I. The effect of salinity and temperature on larval development. *Physiol. Zool.*, 1996, **39**, 81–100.
7. Castile, Jr. F. L. and Lawerence, A. L., A comparison of the abilities of juvenile and adult *Penaeus setiferus* and *Penaeus stylirostris* to regulate the osmotic and chloride concentrations in the haemolymph. *Comp. Biochem. Physiol. A*, 1981, **68**, 677–680.
8. Dall, W., Hill, B. J., Rothlisberg, P. C. and Staples, D. J., The biology of the penaeidae. *Adv. Mar. Biol.*, 1990, **27**, 1–48.
9. Anger, K., Influence of salinity on larval development of the spider crab, *Hyas arameus*, reared in the laboratory. In *Marine Biology of Polar Regions and Effects of Stress on Marine Organisms* (eds Gray, J. S. and Christiansen, M. E.), John Wiley, Chichester, 1985, pp. 463–474.
10. Anger, K., Effects of temperature and salinity on the larval development of the Chinese mitten crab, *Eriocher sinensis* (Decapoda: Grapsidae). *Mar. Ecol. Prog. Ser.*, 1991, **72**, 103–110.
11. Anger, K., Salinity tolerance of the larvae and first juveniles of a semi-terrestrial grasped crab, *Armases miersi* (Rathbun). *J. Exp. Mar. Ecol.*, 1996, **202**, 205–223.
12. Anger, K., Harms, J., Montu, M. and Beker, De, C., Effects of salinity on the larval development of a semi-terrestrial tropical crab, *Sesarma angustipes* (Decapoda: Graspsidae). *Mar. Ecol. Prog. Ser.*, 1990, **62**, 89–94.
13. Brown, S. D., Bert, T. M., Tweedale, W. A., Torres, J. J. and Lindberg, W. J., The effects of temperature and salinity on survival and development of early life stages of the Florida stone crabs, *Menippe mercenaria* (Say). *J. Exp. Mar. Biol. Ecol.*, 1992, **157**, 115–136.

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Estimation of geothermal gradients and heat flow from Bottom Simulating Reflector along the Kerala–Konkan basin of Western Continental Margin of India

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Temperature at the Bottom Simulating Reflector (BSR) can be estimated from the pressure–temperature relation of the gas-hydrate stability phase curve. The geothermal gradient and hence the heat flow could be deduced if the seafloor temperature and thermal conductivity of sediments are known. In the present study we have studied a seismic line of the Kerala–Konkan basin of the Western Continental Margin of India, where BSR is identified on a seismic section. The sea-bottom temperature was used from the oceanographic data available from the region. Geothermal gradients and heat flow were estimated from the position of BSR using the phase relation system of gas hydrate and thermal conductivity of the sediments. The estimated geothermal gradient and heat flow in the area around this line are 34.88°C/km and 69.76 mW/m^2 respectively.

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NATURAL gas hydrates or clathrates are ice-like crystalline solids, composed of cages of water molecules that host low-molecular-weight gases (mainly methane), which are thermodynamically stable within a limited range of pressure and temperature. They are known to occur in the polar regions in association with permafrost and in the sediments within the upper few hundred metres of ocean floor on many continental margins[1–4]. Pressure and temperature conditions control gas hydrate formation in the submarine sediments. Figure 1 displays the phase diagram of gas hydrates. The solid line represents the pure methane-hydrate phase curve with the pressure converted to depth assuming hydrostatic conditions in both water and sediments. The dashed line represents the hydrothermal curve as a function of depth. Figure 1 shows the zone from the seafloor down to a depth of up to a few hundred metres, where gas hydrates are stable. At the point where the curve of the conditions in the sediments (dashed line) crosses the phase boundary, we reach the bottom of the zone where methane hydrate is stable. The base of the hydrate stability field represents the phase boundary between the gas hydrate-bearing sediments above and the free gas or gas charged or water-bearing sediments below. The characteristic reflector, which in principle coincides

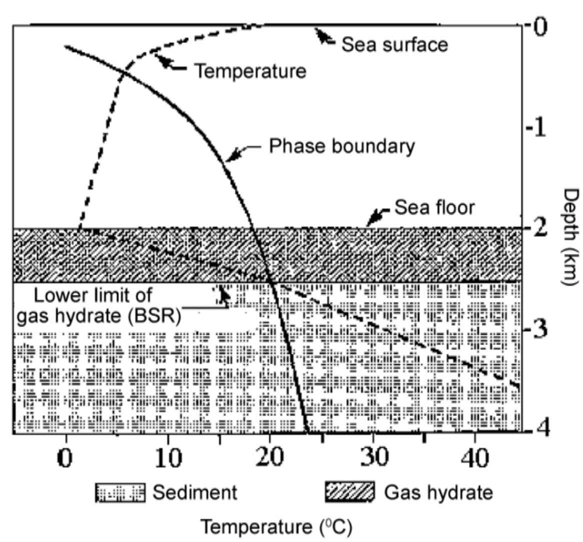

Figure 1. Stability region of methane hydrate in sea water as defined by temperature (T) and pressure (P, indicated as water depth).

with the predicted base of methane hydrate stability field[2] and mimics the seafloor, is known as the Bottom Simulating Reflection (BSR).

Heat-flow measurements of the seafloor provide useful input to derive the thermal structure which facilitates to address various issues related to fluid expulsion process, heat transport mechanism, sediment overburden and its influence on the lithosphere, and evaluation of continental margins, etc. However, heat-flow measurements in the marine environment are cost-prohibitive. In such places heat flow and geothermal gradients could be derived from the location of the BSR on reflection seismic sections. Such studies were made from several margins, viz. Blake Ridge and Nankai Trough[5,6], Makran offshore[7], Cascadia[8,9], Barbados[10], Oregon[11], Chile Triple Junction[12], North Sulawesi[13]. The present study aims at the estimation of geothermal gradient and heat flow from the observed BSR on the Multi Channel Seismic (MCS) reflection data along the Kerala–Konkan basin of Western Continental Margin of India (WCMI)[14] (Figure 2).

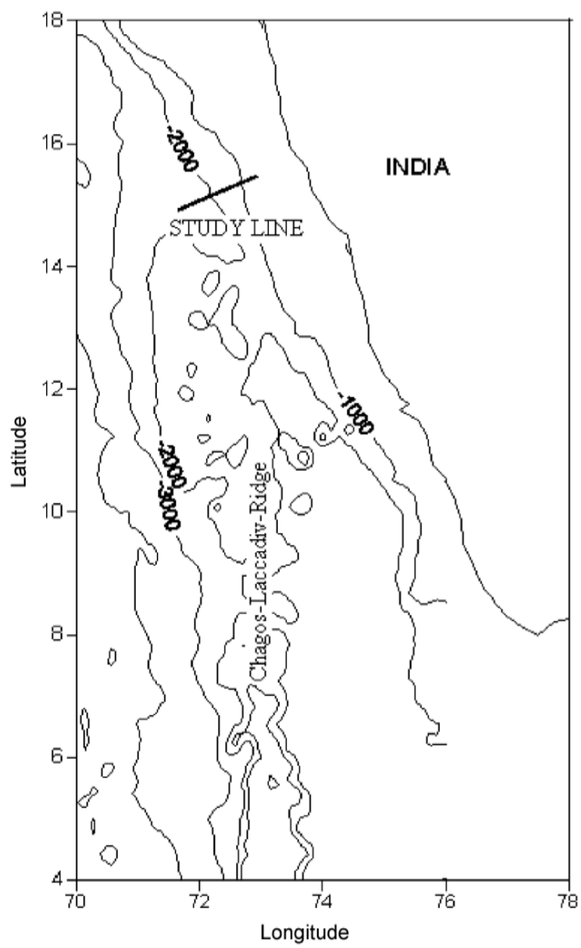

Figure 2. Study area in the Kerala–Konkan basin, WCMI. Solid line indicates the seismic line under study. Contours represent the bathymetry over the region from GEBCO data.

The Kerala–Konkan offshore basin forms an important element in understanding the evolution of WCMI and geodynamics of the Indian Plate. This offshore basin is a pericratonic rift basin located in the southern part of the west coast of India. The basin covers an area of about 580,000 km^2 including deep waters. The regional stratigraphy and tectonic elements in the Kerala–Konkan offshore area have been brought out by Mitra *et al.*[15]. About 3000 m thick sediments of Palaeocene to Recent have been recognized with several unconformities. The top of the Palaeocene, early Oligocene and middle Miocene constitutes the major unconformity surfaces in the area. The period between late Oligocene and middle Miocene witnessed a westerly tilt, giving rise to an environmental setting suitable for the development of lagoonal carbonate facies at specific places. During post-middle Miocene period, the area received terrigenious influx concomitant with peninsular tilt and uplift[16].

Several contiguous NW–SE trending tectonic elements have been identified in the WCMI[17,18]. With the initiation of tectonic pre-Santonian time, the basin evolved through two main phases of passive margin development – early rift phase and post-rift phase. Depositional phases of the evolutionary phases favoured development of abundant sandstone reservoirs, reefs and large carbonate platforms and carbonate banks, which are flanked by possible source areas. Organic carbon content and maturity point of the rock indicate petroleum generation potential in this region. Favourable geology makes the basin attractive for petroleum exploration[17].

Stability of gas hydrate in marine sediments can be better understood from gas hydrate phase equilibrium studies[4]. The BSRs observed on reflection seismic sections are believed to represent the base of gas hydrate stable zone[3]. It is observed that inferred BSR depths coincide with the imaginary line drawn parallel to the existing seabed from the point of intersection of the geotherm and hydrate phase equilibrium curves. In a given region, phase equilibrium is governed by physical parameters such as pressure, temperature and salinity. Based on gas hydrate phase-equilibrium studies for pure water and sea water, a schematic phase diagram was prepared by Sloan[4] with 4% pore water salinity (Figure 3). The choice of 4% in the present study is based on earlier studies[19] of core samples from the WCMI, where the pore water salinity has a range of 3.84 to 4.59%. The available ODP site information on gas hydrates plotted in Figure 3, reveals that most sites are on the lower side of pure water–methane hydrate curve and near the sea water–methane hydrate curve with 4% wt of NaCl. For temperature determination at the BSR depth, the methane hydrate system with sea water with 4% wt of NaCl over pure water seems to be reasonable.

Depth to the BSR can be determined by converting two-way travel times (TWTs) using interval velocity information. Seafloor temperature (T_0) can be taken either from *in situ* measurements or from the appropriate hydrothermal chart of the study area[20]. The temperature at the BSRs (T_Z) can be estimated from the phase diagram (Figure 3) by knowing the thickness of the stability zone (Z). From the knowledge of Tz, Z and geothermal gradients, the heat flow (Q) of a region can be determined. Q is a product of thermal gradients and thermal conductivity (k)[21].

The accuracy of these estimates depends upon velocity information in the sediments above the BSR, pore-water salinity, gas molecular composition, choice of hydrate system considered and the type of conductive regime assumed. The effects of other parameters (like pore pressure, sediment density, grain size and variation in seafloor temperature) may not significantly influence heat-flow estimates, as suggested by Ferguson *et al.*[10]. Hence they are ignored in the present computations.

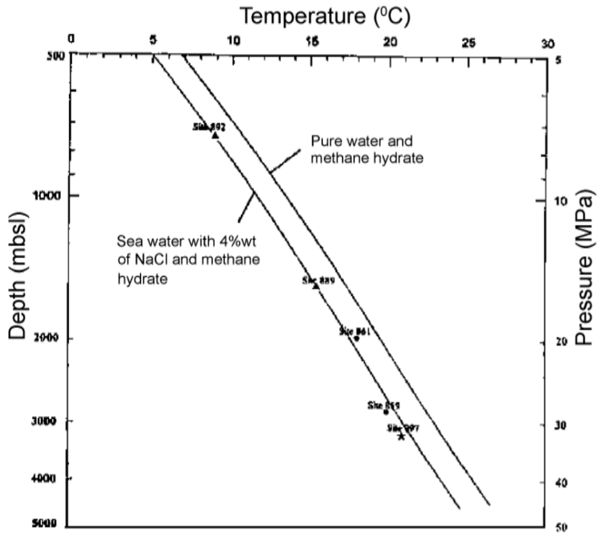

Figure 3. Methane hydrate stability condition for the pure water–methane hydrate and sea water–methane hydrate systems[4].

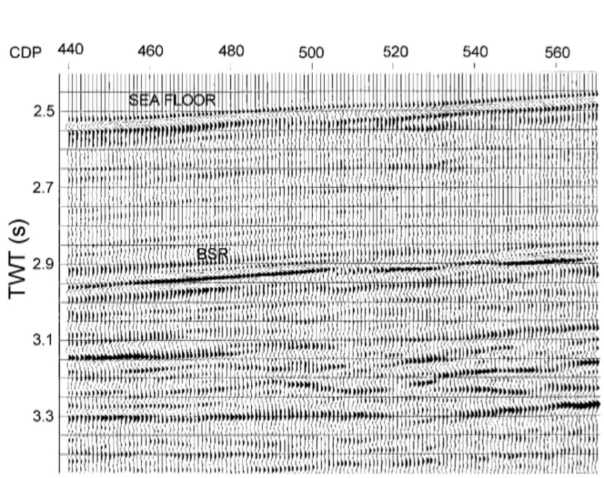

Figure 4. Multi-channel stack section along the line of study.

In Figure 4, a BSR can be traced from the seismic stack section of line K-743 of the Kerala–Konkan basin of WCMI. The reflector extends over CDP 440–570. The seafloor and the BSR are observed at TWTs of 2450 and 2880 ms respectively. The BSR reflection occurs at 430 ms below the seafloor. The 430 m thickness of the stability zone is computed by considering an average interval velocity of 2000 m/s for the sediments above the BSR. The sea-bottom temperature for the corresponding water depth (1837.5 m), derived from bathymetry–temperature charts[20], is about 3°C. The temperature at the BSR from the pressure–temperature phase relation of gas hydrate system with pore water having 4% wt of NaCl, is 18°C. Geothermal gradient is calculated from the temperatures at the seafloor and BSR, and thickness of gas hydrate stability zone. The geothermal gradient estimated along the Kerala–Konkan basin of WCMI is 34.88°C/km. Taking the average thermal conductivity of 2 W/m °C for the sediment[22] of study area, the heat-flow value thus calculated is 69.76 mW/m^2.

It is possible to calculate heat-flow from the identified BSR on seismic section in a region using the physical properties of marine sediments without any heat-flow probe data. The BSR-derived heat-flow map can be utilized to understand better the geothermal structure and related phenomenon over a large area. The accuracy of the estimated heat flow depends on the accuracy of the values of seafloor temperature, thermal conductivity, salinity and density of the sediments. Here we have estimated the heat flow in the Kerala–Konkan region as 69.76 mW/m^2, which falls in the range of 50–130 mW/m^2 estimated by Rao *et al.*[23] for the WCMI.

1. Kvenvolden, K. A. and Barnard, L. A., Hydrates of natural gas in continental margins. In *Studies of Continental Margin Geology* (eds Watkins, J. S. and Drake, C. L.), AAPG Memoir, 1983, vol. 34, pp. 631–640.
2. Kvenvolden, K. A., Methane hydrate – A major reservoir of carbon in the shallow geosphere. *Chem. Geol.*, 1988, **71**, 41–51.
3. Kvenvolden, K. A., Gas hydrates – Geological perspective and global change. *Rev. Geophys.*, 1993, **31**, 173–187.
4. Sloan, E. D., *Clatharate Hydrates of Natural Gases*, Marcel Decker, New York, 1998, p. 705.
5. Yamano, M., Uyeda, S., Aoki, Y. and Shipley, T. H., Estimates of heat flow derived from gas hydrates. *Geology*, 1982, **10**, 339–343.
6. Ashi, J. and Taira, A., Thermal structure of Nankai accretionary prism as inferred from the distribution of gas hydrate BSRs. In *Thermal Evaluation of the Tertiary Shimanto Belt, Southwest Japan: An Example of Ridge–Trench Interaction* (ed. Underwood, M. B.), Geo. Soc. Am., 1993, vol. 273, pp. 137–149.
7. Minshull, T. and White, R., Sediment compaction and fluid migration in the Makran accretionary prism. *J. Geophys. Res.*, 1989, **94**, 7387–7402.
8. Davis, E. E., Hyndman, R. D. and Villinger, H., Rates of fluid expulsion across the northern Cascadia accretionary prism: Constraint from new heat flow and multi-channel seismic reflection data. *J. Geophys. Res.*, 1990, **95**, 8869–8889.

9. Hyndmann, R. D., Wang, K., Yuan, T. and Spence, G. D., Tectonic sediment thickening, fluid expulsion and thermal regime of subduction zone accretionary prisms – the Cascadia margin off Vancouver Island. *J. Geophys. Res.*, 1993, **98**, 21865–21876.
10. Ferguson, I. J., Westbrook, G. K., Langseth, M. G. and Thomas, G. P., Heat flow and thermal models of the Barbados Ridge accretionary complex. *J. Geophys. Res.*, 1993, **98**, 4121–4142.
11. Zwart, G., Moore, J. C. and Cochrane, G. R., Variation in temperature gradients identify active faults in the Oregon accretionary prism. *Earth Planet. Sci. Lett.*, 1996, **139**, 485–495.
12. Brown, K. M., Bangs, N. L., Froelich, P. N. and Kvenvolden, K. A., The nature, distribution and origin of gas hydrate in the Chile Triple region. *Earth Planet. Sci. Lett.*, 1996, **139**, 471–483.
13. Delisle, G., Beiersdorf, H., Neben, S. and Steinmann, D., The geothermal field of the North Sulawesi accretionary wedge and a model on BSR migration in unstable depositional environments. In *Gas Hydrates: Relevance to World Margin Stability and Climate Change* (eds Henriet, J. P. and Mienert, J.), Geological Society of London Special Publication, 1998, vol. 137, pp. 267–274.
14. Reddi, S. I., Thakur, N. K., Ashalatha, B. and Kalachand Sain, Reprocessing of multi-channel seismic data of ONGCL for gas hydrate exploration in offshore Goa. National Geophysical Research Institute Tech. Rep. No. 2001-EXP-307, 2001.
15. Mitra, P., Zutshi, P. L., Chourasia, R. A., Chuugh, M. L., Ananthanarayannan, S. and Shukla, B., Exploration in western off shore basin. *Pet. Asian J.*, 1983, 15–24.
16. Nani, B. R. and Talwani, M., Structural framework and the evolutionary history of the continental margin of western India. *AAPG Mem.*, 1982, **34**, 167–191.
17. Biswas, S. K. and Singh, N. K., Western continental margin of India and hydrocarbon potential of deep-sea basins. In Proceedings of the 7th Offshore South East Asian Conference, 1988, pp. 170–181.
18. Subrahmanyam, V., Rao, D. G., Ramana, M. V., Krishna, K. S., Murty, G. P. S. and Rao, M. G., Structure and tectonics of the southwestern continental margin of India. *Tectonophysics*, 1995, **249**, 267–282.
19. Marching, V., Geochemistry of recent sediments from the Indian Ocean, Meteorological Vessel Research Report No. 11, 1972, pp. 1–140.
20. Gupta, H. K., Reddi, S. I., Thakur, N. K., Ashalatha, B., Khanna, R., Rao, T. G. and Subramanyam, C., Gas hydrate exploration along the continental margins of India – Evaluation of available geophysical and geological data. National Geophysical Research Institute Tech. Rep. No. 96-Lithos-193, 1996.
21. Lee, W. H. K. and Uyeda, S., Review of heat flow data. In *Terrestrial Heat Flow* (ed. Lee, W. H. K.), Am. Geophys. Union, 1965, vol. 8, pp. 87–90.
22. Ravi Shankar, Heat flow map of India and discussions on its geological and economic significance. *Indian Miner.*, 1988, **42**, 89–110.
23. Rao, Y. H., Subrahmanyam, C., Sharma, S. R., Rastogi, A. A. and Deka, B., Estimates of geothermal gradients and heat flow from BSRs along the Western Continental Margin of India. *Geophys. Res. Lett.*, 2001, **28**, 355 (2000GL008528).

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