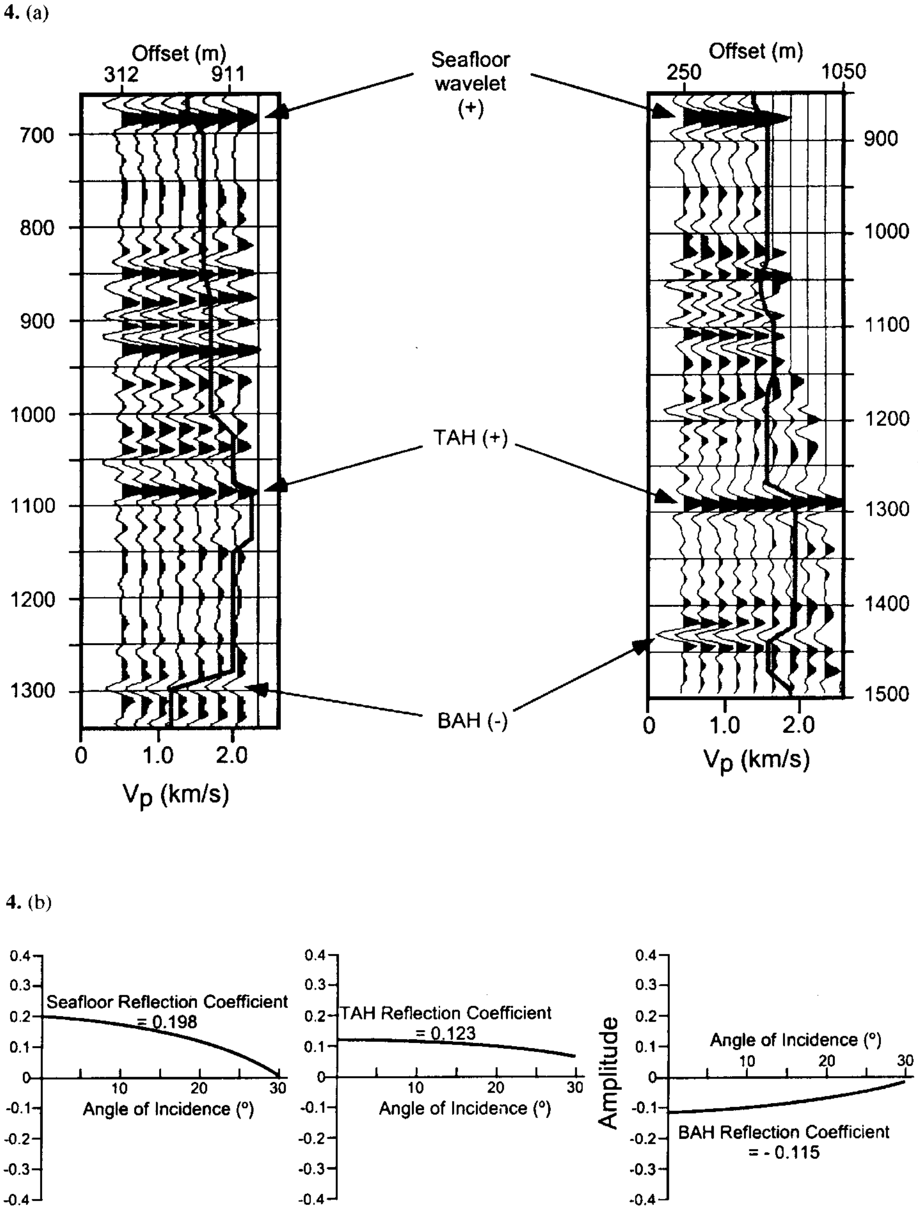

Figure 4. (a) Amplitude corrected CMP gathers representative for lines ABSHERON 1 (left), and ABSHERON 2 (right) for a 0-30° range of angles of incidence at the depth of the BAH reflector. Exact location of these CMP gathers is shown with arrows in Figure 3. BAH is a negative polarity (trough) reflection, and becomes less negative with increasing offset. Gray curves overlaying the CMP gathers represent interval velocities (V_p). TAH is a positive (peak) polarity reflection.
(b) Amplitude variation with the angle of incidence displays for the seafloor, TAH and BAH reflections.

gas compositions near the profiles (C on Figure 1) suggest this should not be the case. On this basis, it does not appear that the presence of gas hydrates is either strictly or even largely controlled by the Absheron structure.

Comparison of the gas hydrate distribution on the two seismic profiles with the seafloor bathymetry in the region suggests a close spatial relationship with the nearby Absheron mud volcano and its associated moat (Figure 1). While the Absheron volcano is not imaged directly with the seismic profiles, the position of this mud volcano appears to coincide with the crest of the Absheron anticline, and could provide a likely source of thermogenic gas for hydrate formation. Since the southern and eastern flanks of the volcano were not imaged with this study, it is not possible to determine at present if the distribution of gas hydrate is concentric about the Absheron volcano, but extrapolation of the occurrences to the west and north suggests an area of tens of square kilometers is characterized by buried gas hydrates.

A striking feature of the seismic sections is the close association of the gas hydrate occurrences and the presence of young shallow faulting which deforms the modern seafloor. While not a one-to-one correspondence, the gas hydrates where present, are commonly associated with the base of numerous high-angle strike-slip(?) and reverse faults which affect the upper 500-600 m of the sedimentary section (Figure 3). On the ABSHERON 1 profile, such evidence for shallow structural deformation is distinctly lacking on the western half of the section (Figure 3), despite the suggestion of active faulting from examination of the seabed morphology (Figure 1). In the case of the ABSHERON 2 profile, the gas hydrate continues well down-dip of the southern extent of shallow faulting, but coincides with a marked change in seabed slope at the boundary between continental rise and abyssal plain.

Examination of the spatial association of gas hydrates, shallow faulting, and seabed morphology (Figure 1) suggests that gas hydrates may have played (and continue to play?) a critical role in structural destabilization of the continental slope in this region. An area in excess of 200 km^2, covering the eastern half of the ABSHERON 1 profile, and extending tens of kilometers up-dip of the Absheron mud volcano is characterized by a structurally complex and actively deforming(?) seabed. Given the complexity of disruption, the relatively sharp boundaries to the zone of deformation, the discontinuity of stratigraphy across these boundaries, and the shallow level of detachment, we here refer to this feature as the Absheron allochthon (Figure 5). Comparison of the slope of the continental rise in this region shows a much shallower slope than the areas to both the northeast and west (inset on Figure 1). While it might be tempting to relate this change in slope to recent deltaic deposition, evidence from the seismic data presented here suggests this continental slope is in structural failure, and is controlled at the base and toe by the presence of gas hydrates in the subsurface. This interpretation, if correct, implies that the slope region within the Absheron area is highly unstable, and subject to continuing structural failure under natural geologic processes.

Deformation within the Absheron allochthon must be very recent (and ongoing?) process, as suggested by the exaggerated seabed topography and evidence for faulting at the seabed on the seismic profiles. Close inspection of the zone of gas hydrate at the toe of the Absheron allochthon on the ABSHERON 2 profile indicates that the frontal thrust can be traced from the base of the gas hydrate (BAH) and cutting across the top of the hydrate

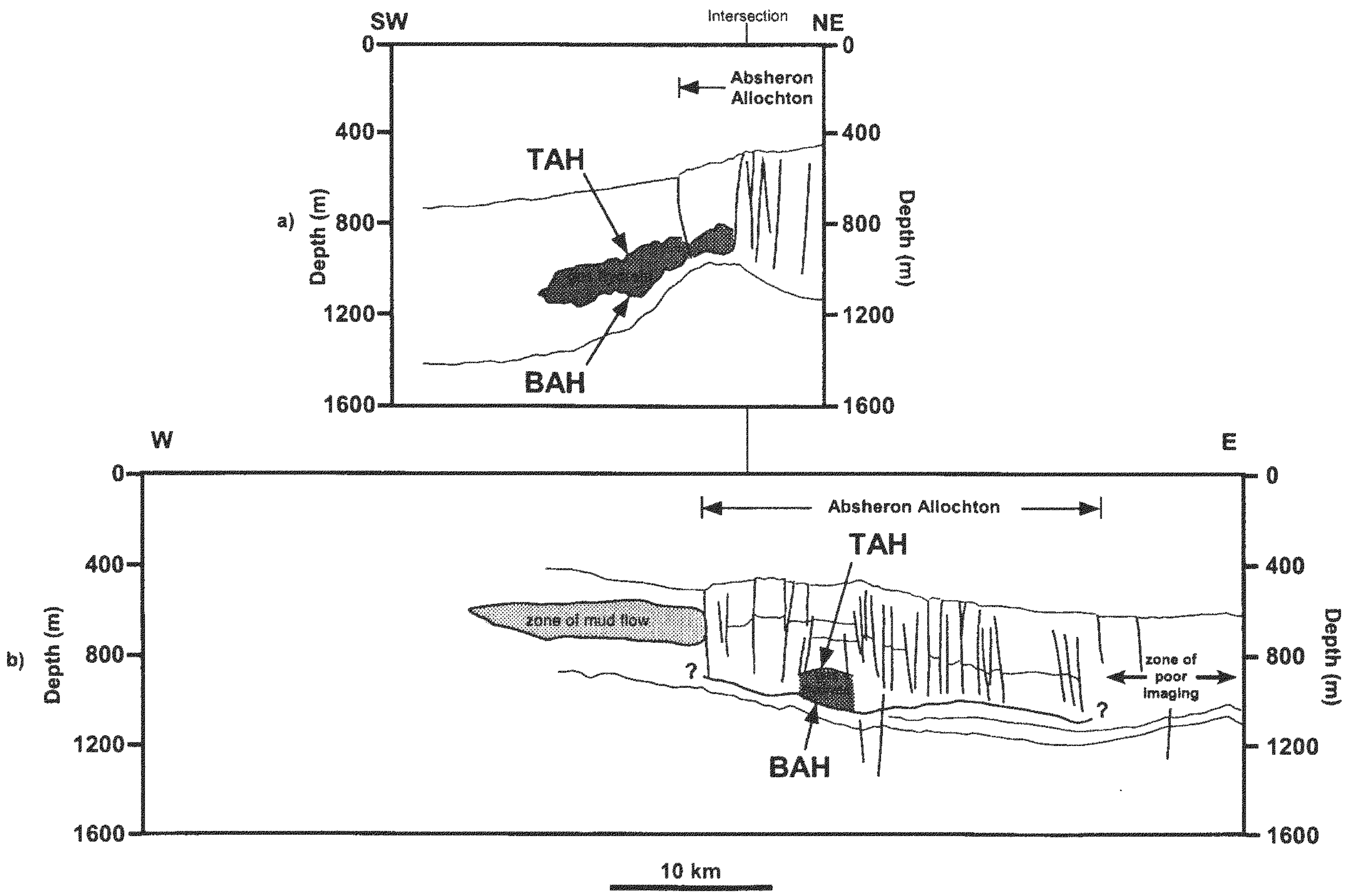

Figure 5. Structural interpretation of the ABSHERON 1 and 2 profiles shown in Figure 3, as it relates to the presence of buried gas hydrates well beneath (~300 m) the seafloor. The shallow faulting inferred to be related to gas hydrate occurrence is labelled as the Absheron allochton

(TAH), but without significant offset. We interpret this relationship as further evidence that the presence of the gas hydrate is serving to localize deformation in the overlying allochthon, and that the hydrate body is thermodynamically maintained, resulting in rapid re-equilibration of gas hydrate across the frontal toe thrust of the allochthon.

3. ABSHERON GAS HYDRATES AS GEOLOGIC HAZARDS

Absheron gas hydrates represent one of the first examples of buried gas hydrates found in marine sediments. The thickness and depth of the interpreted gas hydrate occurrence on the ABSHERON profiles fit within the hydrate stability field predicted from thermobaric modelling, but in considerably thinner layers. Such a potential discrepancy between the observed and predicted top and base of the gas hydrate stability field was theoretically documented by Xu and Ruppel (1999). These seismic reflection data confirm that gas hydrates could form in buried layers well beneath the seafloor. Among possible causes of this discrepancy could be: (1) variation of gas migration rates as well as fluctuation in mass fraction of hydrocarbon gases in bottom water (Xu and Ruppel, 1999), (2) irregular gas supply (gas hydrates are stable at the seafloor only if there is a constant supply of gas at sufficient rates (~2 km/My for the past 5 My; Devlin et al., 1999; Diaconescu et al., in review, b), (4) continuing shallow slope failure which appears to detach at the base of the gas hydrate layer (Figure 5) and it does cause or/and is caused by dissociation of the gas hydrate structures within the host sediments.

Thermobaric modelling of gas hydrates in the study area, based on both thermogenic and biogenic gas compositions as identified from coring at the seafloor (C in Figure 1), suggests that gas hydrates may be stable in water depths as shallow as ~150 m, much shallower than other areas reported worldwide for gas hydrate formation (Malone, 1994). Moreover, the maximum predicted thickness of the gas hydrates in the South Caspian sediments reaches ~1,225 m (for water depth of 475 m; Figure 2), considerably thicker than other known hydrate occurrences (Malone, 1994). These predictions corroborated by the evidence for buried gas hydrates, place the gas hydrates of the South Caspian Sea ahead others with respect to potential geo-hazards.

Based on their geophysical signature, the gas hydrates of the South Caspian Sea are characterized by (1) a depth-restricted, lenticular body well beneath the seafloor, (2) the apparent accumulation of free gas within the underlying sediment, and (3) evidence of associated recent slope failure in the overlying strata. Such attributes make these gas hydrates important, and perhaps previously underestimated, geo-hazards of the South Caspian region. Primary among these are uncontrolled release of free gas trapped beneath the hydrate seal, or disruption of the gas hydrate stability field leading to either explosive dissociation of the gas hydrate, or reduction in sediment strength, slope instability, and mass sediment transport. Association of gas hydrates with active mud volcanoes in the South Caspian Sea, such as the Absheron mud volcano, increases the potential for offshore flaming eruptions, as attested to in historical records (Bagirov and Lerche, 1997). Documentation of the presence and distribution of gas hydrates, especially when concealed at depth in the subsurface, is a clear pre-requisite for exploration activities in the deepwater region of the South Caspian.

Shallow faulting (SF) associated with slope failure on the flanks of the Absheron anticline appears to be controlled by the base of the gas hydrate layer (Figs. 3 and 5). In turn, the gas hydrate stability field appears to have re-equilibrated across a set of young structures that deform the seafloor. The gas hydrate zone disappears on the seismic section toward the north-east and west (beyond 20 km in Figure 2) due most likely to the decrease of pressure derived from decreasing water depth, as well as possibly lower supply of hydrocarbon gas as it departs from the location of the Absheron mud volcano.

Summary information on the hydrate stability field in our study area was used to build a tornado-type diagram (Figure 6) that aims to emphasize the sensitivity of the hydrate thickness to the geothermal gradient, seawater depth, salinity, sea floor temperature, and gas composition. The base values used to build the tornado-type diagram were chosen toward the lowest temperatures in the study area (5.85°C for the sea floor temperature and 11°C/km for the geothermal gradient). Regarding the variation of the thickness of the hydrate stability field with the gas composition, only 10% ethane added to 90% methane was considered in Figure 6. If heavier hydrocarbon gases are introduced in system, then the upper limit of the gas hydrate thickness in the study area increases beyond the limit of the 1,350 m. As is shown in Figure 6, the geothermal gradient and the water depth have the greatest influence on the gas hydrate thickness. The predicted thickness of the gas hydrate stability field below the seafloor varies between 0-1,350 m. The upper limit of the predicted gas hydrate thickness was calculated for a maximum water depth of 690 m, which corresponds to the maximum water depth of gas hydrate occurrences on the ABSHERON profiles. Since the activity in the Caspian Sea has moved recently in the deep water that provides new potential for future petroleum discoveries, the presence of buried gas hydrates in the shallow sediments is a significant concern for exploration related hazards.

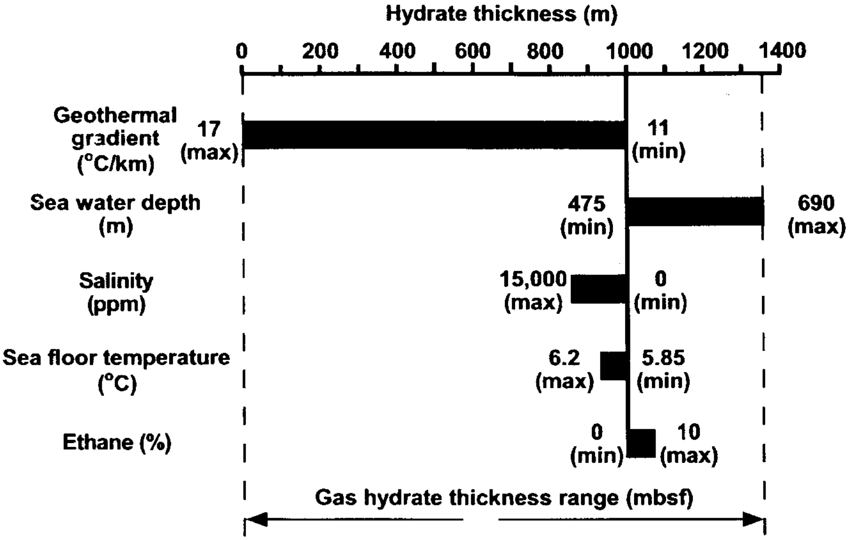

Figure 6. Tornado-type diagram for predicted thickness variation of the gas hydrate stability field in the study area. Base line was considered at 1,000 m. Most conservative scenario is shown, without consideration of seawater salinity and ethane addition. If heavy hydrocarbon gases are added, the thickness of the gas hydrate layer can exceed the upper limit of 1,350 m shown. Why most conservative? Because of safety issues in drilling hazards.

4. CONCLUSIONS

The results of this study suggest that gas hydrates (1) are possibly widespread features in the deepwater of the South Caspian Sea, (2) can occur as buried deposits well beneath the seafloor, and accordingly, (3) may represent significant and previously underestimated geo-hazards. Conversely, given the growing demand for natural gas, the predicted presence of the South Caspian gas hydrates in thick (~1,350 m in the study area) layers could make them attractive to the petroleum industry in the years to come.

Seismic evidence for the thermobaric modelling of gas hydrates in the South Caspian Sea, offshore Azerbaijan, reveal some of, if not, the first buried gas hydrates found in marine sediments. The Absheron gas hydrates occur within a relatively restricted depth range (800-1,200 m), and are seismically defined by higher ($V_p \approx 2.1$ km/s) seismic velocities, seismic blanking, a positive-polarity top (TAH) and a negative-polarity bottom (BAH; Figs. 3 and 5). In all cases, the observed Absheron hydrate occurrence falls within the modeled stability field, but typically at shallower depths and in thinner (~200 m) layers.

The gas hydrates in the study area are buried well beneath the seafloor, and possibly serve as a seal for free gas accumulation underneath. This characteristic, in association with the close spatial relationship of the gas hydrates with the nearby mud volcano make them important drilling hazards. The slope region within the Absheron area (Figure 1) appears to be highly unstable, and subject to continuing structural failure under natural geologic processes controlled by the presence of gas hydrates (the Absheron allochton). The gas hydrate layer appears to be a dynamic feature that re-equilibrates across the overlying shallow structural faulting.

The gas hydrates of the South Caspian Sea pose a significant potential safety problem during conventional hydrocarbon operations, including (1) uncontrolled release of free gas trapped beneath the hydrate seal, (2) man-triggered or natural disruption of the gas hydrate stability field leading to either explosive dissociation of the gas hydrate, or/and (3) reduction in sediment strength, slope instability, and mass sediment transport.

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