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# Observation and tentative interpretation of a double BSR on the Nankai slope

Jean-Paul Foucher[a,*], Hervé Nouzé[a], Pierre Henry[b]

[a] Département Géosciences Marines, Centre IFREMER de Brest, P.O. Box 70, 29280 Plouzané, France
[b] Laboratoire de Géologie CNRS UMR 8538, Ecole Normale Supérieure, 24 rue Lhomond, 75231 Paris Cedex 05, France

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## Abstract

Seismic data collected during the French–Japanese KAIKO-Tokai cruise of R/V *L'Atalante* on the upper slope of the eastern Nankai margin reveal the simultaneous presence at two distinct depths below the seafloor of two bottom simulating reflector (BSR)-type reflectors. The upper BSR is traced as a continuous reflector over about 10 km. As water depth decreases from 850 m to 550 m, its depth below seafloor decreases from 200 m to 40 m. The lower BSR is traced at 50–100 m below the upper one. The two BSRs end abruptly near the summit of the Daichii-Tenryu Knoll into an area where the 3.5-kHz record suggests active gas expulsion through the seabed. The observed depth of the upper BSR fits the predicted one for the base of the methane gas hydrate stability zone as estimated from present temperature and pressure conditions at the seafloor and in the slope sediments. Thus, we interpret the upper BSR as an active methane hydrate BSR. We further suggest that the lower BSR is a residual hydrate-related BSR. This could have followed a recent migration of the base of the methane hydrate stability zone from the lower BSR to the upper one. As possible causes for this migration we discuss sea bottom warming and tectonic uplift. The BSR migration could have occurred as a response to a 1–2°C sea bottom warming or, with an equivalent effect, an event of fast uplift of the seafloor by about 90 m. We do not discard other interpretations of the lower BSR, such as an active hydrate-related BSR formed from a mixture of gases. 

*Keywords:* active margins; bottom-simulating reflectors; gas hydrates; fluid dynamics

## 1. Introduction

Bottom simulating reflectors (BSRs) form at the transition from sediments containing a variable amount of solid gas hydrate, above, to sediments containing a small volumetric fraction, typically a few percent, of free gas, below (Andreassen et al., 1995; MacKay et al., 1994; Miller et al., 1991; Paull et al., 1996; Singh et al., 1993; Tinivella et al., 1998). Hydrate-related BSRs consequently lie at depths that closely correspond to the base of the hydrate stability zone (Hyndman et al., 1992), although discrepancies have been reported (Bangs et al., 1993; Ruppel, 1997). BSR depths are thus dictated to a large extent by the temperature and pressure conditions existing in the seafloor. Furthermore, in response to variations of temperature and pressure in the seafloor, BSRs are expected to change position, mov-

* Corresponding author. Tel.: +33-298-22-42-69; Fax: +33-298-22-45-70.
*E-mail address:* jfoucher@ifremer.fr (J.-P. Foucher).


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ing up or down, in conjunction with the vertical migration of the base of the hydrate stability zone induced by those variations (e.g. Delisle et al., 1998). A number of questions remain as to the nature of the migration of the BSR that one expects to occur, among them how long a residual BSR can last or how fast a new BSR gains its reflectivity. While one may suggest that answers to those questions depend on the nature and time constant of such governing phenomena as gas diffusion away from a dissociating gas hydrate or hydrate formation in a gas flux, there is a need for field data that document the migration of BSRs.

This paper brings attention to a particular BSR feature observed on the upper slope of the eastern Nankai margin. The area examined is on the southern flank of the Daichii-Tenryu Knoll, in water depths of less than 800 m. Seismic data, acquired during a French–Japanese KAIKO-Tokai cruise on board *L'Atalante* in March 1996, show the simultaneous presence at two distinct depths below the seafloor of two BSR-type reflectors. The two reflectors display characteristic properties of BSRs: they crosscut stratigraphic horizons and exhibit negative amplitudes. While BSRs are commonly observed on the Nankai margin, the occurrence of what we will refer to, in the following, as a double BSR is quite unusual. Its geographic extension appears to be restricted to the shallowest portions of the seismic lines exhibiting BSRs across the eastern Nankai slope. The nature of this double BSR is intriguing.

Posewang and Mienert (1999) have previously reported the occurrence of a double BSR on the margin west of Norway. Although these authors do not propose any definitive explanation to account for it, they suggest that the lower BSR may represent a relict of former changes of the gas hydrate stability field from glacial to interglacial times or the base of gas hydrates with a gas composition including heavier hydrocarbons. In the following, we present seismic evidence from eastern Nankai and examine the significance of the double BSR, focusing our discussion on the effects of a change in temperature or pressure in the seafloor.

## 2. Seismic data

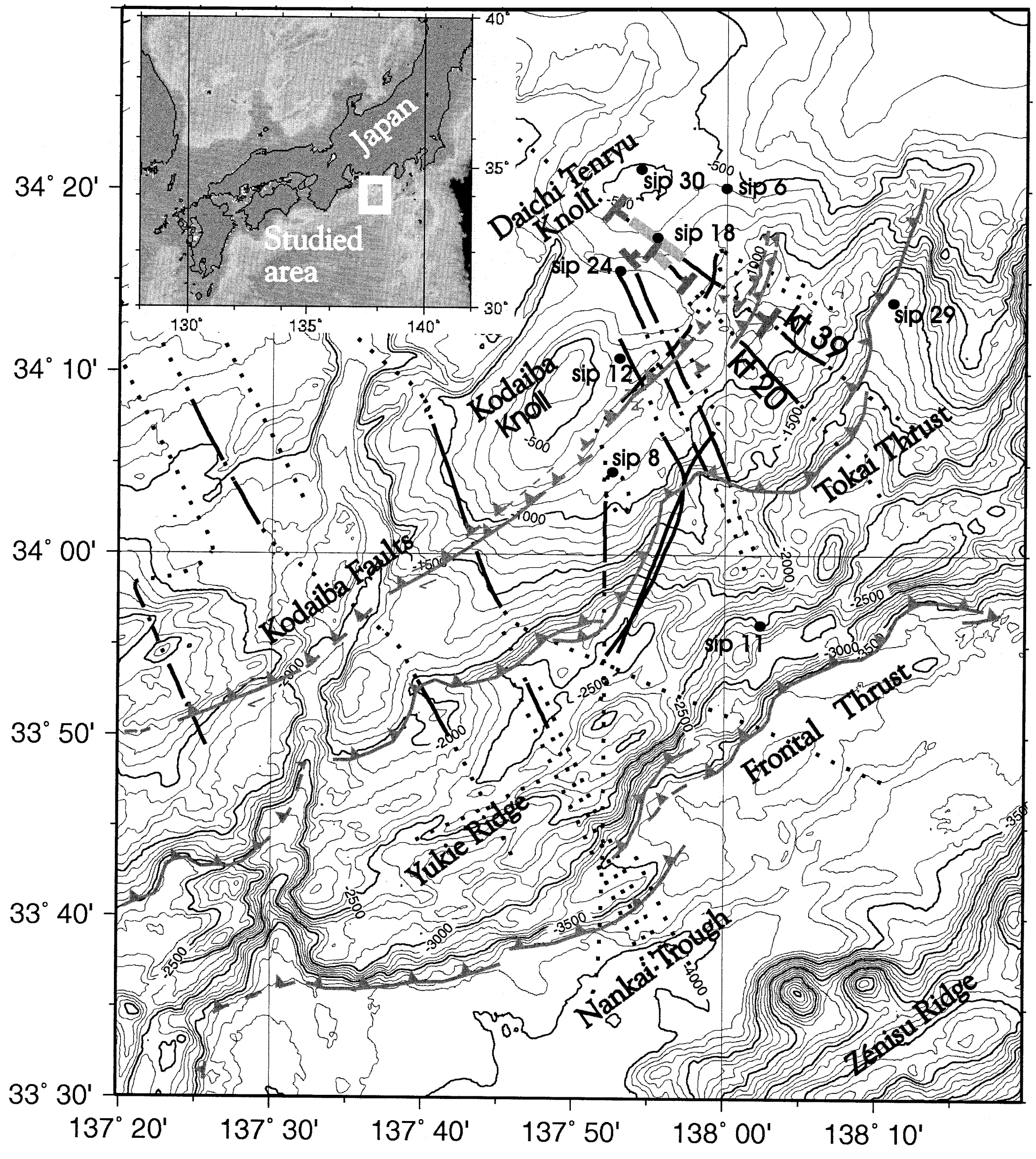
### 2.1. Seismic acquisition and processing

The seismic acquisition method is outlined in Fig. 2. The seismic source consisted of two air guns (GI guns with two chambers, a generator chamber and an injector chamber). The two guns were shot every 11 s. At the ship's speed of about 2 knots, the distance between shot points was about 11 m. The receiver configuration was unusual. A deep-tow hydrophone streamer, navigated about 100 m above the seafloor (the PASISAR seismic receiver; Savoye et al., 1995), was used jointly with a conventional streamer towed at the surface. The two streamers are single channel receivers. Data from both streamers were recorded at a sampling frequency of 500 Hz. To account for the time-varying source–receiver geometry with PASISAR, a correction is applied to the deep-tow data, assuming subhorizontal reflectors and a uniform 1500-m/s acoustic velocity (Nouzé et al., 1997). As shown in Fig. 3, this correction gives good results. The corrected deep-tow profile is similar to the surface one but spatial and temporal resolutions are higher on the deep-tow profile.

### 2.2. BSR distribution on the eastern Nankai slope

BSRs are commonly observed on the slope of the Nankai margin, on both its western (Yamano et al., 1982; Ashi and Taira, 1993) and eastern (Ashi et al., 1998) parts. They appear to be continuous on seismic sections over distances of up to several kilometers. In our study area, BSRs are observed in water depths ranging from 3 km to about 700 m, from the outer portion of the accretionary prism to the flanks of the Kodaiba and

Fig. 1. Location map of PASISAR deep-tow seismic profiles and SIPPICAN depth profiling temperature measurements on the eastern Nankai margin. Active faults after The Research Group for the Active Submarine Faults off Tokai (1999).




Thin line : single BSR observed

Thick grey line : double BSR observed

..... Dotted lines : deep-tow profiles

displayed sections

• sip Sippican temperature profile

Fault locations after atlas published by the Research Group For Active Submarine Faults Off Tokai, 1999.

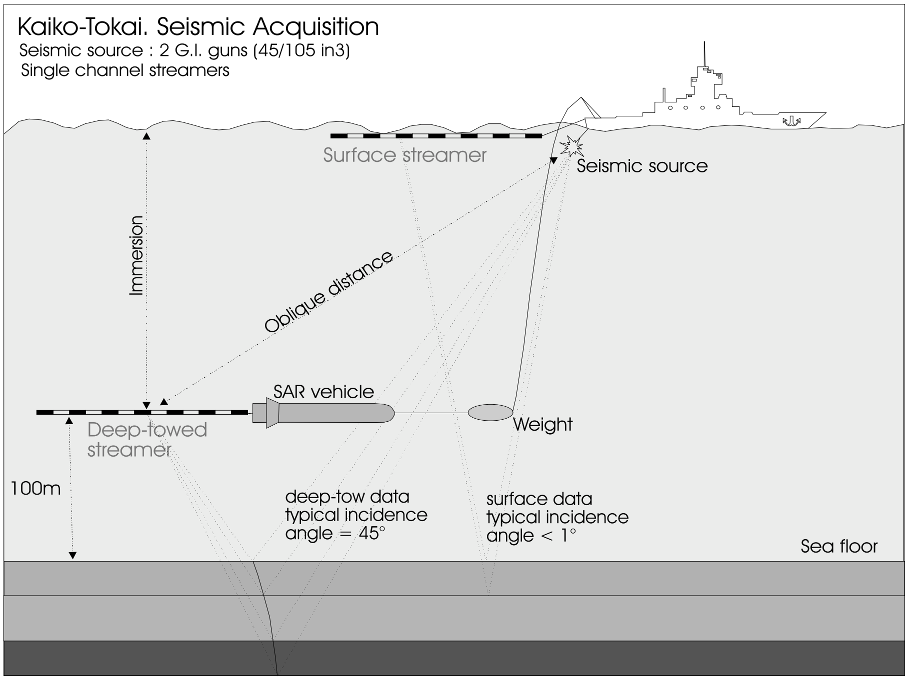



Fig. 2. Sketch illustrating the use of a deep-tow streamer (PASISAR towed at 100 m above seafloor) during the KAIKO-Tokai cruise, in addition to a conventional surface streamer. Reflection points plot on a hyperbola, assuming horizontal reflectors and uniform velocity (1500 m/s) in water and sediments.

Daichii-Tenryu knolls on the upper slope (Fig. 1). The depth of the BSR below the seafloor decreases upslope from about 500 m to less than 100 m at its shallowest occurrence. Assuming that the BSR lies at the base of the methane hydrate stability zone, Ashi et al. (this issue) inferred temperature gradients between the seafloor and the BSR depth of 35–75°C/km.

### 2.3. Seismic evidence for a double BSR

The following description is based on profile 39, but similar observations are made along profile 20 over the limited record available. The uppermost BSR (BSR1 in Fig. 3) is traced as a continuous reflector over about 10 km (between $x = 5$ km and $x = 15$ km in Fig. 3). As water depth decreases from 850 m to 550 m, the depth below seafloor of BSR1 decreases from 200 m to 40 m. BSR1 has a strong negative amplitude throughout its lateral extent (Figs. 3 and 4). Stratigraphic reflections are enhanced below it between 11 and 15 km (Fig. 3). This amplitude enhancement is likely to be related to the presence of gas in the sediment. A different situation prevails between 6 and 11 km. There, the transition from acoustic blanking to amplitude enhancement is traced as a distinct boundary, which does not coincide with BSR1 but instead lies up to 60 m above it (Figs. 3 and 5). The reason for this excursion above BSR1 of the amplitude enhancement domain is not known (indication of some free gas above BSR1?).

The lower BSR (BSR2 in Fig. 3) is traced at a variable depth, increasing upslope from 50 m to 100 m, below the upper one (BSR1). Its signature is unambiguous between 8 km and 10 km on profile 39. Although seismic penetration in the sediment below BSR2 is unfortunately very limited, BSR2 appears to crosscut dipping stratigraphic reflectors, which is an important observation made on the PASISAR record but is also confirmed by the record from the surface streamer

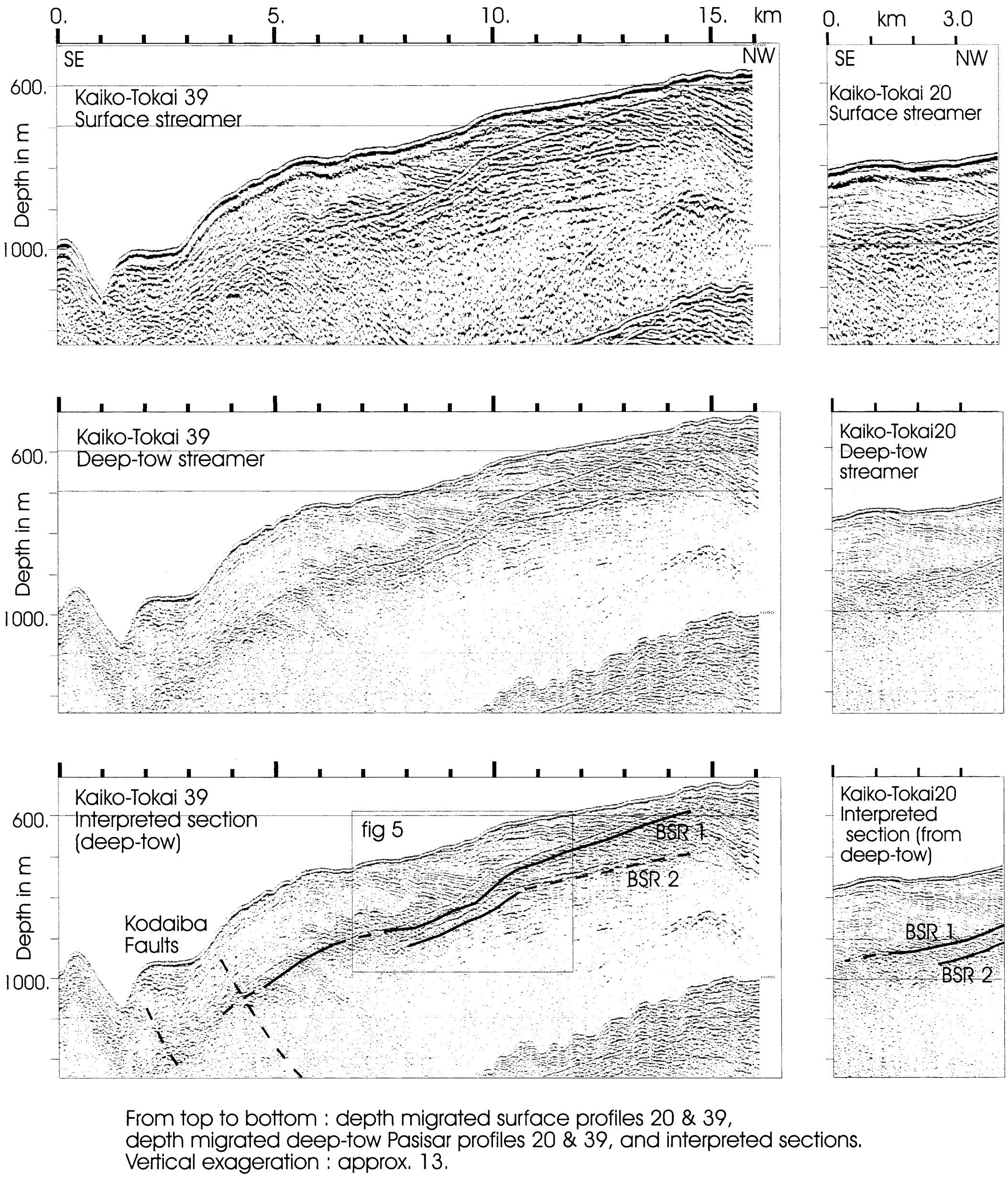



Fig. 3. Seismic sections 20 and 39 (locations in Fig. 1) showing the two BSRs in water depths of 550–850 m. Seismic section 20 ends after a short distance upslope along the double BSR extension (Fig. 1).

(Fig. 5), thus precluding any acquisition or processing artefact that could be feared if visible only on the unusual PASISAR record. BSR2 has a negative amplitude (Fig. 4). Beyond point 10 km (Fig. 3), the polarity of the reflection appears to change to positive but cannot be assessed with certainty because of the interaction with sedimentary reflectors.

Short segments of high amplitude reflections can also be traced between BSR1 and BSR2

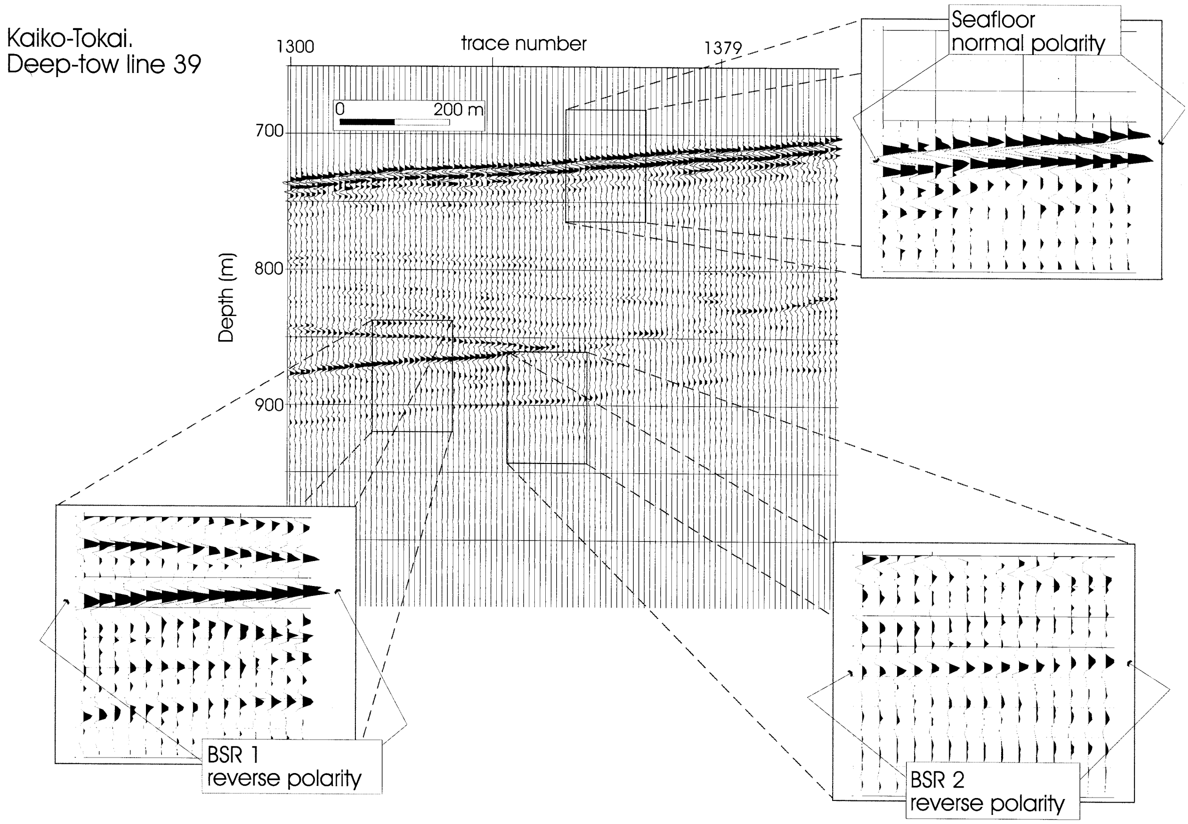



Fig. 4. Zoomed seismic section 39 (water depth 720–730 m) displaying amplitudes and phases of the two BSRs.

(Fig. 5). These segments have the same dip as BSR2 and appear to crosscut stratigraphic reflectors as well.

*2.4. BSR termination on Daichii-Tenryu Knoll*

On profile 39, the two BSRs end abruptly near the summit of the Daichii-Tenryu Knoll (Figs. 3 and 6). At this point, the upper and lower BSRs are at their shallowest depth below the seafloor, 40 m and 190 m respectively. Beyond this point and for a distance of approximately 800 m, the 3.5-kHz record shows a zone of high backscatter where sedimentary reflectors are masked (acoustically opaque zone). Sedimentary strata are, however, imaged on either side of the opaque zone (Fig. 6). This type of observation is typical of zones where gas is present at a shallow depth in the sediment (e.g. Veerayya et al., 1998). We hypothesize that gas emission occurs in the region where the opaque zone reaches the seafloor.

## 3. Nature of the reflectors

Of the two BSRs identified on the flank of Daichii-Tenryu Knoll, the upper one (BSR1) has the strongest amplitude and greatest length of continuous occurrence. It also shows a clear reverse polarity phase throughout its lateral extent. Consequently, we infer that the upper reflector most likely corresponds to the present-day base of hydrate stability (the active BSR). In 3.1. The upper reflector: an active methane hydrate BSR, we show that this inference is coherent with our knowledge of the present-day temperature and

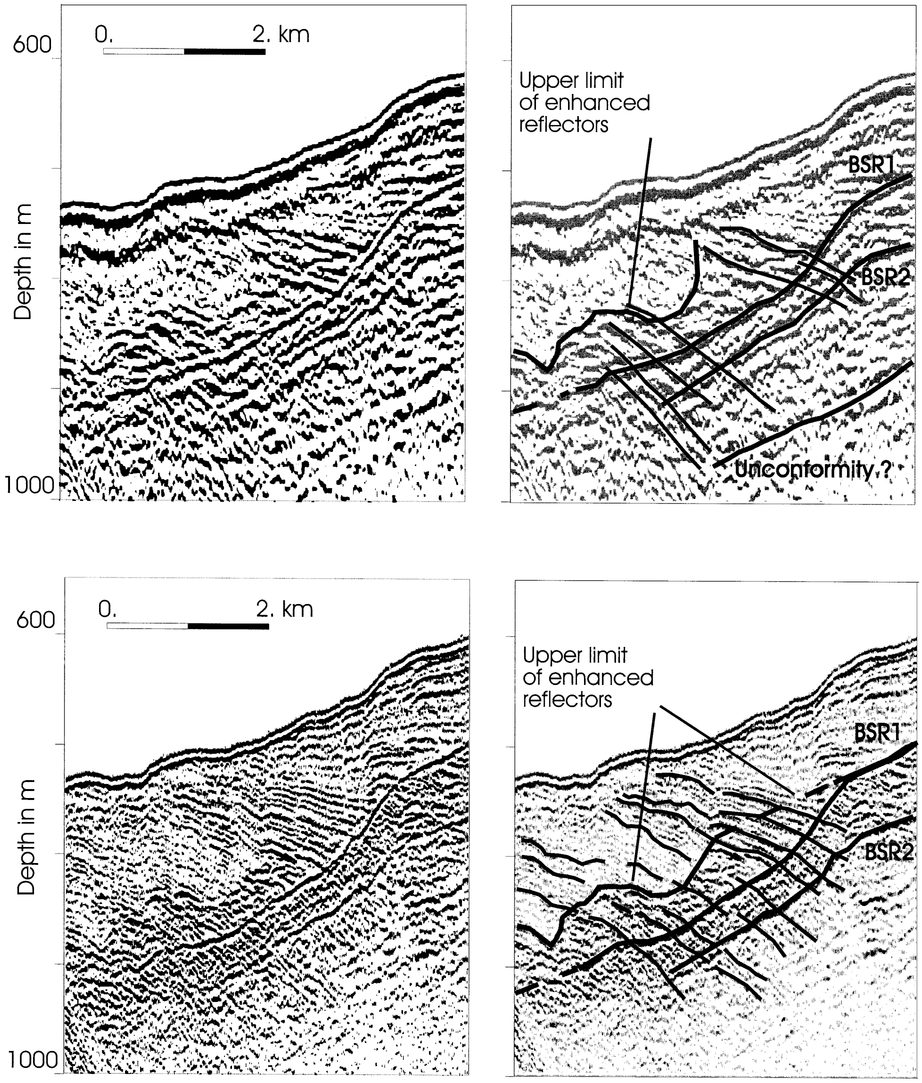



Fig. 5. Zoomed seismic section 39 (location in Fig. 3) showing seaward dipping stratigraphic reflectors and BSRs cutting across those stratigraphic reflectors. Note the enhanced amplitudes of stratigraphic reflectors above BSR1. Surface streamer: top. Deep-tow streamer (PASISAR): bottom.

pressure conditions at the seafloor and that the hydrate-forming gas is probably pure methane. We then consider various hypotheses that may explain BSR2.

### 3.1. The upper reflector: an active methane hydrate BSR

In Fig. 8, the *P–T* dissociation curve of pure methane hydrate in seawater (Dickens and Quinby-Hunt, 1994) is plotted together with all eight SIPPICAN temperature profiles that we collected in water depths of less than 1.8 km during the KAIKO-Tokai cruise primarily for the purpose of processing swath bathymetry data. The average SIPPICAN temperature profile intersects the dissociation curve of methane at a depth of 520 m (between 480 m and 560 m for extreme temperature profiles; Fig. 8). This depth closely approaches the water depth of 510 m at which the

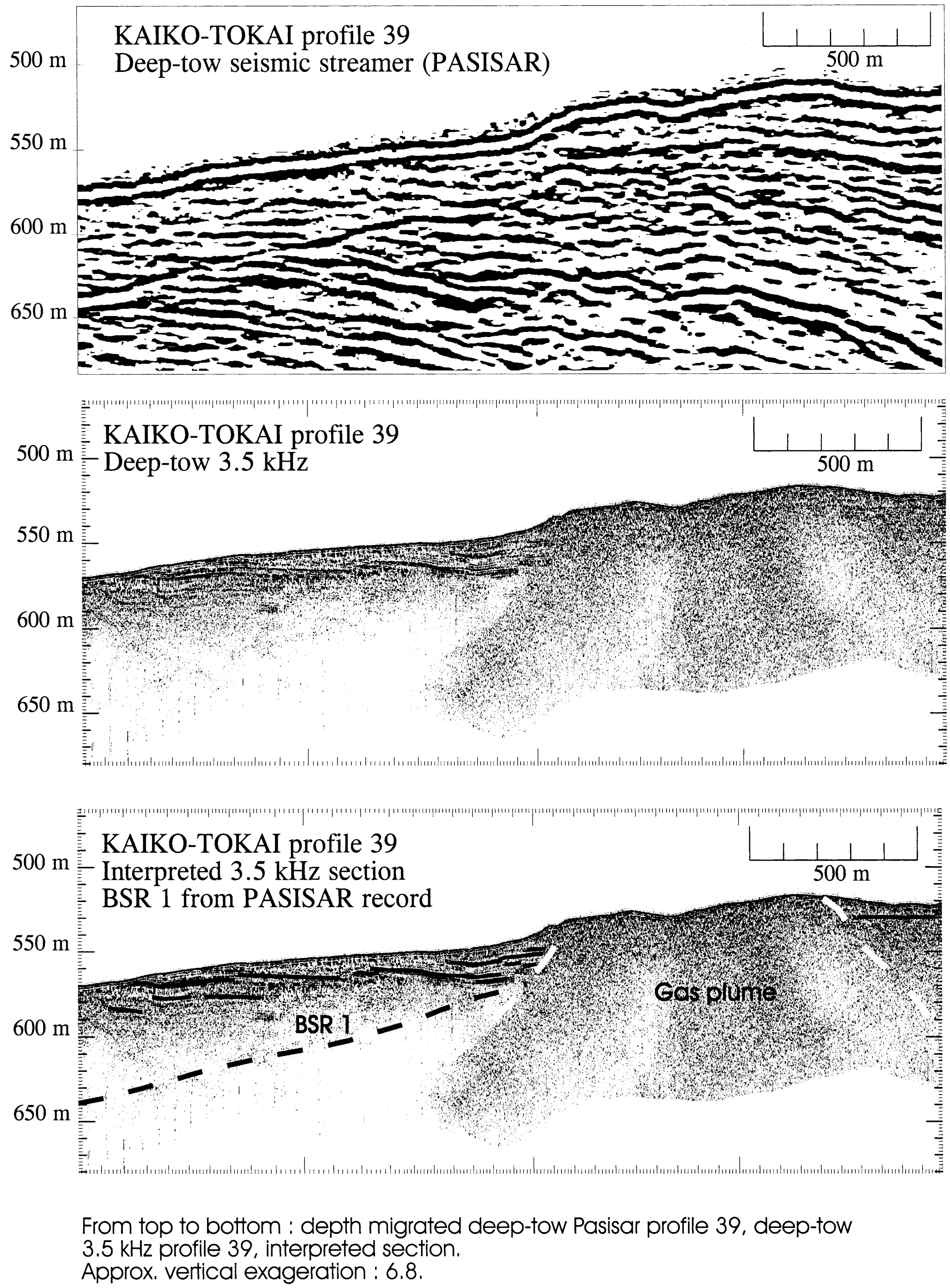



Fig. 6. From top to bottom: upper end of BSR1 on the southern flank of the Daichii-Tenryu Knoll (from seismic section 39), deep-tow 3.5-kHz record for the same area at the same horizontal and vertical scales, and interpreted 3.5-kHz record with indication of a large gas plume in sediments upslope of the BSR's end.

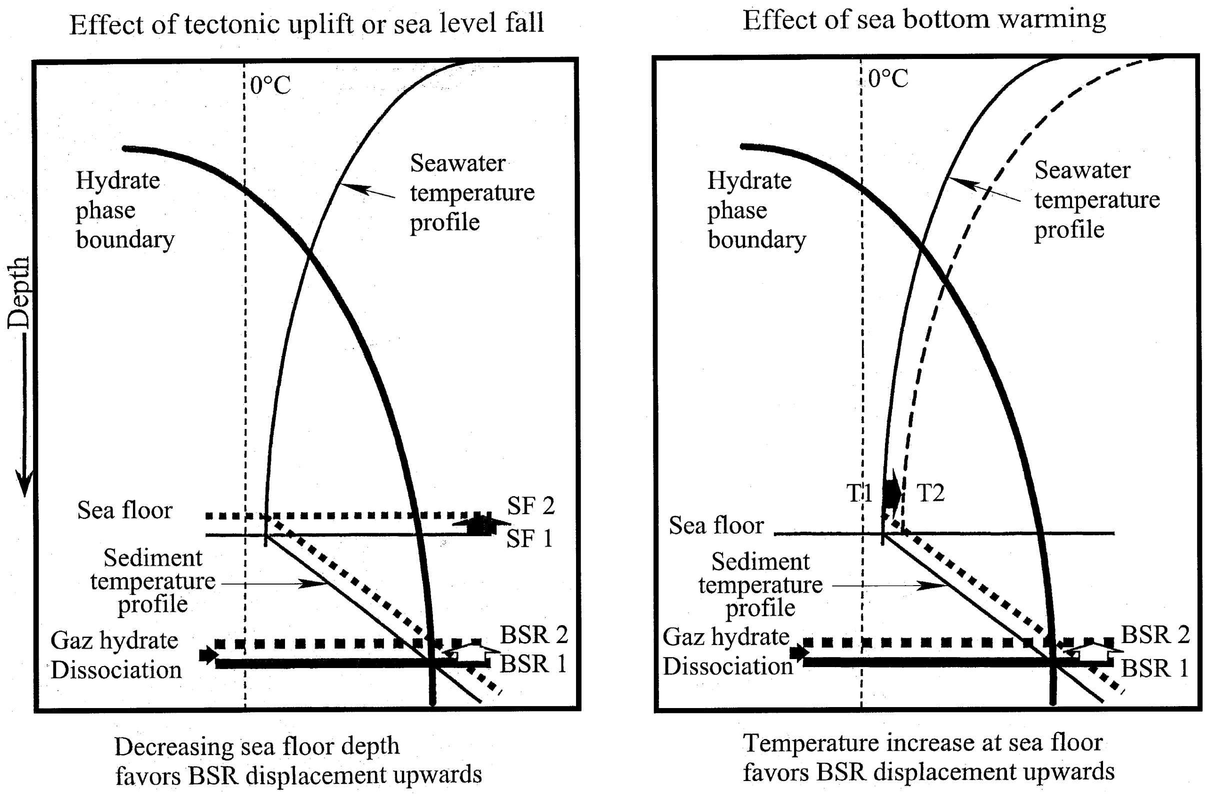



Fig. 7. Sketch illustrating migration of BSR (at base of gas hydrate stability zone) as a consequence of a retracting zone of gas hydrate stability in response to a pressure decrease at the seafloor consecutive to tectonic uplift or sea level fall (left), or a sea bottom warming (right).

upper reflector (BSR1), if linearly extrapolated, would intersect the seafloor on profile 39 (Fig. 5). This is a strong indication that this upper reflector is an active methane hydrate BSR.

We further compared the predicted and observed depths of the BSR over the total lateral extent of the upper reflector, between points 5 km and 15 km on profile 39. The depth of BSR1 is estimated from the seismic travel time data, assuming a constant P-wave velocity of 1.7 km/s, which is in the range of velocities between 1.7 and 1.8 km/s which we found to be acceptable from a comparison of the travel time data, from the surface streamer working at small (2–3°) incidence angle on the one hand, and the deep-tow streamer working at large (about 40°) incidence angle on the other hand (Fig. 2). BSR1 depths best match the base of the pure methane hydrate stability zone when a temperature gradient of 35°C/km from the seabed to this reflector is assumed (Fig. 9). This temperature gradient of 35°C/km compares well with a 38°C/km preliminary estimate from borehole temperature measurements made at the nearby JNOC drilling site (Matsumoto et al., 1998). The good agreement between the observed and computed depths confirms our interpretation of the upper reflector as an active methane hydrate BSR.

### 3.2. *A tentative interpretation of the lower reflector*

We consider in this section several interpretations of the lower BSR, from a reflector that is related to a diagenetic front, such as the opal-A/opal-CT transition, to two hydrate-related interpretations, either that BSR1 and BSR2 relate to

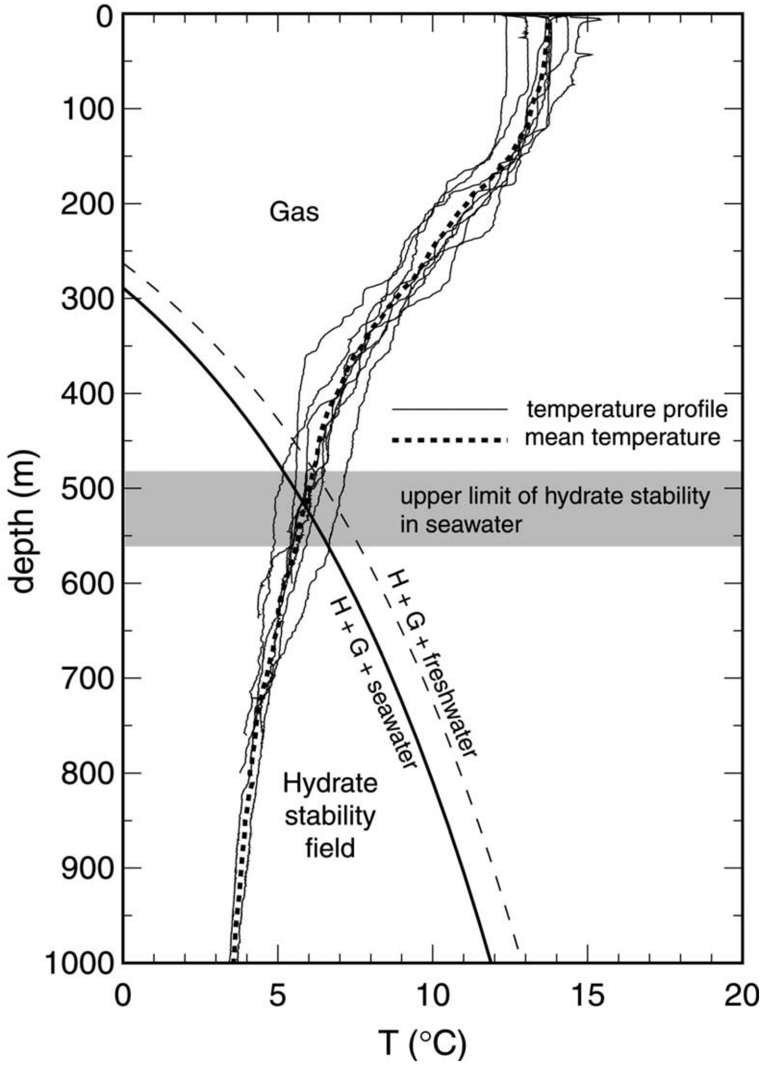



Fig. 8. Measured SIPPICAN temperature profiles with depth, intersected by the stability curves for methane hydrate+gas+freshwater (dotted line) and methane hydrate+gas+seawater (thick continuous line). The inferred upper limit of methane hydrate stability in seawater (the water depth at which a methane hydrate BSR is expected to intersect the seafloor) is between 480 and 560 m (in gray).

distinct stability fields for hydrates formed from two different gas mixtures, or that BSR2 is a residual BSR left in the sediment after migration upward of the stability field.

### 3.2.1. *BSR2 as a diagenetic front*

Diagenetic reactions, such as the opal-A/opal-CT transition, are known to produce reflectors that, similarly to hydrate BSRs, have the characteristics to mimic the shape of the seabed and to crosscut stratigraphic reflectors. However, those reflectors related to a diagenetic front are not expected to show a reverse polarity. BSR2, instead, shows several segments with a reverse polarity. Furthermore, the opal transition occurs at a higher temperature than that estimated at BSR2 (Kuramoto et al., 1992; Langseth and Tamaki, 1992). It is also worth noting that the sediments on the Nankai margin have a dominantly detrital component and are thus not expected to produce a

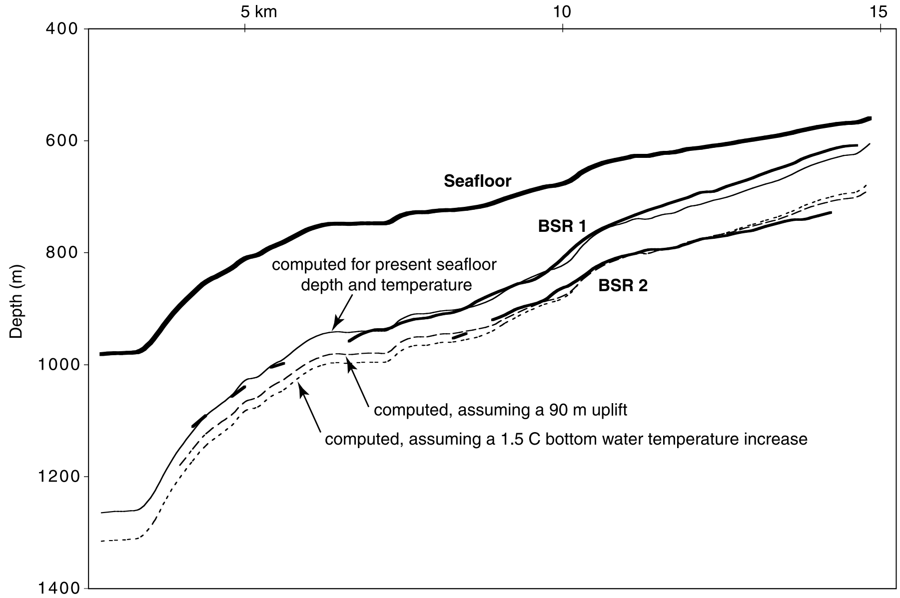



Fig. 9. Plots of observed depths to seabed, BSR1 and BSR2 (thick continuous lines) for comparison with computed positions of BSR1 (thin continuous line) for present temperature and pressure conditions at seafloor and in sediments, and computed positions of BSR2 assuming that displacement from BSR2 to BSR1 followed a 1.5°C sea bottom warming (short dashes) or a 90-m uplift (long dashes).

sharp opal-CT transition, although siliceous layers are occasionally found. We conclude that BSR2 is very unlikely to be produced by the opal-A/opal-CT transition. On the basis of the reverse polarity observed along several segments of BSR2, any other diagenetic reaction is also unlikely to explain BSR2.

### *3.2.2. BSR2 as a hydrate BSR formed from a mixture of gases*

We assumed previously that the composition of the hydrate-forming gas at BSR1 was pure methane. Adding minor quantities (1–10%) of other gases such as ethane, propane, hydrogen sulfide or carbon dioxide to methane causes displacement of the hydrate stability threshold to higher temperature or pressure values than those of the stability threshold for a gas hydrate formed from pure methane (Sloan, 1998). When interpreting the upper reflector BSR1 as a pure methane BSR, we could explain the lower reflector BSR2 as a hydrate-related BSR formed from a gas mixture. Posewang and Mienert (1999) have put forward this explanation for the double BSR they observed on the Storegga margin off Norway. Analyses of dissolved gases at eastern Nankai seepage sites indicate a microbial origin of methane, whereas thermogenic methane was detected in a seawater plume further north in Suruga Trough (Gamo et al., 1998; Tsunogai et al., 1998). The presence of thermogenic methane may occur in association with other hydrocarbon gases such as ethane or propane, but observations of those gases, which would give support to interpret the lower BSR as formed from a gas mixture, have not been reported. The interpretation of the two BSRs on the Nankai margin by formation from two different gas mixtures does not appear to be supported by chemical data presently available. However, it cannot be totally discarded.

### *3.2.3. BSR2 as a residual hydrate BSR*

Pressure and temperature changes, when they occur in the sediment, displace the hydrate stability field. A pressure drop or a temperature increase similarly are expected to move upwards the base of the stability field (Fig. 7). We hypothesize here that the bottom of the hydrate stability field has moved upwards, from a previous depth where BSR2 is observed, to the current depth where BSR1 is found. We therefore interpret BSR2 as a residual BSR.

This interpretation holds as long as the concentration of free gas trapped in the sediment below BSR2 remains large enough for BSR2 to be reflective. A crude estimate for the duration of persistence of a reflective free gas layer is derived in the following. For gas saturation lower than the percolation threshold, gas bubbles are trapped and the process of gas dissipation is controlled by transport in the liquid phase (Henry et al., 1999). In this scenario, which assumes no advective transport, when taking the diffusion coefficient of methane in the sediment as 0.02 $m^2$/yr in the first 500 m of sediment (Martin et al., 1996), diffusion over 10 m (half the seismic wavelength) would occur in about 1000 yr for dissolved methane. Accounting for the presence of free gas, this characteristic diffusion time would be increased proportionally to the ratio of total methane concentration over dissolved methane concentration. A maximum value of the characteristic diffusion time, in the presence of free gas, can then be simply estimated by multiplying the characteristic diffusion time in the absence of free gas by this ratio. From measurements of total methane content on the cores drilled through the BSR on Blake ridge, this ratio may be up to 3–10 (Dickens et al., 1997), thus giving an estimate of the maximum characteristic diffusion time of the order of 10 000 yr. This crude approach suggests that the reflectivity of a diffusing gas layer may persist for several thousand years, with a maximum duration of the order of 10 000 yr. Persistence would tend to be shorter in case of active fluid flow. We conclude that BSR2 is unlikely to have persisted, as a residual BSR, for more than 10 000 yr or so.

## 4. Discussion

Whereas there is little doubt about the nature of BSR1, which was shown to have all characteristic properties of an active methane hydrate BSR, the nature of BSR2 appears to be more controversial. We suggested above that BSR2 could be a hydrate BSR formed from a mixture of gases or that it could be a residual BSR. Well data are probably needed to validate or discard the former interpretation. We focus our discussion here on the latter interpretation. We examine mechanisms that could be at the origin of the migration of the BSR in the sediment. The upward shift in depth of the BSR, from BSR2 to BSR1, may follow a rise of the bottom water temperature, or, which has similar effects, a pressure decrease in the seafloor such as one would expect after a sea level fall or an event of rapid tectonic uplift (Fig. 7). Fig. 9 shows that a sea bottom temperature rise of 1–2°C would account for the upward displacement of the BSR from BSR2 to BSR1 (predicted depth of the BSR shown for a 1.5°C rise in Fig. 9). Sea bottom warming could be explained by a downward shift of the thermocline or, more generally, by a temperature rise of the surface and intermediate waters, both phenomena affecting only the bottom sea water temperature on the upper slope, consistent with the observation of double BSRs only for the shallowest BSRs on the upper slope. Surface water temperatures in the area south of Tokai may be affected by the variability of the path of the Kuroshio that fluctuates not only on short (annual and decadal) but also on millennial timescales (Sawada and Handa, 1998). These authors document an increase of the surface water temperature of 3–4°C over the last 18 000 yr.

It is probably worth remembering that temperature changes at the sea bottom reach BSR depths only after some delay needed for heat propagation from the seafloor. The time constant, $T_C$, for conductive heat propagation to a depth $z$ of a step change in temperature occurring at the seafloor is inferred from erf $(z/2(\kappa T_C)^{0.5}) = 0.5$ (Louden and Wright, 1989), where $\kappa$ is the thermal diffusivity of the sediment. Taking $\kappa = 3\times10$–7 $m^2$/s, the time constant for conductive heat propagation from the seafloor to a depth of 200 m is 4700 yr, but to 100 m it is only 1200 yr. A sea bottom warming event, at the origin of the present migration of the BSR, could therefore have occurred a few thousand years ago. Should the sea bottom warming event be older and coincide for example with the end of the last glaciation (about 15 000 yr), an additional temperature rise at the seafloor of 1–2°C would be needed to balance the competing effect of the post-glacial rise in sea level, globally estimated at about 120 m (Chappell and Shackleton, 1986). However, a large temperature increase at the seafloor of as much as 3–4°C since the last glaciation may appear an unlikely event, and the scenario of a comparatively recent warming event of only 1–2°C may thus be favored. Also, it should be remarked that the scenario of a recent warming is more consistent with a shift of the BSR that occurred only recently, as required by the estimated short duration of persistence of the reflectivity of a residual BSR.

Fig. 9 shows that a uniform 90-m uplift of the seafloor would also explain the postulated migration of the BSR. The area where the double BSR is observed lies above the active Kodaiba thrust (Fig. 1). Compressive and strike-slip deformation of the inner part of the eastern Nankai wedge has been related to the subduction of NE–SW ridges that extended before subduction from the Izu–Bonin volcanic arc into the adjacent Shikoku basin (Lallemand et al., 1992; Huchon et al., 1998). A recent event of rapid uplift of the seafloor at Kodaiba and Daiichi-Tenryu knolls, which would explain the 90-m uplift required for the BSR shift, could be related to the subduction of such a ridge, the so-called paleo-Zenisu ridge (Le Pichon et al., 1996; Mazzotti et al., 2002). The seafloor uplift history at Daiichi-Tenryu Knoll is poorly documented. However, our present knowledge of the uplift history of Yukie Ridge, located about 15 km seaward of Daiichi-Tenryu Knoll (Fig. 1), which would consequently have undergone the effects of underthrusting of a paleo-Zenisu ridge at an earlier time than Daiichi-Tenryu Knoll, provides clues as to possible uplift rates at Daiichi-Tenryu Knoll. Lallemand et al. (1992) observe that the transition from sediment deposition to erosion on Yukie Ridge started 500 000–800 000 yr ago. They relate this transition either to incorporation of the Yukie Ridge sedimentary sequence from the trench fill into the accretionary wedge, or to uplift of the wedge slope above the underthrust paleo-Zenisu ridge. According to the latter scenario, the total amount of uplift of Yukie Ridge was 800–1600 m (from a seafloor depth of 2800–3600 to 2000 m) over 500 000–800 000 yr. The corresponding mean uplift rate is 1–2 mm/yr, whereas a 90-m uplift of Daichii-Tenryu Knoll for the last 10 000 yr or so (a maximum persistence time of a BSR reflector as discussed previously) would imply an uplift rate of the order of 1 cm/yr. Thus, the mean uplift rate inferred for Yukie Ridge, 1–2 mm/yr, is considerably smaller than that required at Daichii-Tenryu Knoll, 1 cm/yr, but was estimated over a much broader period of time, which may encompass peak uplift rates as high as a few cm per year which would easily account for the 90-m uplift of Daichii-Tenryu Knoll for the last 10 000 yr, and thus makes seafloor uplift a plausible explanation to the BSR shift.

One should further note, as reported earlier in this paper, that gas-loaded sediments are probably present in places at depths well above BSR1 (Figs. 3 and 5; between distances of 7 and 10 km). This might result from active updip gas migration from a free gas zone below BSR1. With respect to the interpretation of BSR1 as an active methane hydrate BSR and BSR2 as a residual BSR, this could also indicate that migration of the BSR is still an on-going process at these places. The inferred degassing at the upper termination of the BSRs (Fig. 6) may also be related to active hydrate dissociation in the seafloor in response to a changing pressure or temperature in the seafloor. These observations give additional support to the hypothesis of a fast evolving gas hydrate system active on the southern flank of Daiichi-Tenryu Knoll, on the Nankai slope, and to the interpretation of BSR2 as a residual BSR related to the reduction of the hydrate stability zone.

We finally comment that sediment heterogeneity and its interplay with the distribution of gas hydrate and free gas in the sediment, or with the dynamics of the gas hydrate system, have not been considered in this paper. In addition to a heterogeneity of the sediment properties inherited from deposition, irreversible sediment alteration may occur in zones where hydrates form or dissociate. For example, near surface precipitation of authigenic carbonates is a common occurrence at seepage sites and outcrops of cemented sediments have been observed at many locations on the eastern Nankai margin (Ashi and Tokuyama, 1998; Lallemand et al., 1992; Henry et al., this issue). It has also been remarked that bacterial methane oxidation is more active near hydrate accumulations in the sediment (Cragg et al., 1995). Carbonate precipitation may have occurred, in particular at the BSR2 level, with potentially significant effects on the permeability and reflectivity properties of the sediment. The purpose of our tentative interpretation of the double BSR in this paper was to outline explanations of available observations. Sediment heterogeneity would certainly need consideration when relevant data become available.

## 5. Conclusion

The KAIKO-Tokai seismic data reveal the presence of a double BSR on the upper slope of the eastern Nankai margin. We have focused our attention on the interpretation of this feature as a result of a recent (within the last 10 000 yr or so) upward migration of the base of the hydrate stability field. Among possible causes for BSR migration, we have examined sea bottom warming and tectonic uplift of the seafloor. Both mechanisms may have contributed to reduce the hydrate stability zone on the Nankai slope. Gas fractionation is a possible alternative explanation for the double BSR. Further high resolution surveys would greatly help to map the distribution and properties of the double BSR on the upper slope of the Nankai margin, while shallow drilling would eventually be essential to establish the nature of the double BSR.

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