Rapid sedimentation, overpressure, fluid flow and slope instability at the Gulf of Mexico continental margin

Integrated Ocean Drilling Programme (IODP) Expedition 308 studied overpressure and fluid flow on the Gulf of Mexico continental slope. The scientific program examined how sedimentation, overpressure, fluid flow, and deformation are coupled in a passive continental margin setting. The expedition investigated the model of how extremely rapid deposition of fine-grained mud leads to rapid build-up of pore pressure in excess of hydrostatic (overpressure), underconsolidation and continental slope instability. Expedition 308 tested this model by examining how physical properties, pressure, temperature, and pore fluid compositions vary within low-permeability mudstones that overlie a permeable, overpressured aquifer. Three sites were drilled in the Ursa Basin off the Mississippi Delta, using the research drillship R/V JOIDES RESOLUTION (Fig. 1). In the Ursa Basin rapid, late Pleistocene sedimentation was known to be present. Drilling documented severe overpressure in the mudstones overlying the aquifer. The most important achievement of IODP Expedition 308 is to have successfully recorded in situ formation pressure and temperature in an overpressured basin. This is the first time that a coherent data set of such measurements has been obtained.

Rapid sedimentation (>1 mm/y) generates overpressure in many sedimentary basins around the world. When low permeability sediments are rapidly loaded, pore fluids cannot escape and the fluids bear some of the overlying sediment load. In this situation pore pressures higher than the hydrostatic pressure develop. Recent work has focused on how rapid sedimentation and stratigraphic architecture couple to produce two- and three-dimensional flow fields. For example, if a permeable sand is rapidly buried by low-permeability mud of laterally varying thickness (Fig. 2), fluids flow subhorizontally through the sand layer to regions of thin overburden before they are expelled into the overlying sediment. This creates characteristic distributions of sediment properties, fluid

Fig. 1: R/V JOIDES RESOLUTION, drillship of the Integrated Ocean Drilling Program (IODP), in the port of Mobile, Alabama, before leaving for the Gulf of Mexico.

pressure, effective stress, temperature and fluid chemistry in the aquifers and the bounding mud (Fig. 2). This simple flow-focusing process can cause slope instability near the seafloor. In the deeper subsurface, overpressures created by flow focusing can drive fluids through low-permeability strata to ultimately vent them at the sea-floor. This is a globally important mechanism for the transfer of fluids from the solid earth to the hydrosphere and the atmosphere.

Ursa Basin is approximately 150 km south-southeast of New Orleans, Louisiana (USA) in about 1000 m of water. The region is of economic interest because of its prolific oilfields that lie at depths >4000 meters below seafloor (mbsf). We were interested in the sediments from 0 to 1000 mbsf. Three-dimensional (3-D) seismic data sets were used to constrain the stratigraphy within the Ursa Basin. Fig. 3 shows the seismic transect along which the three IODP Sites (U1322, U1323, U1324) were drilled. The sand-dominated Mississippi Canyon Blue Unit is overlain by a levee-channel assemblage that is mud-dominated. The most spectacular feature is the sand-cored levee-channel of the Ursa Canyon (Fig. 3), overlain by the muddy eastern levee deposits of the Southwest Pass Canyon, and a hemipelagic drape cover. The post-Blue Unit mudstone package has numerous detachment surfaces that record slumping and attest to a history of repeated continental margin instability.

The Ursa Basin sites provided a west-east transect that tested the flow focusing model of differential loading on a permeable aquifer. Overburden was drilled and sampled to 608 mbsf at Site U1324 (thick overburden) and to 234 mbsf at Site U1322 (thin overburden). Penetrometer measurements (Fig. 4) measured overpressure below 100 mbsf at both sites. Normalized overpressure of approximately 0.6 was determined at the base of each sites (i.e. the pore pressure lies 60% of the way between hydrostatic pressure and lithostatic pressure). Some of the penetrometer measurements at Site U1322 show almost lithostatic pore pressure. These overpressured stratigraphic horizons could be potential detachment surfaces leading to future slope instability.

Average sedimentation rates are considerably faster at Site U1324 than at Site U1322 (10 vs. 3.8 mm/y). The similar overpressure gradients present at both sites in spite of the almost 3-fold difference in sedimentation rate imply a component of lateral flow between them: this flow drives fluids from Site U1324 toward Site U13222, increases the pressure at Site U1322 relative to a system with only vertical fluid migration. The Blue Unit, composed of interbedded sheet sands and mudstones is interpreted to facilitate the lateral transfer of fluids from Site U1324 to Site U1322, which makes the regional pressure field diverge from a simple one-dimensional, compaction system. Core, log and sesimic interpretations document numerous scales of slumping, faulting, and soft-sediment deformation with increased occurrence at Site U1322. This deformation is consistent with prediction of the flow focusing model. Viewed at the basin scale, this type of lateral fluid flow

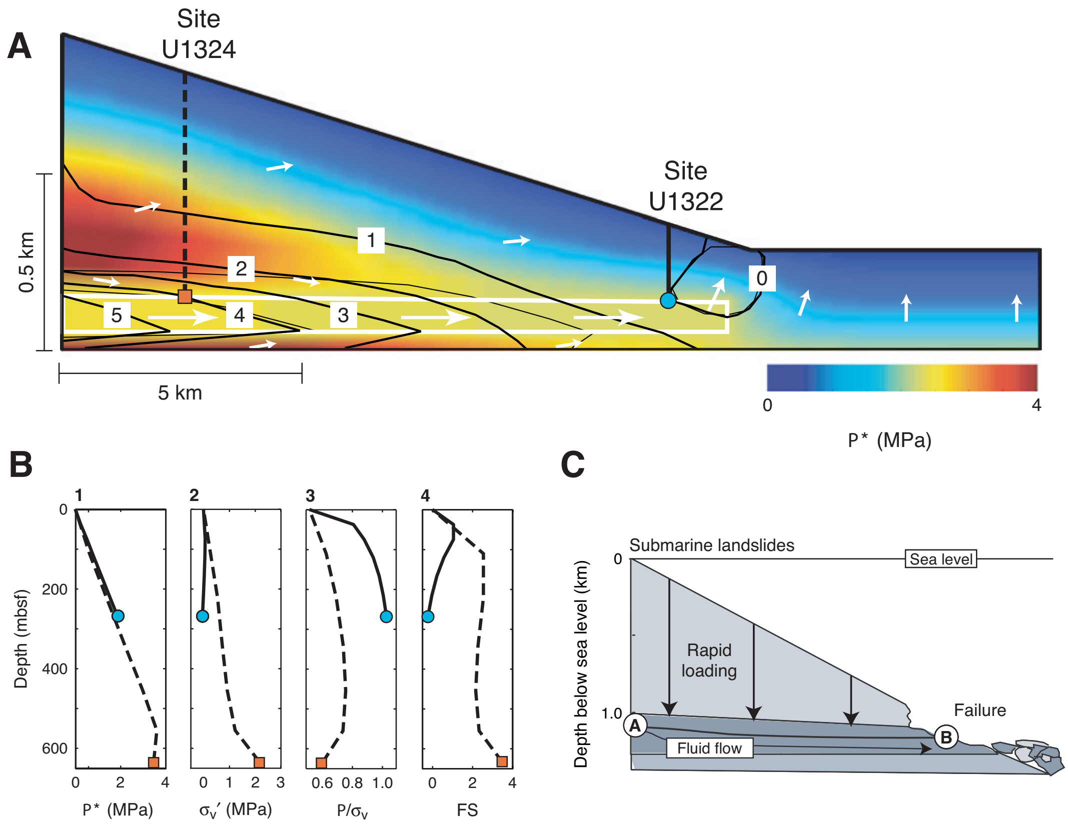

Fig. 2. Flow-focusing model approximating conditions in the Ursa Basin. A) Low permeability sediments are rapidly deposited on a high permeability aquifer (outlined in white). Sedimentation rate decreases from left to right, resulting in the final wedge-shaped geometry. Rapid sedimentation generates overpressures (P; color contours) that are greatest on the left (red). Flow is driven laterally (left to right) along the aquifer and expelled at the toe of the slope where the aquifer ends (white arrows). The vertical effective stress (black contours) is lowest on the right. (B) Predicted overpressure profiles where overburden is thick (Site U1324) and thin (Site U1322). (1) Overpressure at Site U1324 is greater than at Site U1322 for equivalent depths. (2) The vertical effective stress (σ_v') is much lower at Site U1322 than at Site U1324. (3) Pore pressures (P) equal the overburden stress (σ_v) at Site U1322. (4) Slope failure is predicted by infinite slope analysis near Site U1322 for FS < 1. FS relates the failure-driving stress to the available shear strength for shallow failures. Model parameters: low permeability mudstone $k_v < 5 \times 10^{-8}$ m^2 and $k_h < 5 \times 10^{-16}$ m^2; aquifer permeability $k_h = k_v\, 5 \times 10^{-14}$ m^2; maximum sedimentation rate 3.5 mm/y; minimum sedimentation rate = 0.8 mm/y. C) Cartoon to illustrate how flow focusing drives slope instability. Reproduced from Behrmann et al. (2006).*

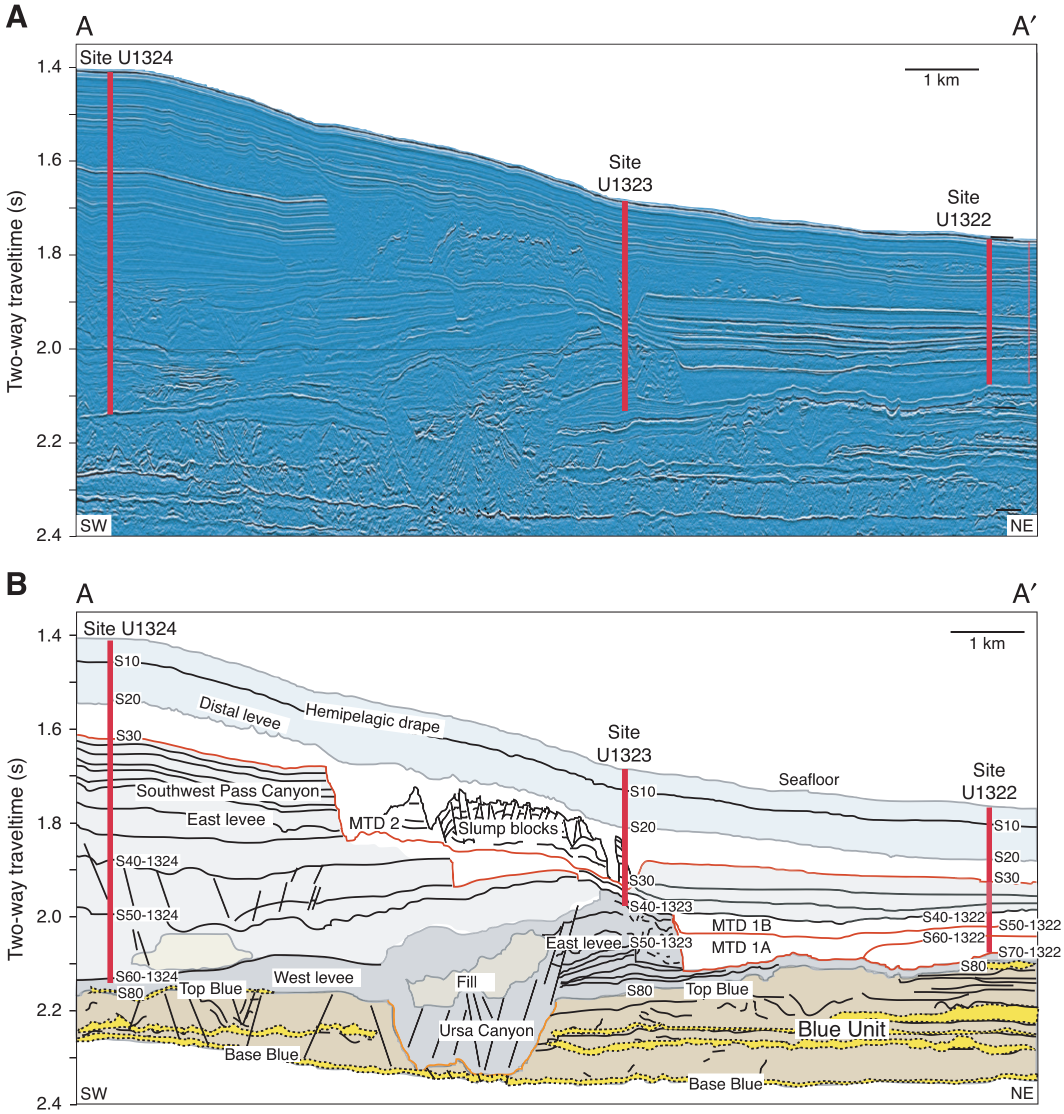

Fig. 3. (A) SW-NE seismic cross-section Ursa Basin. (B) Interpreted cross-section. The sand-prone Blue Unit has been incised by a channel-levee complex and then overlain by a thick and heavily slumped hemipelagic mudstone wedge that thickens to the west (left). The Blue Unit sands are correlated to a distinct seismic facies. Seismic data reproduced with permission of Shell Exploration and Production Company.

may be the prime factor for repeated submarine landslides generating major mass transport deposits.

A fundamental achievement of IODP Expedition 308 is that we directly measured the overpressure profile as a function of depth at Sites U1322 and U1324 in Ursa Basin. These measurements were difficult and we had a high failure rate. However, ultimately we acquired enough data to constrain the overpressure field above the Blue Unit. Preliminary interpretations suggest that flow focusing is occurring in this basin and the process does contribute to deformation and failure of sediments where overburden is thin. To our knowledge, this is the first time in the history of scientific ocean drilling that the spatial variation of the pressure field has been documented at this resolution.

Our data on pore pressure, sediment properties, and overburden stress will provide a basis to assess the potential for slope failure, especially in Ursa Basin, and estimate the conditions that drove previous slope failures. A major component of the ongoing post cruise science is the integration the stratigraphic geometry, physical properties, timing, and pressures associated with these mass wasting processes.

IODP Expedition 308 was the first expedition to monitor downhole pressure and lithology in real time using the Measurement While Drilling approach, and it was the first time that weighted mud has been used as a tool to drill and core overpressured regimes. Real time monitoring allowed us to observe shallow-water flow and to respond to this incident by raising the mud weight in order to hold back flow into the borehole. IODP Expedition 308 science provides the foundation to implement long-term in situ monitoring experiments in the aquifer and bounding mudstones in a future expedition.

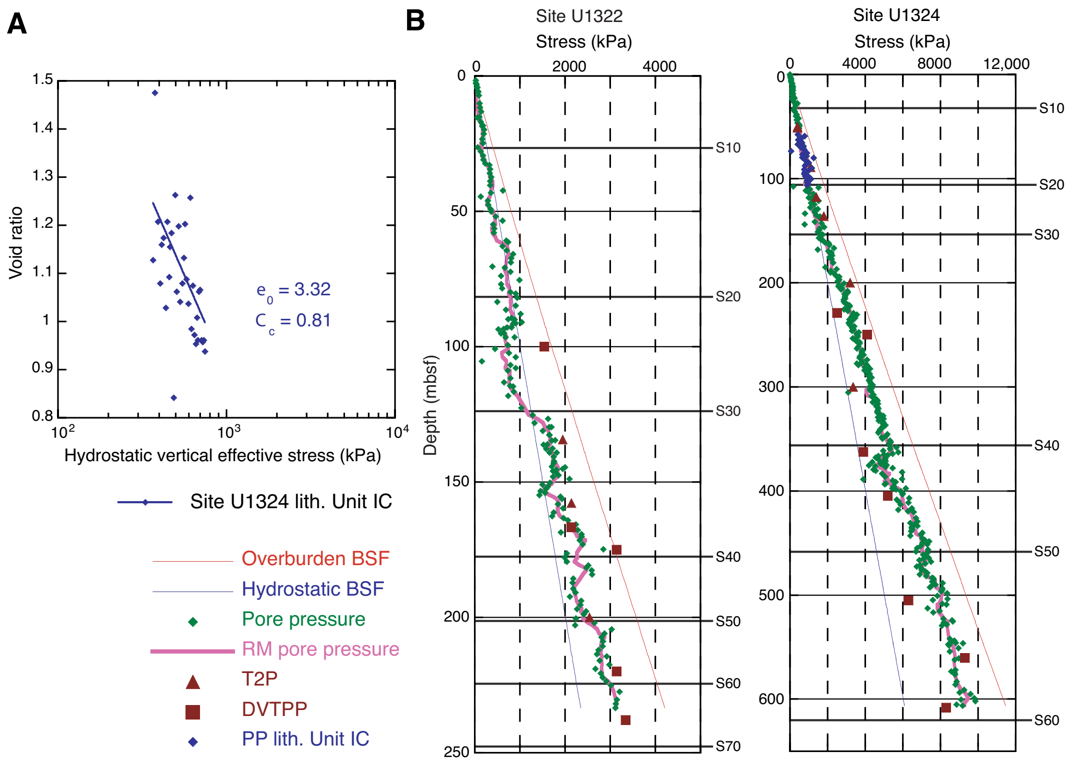

Fig. 4: (A) Void ratio (e) versus hydrostatic vertical effective stress (σ_{vh}) for lithostratigraphic Subunit Ic at Site U1324. The reference void ratio (e_0) and compression index (C_c) are derived from a fit of the type $e = e_0 - C_c \ln(\sigma_{vh})$. (B) Pore pressures for Site U1322 and U1324 are derived from parameters derived in (A) assuming that lithostratigraphic Subunit Ic (blue dots) at Site U1324 is hydrostatically pressured. Pore pressures recorded at the end of temperature and dual pressure probe (T2P) (red triangles) and Davis-Villinger Temperature-Pressure Probe (DVTPP) (red squares) deployments are also shown. BSF = below seafloor, RM = running mean, PP = pore pressure. Reproduced from Behrmann et al. (2006).

We expect research on the cores and data generated during IODP Expedition 308 to break new ground, especially in the field of geotechnical and hydrogeological analysis of continental slopes along passive and active continental margins. We have shown that programmes of in situ measurement of pore pressure in fine-grained sediments can be done with overall success. We have demonstrated that drilling into overpressured formations with riserless technology can be managed using heavy mud, fluid flow into the borehole can be controlled, and operations can be safely concluded without risk to the seafloor environment. Future expeditions in a variety of settings will benefit from the controlled use of weighted mud to stabilize the borehole.

We are grateful for the assistance given to us by the IODP technical and engineering groups, and the TRANSOCEAN marine and drilling staff aboard R/V JOIDES RESOLUTION.

Related Weblink

http://iodp.tamu.edu/scienceops/expeditions/exp308.html

Related Publication

Behrmann JH, Flemings PB, John CM, and the Expedition 308 Scientists (2006) Rapid sedimentation, overpressure and focused fluid flow, Gulf of Mexico continental margin. Scientific Drilling, 3, 12-17. doi:10.2204/iodp.sd.3.03.2006

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