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Capillary sealing in sedimentary basins: A clear field example

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Abstract. Pore fluid overpressures as high as 2 MPa (full lithostatic) are observed at ODP Site 975 starting at depths of 145 mbsf (meters below the sea floor). Sediment porosity increases to near surface values below the top of overpressure, while compaction and pressures above the seal are normal. Spikes in the density log and degassing of core from the overpressured zone indicate the presence of gas. The high porosity sediments are far too permeable to allow the generation and maintainance of fluid overpressures by disequilibrium compaction alone. The presence of two fluid phases in a layered sequence of fine and coarse sediment suggests capillary sealing, and this is shown to be quantitatively feasible.

Introduction

A capillary seal is a permeability barrier created when free gas is present in layered sediments with grain size variations. Capillary seals are well documented in soil sciences [e.g., *Ross*, 1990], and have been produced under laboratory conditions [*Shosa and Cathles*, submitted]. In sedimentary basins, the existence of overpressured compartments bounded by seals has been described in a number of papers [e.g., *Hunt*, 1990; *Ortoleva*, 1994], but unambiguous documentation of the origin and nature of a specific seal has been elusive.

Fluid pressure variations at ODP (Ocean Drilling Program) Site 975 in the Western Mediterranean sea provide a well documented field example of overpressured and undercompacted sediments at shallow depths. These observations cannot be easily explained by disequilibrium compaction alone because the sediment permeability is too high. The overpressured zone at Site 975 is correlated with the presence of free methane and lithological variations in the sediments. Gas capillary sealing provides a natural explanation for this seal.

Data Analysis

The porosity of sediments in sedimentary basins decreases in a regular fashion as effective stress increases. Starting with the model of *Palciauskas and Domenico* [1989], *Revil and Cathles* (submitted) show that the relationship between the hydrostatic porosity, ϕ_H and the depth of burial, z , is:

$$\phi_H(z) = 1 - (1 - \phi_o)\exp\left(z / z_c\right), \tag{1}$$

where ϕ_o is a non-compacted porosity, z_c is a characteristic depth, $1/z_c \equiv \phi_o(\rho_g-\rho_f)g\beta$, ρ_g is the grain density, ρ_f is the density of the pore fluid, g is the gravitational acceleration, and β is a long-term sediment compressibility defined by: $\beta \equiv -1/\phi_o(d\phi/d\sigma_{eff})$, where $\sigma_{eff} \approx P - p$ is the effective confining stress (P is the lithostatic stress and p is the total fluid pressure).

Disequilibrium compaction occurs when sediments are unable to expel their pore fluid in response to sediment loading and fluid overpressures are generated. In such a case, the porosity remains a function of the effective stress [e.g., *Dickinson*, 1953; *Bredehoeft and Hanshaw*, 1968]. The total fluid pressure, p, is equal to the hydrostatic fluid pressure, p_H, plus the fluid overpressure, δp. If the porosity, ϕ, is written as:

$$\phi(z) = \phi_H(z) + \delta\phi(z), \tag{2}$$

Revil and Cathles (submitted) show that under conditions of disequilibrium compaction the "excess porosity", $\delta\phi$, is related exactly to the excess fluid pressure, δp, by:

$$\delta p(z) = \frac{\delta\phi(z)}{\phi_o\beta} - \int_0^z \left(\rho_g - \rho_f\right) g\,\delta\phi(z')\,dz' \tag{3}$$

We apply the above compaction model to ODP Site 975 located on the South Balearic Margin between the Balearic Promontory and the Algerian Basin in water depth of 2426 m. The Plio-Pleistocene unconsolidated or poorly consolidated clay, silt, and marly ooze sediments in this area were deposited in an open marine, tectonically inactive environment and show no trace of erosion. Carbonate content varies between 30% and 70%. The terrigeneous sediment fraction includes clay minerals (illite, kaolinite or chlorite, and smectite), quartz, and minor amounts of feldspar and other minerals. Nannofossil ooze (with silt- and sand-sized grains) alternates with darker nannofossil clay on a centimeter to meter scale. Rare beds (less than 3 cm thick) rich in silt and/or sand are also present. The presence of methane, resulting from methanogenesis of buried organic matter, has been observed in cores. During ODP Leg 161, highly pressured sediments were cored below 150 mbsf. In order to avoid explosions, small holes were drilled every 10 cm in the PVC liner for each of the cores. The sediments often decompressed by expelling a jet several meters high when the pressure release holes were drilled [*Shipboard Scientific Party*, 1996, p. 144].

Selected downhole measurement data are shown in Fig. 1. The porosity is derived directly from the density log assuming water saturation. The high frequency variations in the porosity curve at depth greater than 135 mbsf are due to the presence of methane which was identified in the cores. The porosity decreases in a

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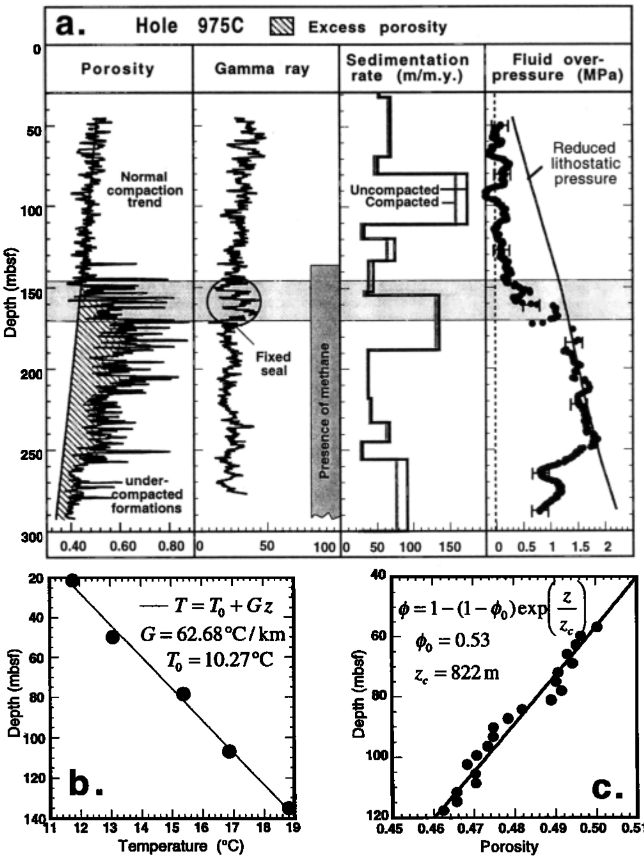

Figure 1. a. Porosity, gamma ray, sedimentation rate and fluid overpressure at ODP Site 975. Porosity, derived from the density log, decreases almost linearly with burial depth in the upper compartment. Such a linear decrease is characteristic of equilibrium compaction, shown by the solid line. Fluid overpressure is computed from the excess porosity, shown by the cross-hatched zone. **b.** Temperature vs. depth for the ADARA temperature tool runs at Hole 975C (ODP Initial Reports, Vol. 161, p.167). The data are used to determine the surface temperature at the sea floor, T_0, and the geothermal gradient, G. **c.** Porosity vs. depth, used to determine the non-compacted porosity and the long-term compressibility of formations in Hole 975C. The porosity data (inferred from the density log) from the upper part of the borehole where pressures are hydrostatic is inverted using Eq. (1). Prior to the non-linear regression, the porosity data were smoothed using a sliding averaging window of 20 m. The values of the non-compacted porosity and the characteristic depth associated with equilibrium compaction are given on the graph.

regular fashion between the surface and 135 mbsf, with a trend characteristic of equilibrium compaction (Fig. 1a, solid line). There is no gas observed at these depths. The non-compacted porosity and the long-term compressibility can be derived for this upper part of the section (38-120 mbsf) using Eq. (1). We obtain: $\phi_o = 0.53$, and $\beta = 1.41 \times 10^{-7}$ Pa^{-1}. This very high compressibility is explained by the fact that irreversible deformation at such shallow depths is probably a combination of pressure solution (a mechanism we have shown is very sensitive to the geothermal gradient which is 63°C/km at this site, Fig. 1b) and mechanical compaction (*Revil and Cathles*, submitted).

Between 140 and 170 mbsf, there is an increase of porosity with depth. Below 170 mbsf, even though the formations remain undercompacted, porosity decreases again with depth. Fluid overpressure can be estimated using Eq. (3) by taking the difference between the normal trend of compaction given by Eq. (1) and the smoothed porosity trend. Lithostatic pressure is directly derived by numerical integration of the density log. A comparison of the computed fluid overpressures to the reduced lithostatic pressure (lithostatic pressure minus the hydrostatic fluid pressure) is given in Fig. 1a. Between 170 mbsf and 240 mbsf, the fluid pressure is equal to the reduced lithostatic pressure, i.e., the effective stress is equal to zero and the sediments are in a condition of incipient fracture. The top of fluid overpressure can be correlated with the presence of a two-meter scale slump at 143 mbsf.

The compacted and uncompacted sedimentation estimated from the age of calcareous nannofossils and planktonic foraminifera rates are shown in Fig. 1a. There is little difference between the two in the interval we analyzed.

Origin of Fluid Overpressures

The fluid mass balance equation can be written [e.g., *McTigue*, 1986; *Palciauskas and Domenico*, 1989]:

$$\frac{1}{\rho_f^o}\frac{\partial m_f}{\partial t} + \nabla . \boldsymbol{q}_f = 0, \tag{4}$$

where ρ^o_f is the fluid density in the reference state ($z = 0$), m_f is the fluid mass content per unit volume of porous medium, and $\boldsymbol{q}_f$ is the macroscopic volumic fluid flux relative to the matrix (Darcy velocity) given by $\boldsymbol{q}_f = (-k/\eta_f)\nabla(\delta p)$, where k is the permeability (in m^{-2}) and η_f is the dynamic fluid viscosity (in Pa s). Neglecting aquathermal effects and grain density variations (which are not significant), the first term of Eq (4) can be rewritten $(\partial m_f/\partial t) = \rho_f d\phi(1-\phi_o)$ [*McTigue*, 1986].

We put Eq. (4) in non-dimensional form by taking: $\delta p = p_S \tilde{p}$, $t = t_S t$, and $z = H\tilde{z}$. For the characteristic time t_S, we take the diffusion time in the absence of sedimentation, i.e., $t_S = H^2/\eta_H$. Where H is the present day thickness of the sedimentary column and $\eta_H = k(1-\phi_o)/(\eta_f \phi_o \beta)$ is the hydraulic diffusivity. For p_S we choose the maximum allowable excess pore pressure, $p_S = (\rho - \rho_f)gH$. A similar analysis can be found in Bredehoeft and Hanshaw [1968]. With these substitutions, Eq. (4) becomes,

$$\frac{\partial^2 \tilde{p}}{\partial \tilde{z}^2} + \dot{R} = \frac{\partial \tilde{p}}{\partial \tilde{t}}, \tag{5}$$

where the non-dimensional number, $\dot{R}$, is defined by,

$$\dot{R} \equiv \frac{H}{\eta_H}\frac{\partial H(t)}{\partial t} = \frac{H\omega}{\eta_H} = \frac{H\omega\eta_f\phi_0\beta}{k(1-\phi_0)}. \tag{6}$$

This equation is similar to one derived in Bredehoeft and Hanshaw [1968] but we reference compaction to the undeformed state following McTigue [1986] and define the non-dimensional variables differently.

When $\dot{R} << 1$, no fluid overpressures develops. When $\dot{R} \approx 1$ fluid overpressures are about half the lithostatic pressure. Taking the depth of the sedimentary column analyzed $H = 160$ m, $\omega = 160$ m/m.y. (Fig. 1a), $\phi_o = 0.53$ (Fig. 1c), $\beta = 1.4 \times 10^{-7}$ Pa^{-1} (Fig. 1c), and $\eta_f = 10^{-4}$ Pa s, we find that the permeability required to maintain fluid overpressure at one half the lithostatic value is $k = 4 \times 10^{-7}$ mD (i.e., 4×10^{-22} m^2) for $\dot{R}$(160 mbsf) = 1. This is an abnormally low permeability for poorly compacted sediments.

Rieke and Chilingarian [1974] reported values higher than 1 md for 50% porosity sediments that do not contain pure smectite. The sediments at Site 975 probably have more than 5 orders of magnitude greater than that required to produce and maintain overpressure. Significant fluid overpressures cannot be generated at Site 975 without a dramatic permeability reduction of some kind. Furthermore, the porosity profile requires that sealing occurred at very shallow depths because the high porosities under the seal indicate the preservation of shallow depth porosities (Fig. 1a) because porosity reduction is not reversible [*Rieke and Chilingarian*, 1974]. The seal must therefore have formed near the surface about 2 millions years ago and subsequently been buried to ~160 mbsf. The question now concerns the nature of this seal.

Capillary Sealing

At Site 975, high fluid overpressures found at shallow depths correlate with the presence of gas in an alternating sequence of clean and shaly sediments [Fig. 1a, gamma ray curve between 140 to 170 mbsf, *Shipboard Scientific Party*, 1996]. These observations provide a natural explanation for the sealing and observed fluid overpressure because capillary effects can block two-phase flow perpendicular to layers of fine and coarse grained sediments [e.g., *Berg*, 1975; *Surdam et al.*, 1995]. We propose the following mechanism of sealing and overpressuring: Sedimentation creates a pore fluid overpressure which drives an upward flow of fluid. When methane is generated, the flow involves two fluid phases. The capillary pressure in the sedimentary formations is given by the Young-Laplace equation: $p_c = (2/r)\gamma K$, where γ is the interfacial tension of the gas-water interface (approximately 72×10^{-3} N m^{-1} at 25°C), r is the effective pore throat radius, and K is the "wetting coefficient" usually taken equal to unity. Free gas accumulates in the coarser-grained sediments. When the saturation of gas reaches a level at which the gas phase becomes interconnected a micro "gas cap" forms, the flow of both water and gas is blocked, and a capillary seal is formed. The gas requires a pressure differential,

$$\delta p_c = 2\gamma\left(\frac{1}{r_{\text{fine}}} - \frac{1}{r_{\text{coarse}}}\right), \tag{7}$$

to push it from a coarser-grained layer into and through an overlying fine-grained layer

This kind of capillary sealing can be described if Darcy's equation is modified [*Lenormand et al.*, 1988]:

$$q_f = \begin{cases} -\dfrac{k k_f}{\eta_f}\left(\dfrac{d(\delta p)}{dz} - \dfrac{dp_c}{dz}\right), \text{ as } \dfrac{d(\delta p)}{dz} > \dfrac{dp_c}{dz} \\ 0, \text{ as } \dfrac{d(\delta p)}{dz} \le \dfrac{dp_c}{dz} \end{cases} \tag{8}$$

where p_c is the capillary pressure and k_f $(0 \le k_f \le 1)$ is the relative permeability for water which is a function of the water saturation. Eq. (8) is supported numerically, theoretically [*Lenormand et al.*, 1988; *Rothman*, 1990], and experimentally [*Shosa and Cathles*, submitted]. Shosa and Cathles (submitted) show experimentally that the total capillary pressure drop in a layered sediment is the sum of the capillary drops at each interface. The capillary seal concept we suggest for Site 975 is a variant of the single interface capillary seal at the top of gas or oil reservoirs that is well known to petroleum geologists [e.g., *Berg*, 1953]. It differs in that it is composed of many small capillary barriers that are additive, rather than a single barrier which, if ruptured, leads to the failure of the whole seal. This important distinction is discussed in Shosa and Cathles (submitted).

From Eq. (7) the capillary pressure drop at the contact between nannofossil ooze (silts and sands) and clay horizons is related to the difference between the inverse fine and coarse pore throat radii. The effective pore throat radii can be related to more conventional geometrical parameters [*Revil et al.*, 1997]:

$$r = \frac{2}{3}\left(\frac{d}{\phi^{-m} - 1}\right), \tag{9}$$

where d is an average grain diameter and m is the electrical cementation exponent, $m \approx 1.6 \pm 0.2$ for clean sands, and 2.5 ± 0.3 for shale [*Revil et al.*, 1997]. Because the specific surface area of an equivalent granular porous media is given by: $V_p / S = (1/6)\,\phi d / (1-\phi)$, we can estimate an equivalent grain diameter from the data of Patchett [1975] for different clay minerals. Taking d=0.3, 0.1, and 7×10^{-3} mm we calculate capillary entry pressures $\delta p_c = 3$ MPa, 10 MPa, and 144 Mpa for kaolinite, illite, and smectite respectively. A single clay layer could account for the 2 Mpa overpressure observed at Site 975 if gas accumulated beneath it. As can be seen in the gamma ray log in Fig. 1a, the sediments at Site 975 are not pure shales. Although the grain size distribution at Site 975 is unknown, Shosa and Cathles [submitted] measure capillary entry pressures of 0.241 MPa per interface between artificial quartz sand with grain diameters of 2 and 45 microns and 45% porosity. This is almost identical to what we can calculate from Eqs. (7) and (9) (0.237 MPa with $m = 1.6$). Even at 0.2 MPa per interface, capillary sealing can clearly account for the overpressuring at ODP site 975 with ~10 capillary barriers, equivalent to the number of gas spikes observed in the density-derived porosity profile shown in Fig. 1a at the seal position.

Discussion

The fluid overpressures observed at ODP Site 975 lie along the lithostatic gradient and hence the capillary barriers are the micro-equivalent of Watt's [1987] hydraulic seal. Approximately 10 layers containing gas are observed at the seal position between 145 and 170 mbsf, which would require a capillary entry pressure greater than 0.14 MPa per interface to produce a lithostatic pressure gradient. As previously discussed the seal would have to have been formed at very shallow depth (above 30 mbsf) to explain the high "frozen" porosity just below the seal (i.e., at 170 mbsf). We believe the seal formed when biogenic gas was generated within the sediment or introduced into the upper sedimentary section from below. The gas generation may have been associated with the period of high sedimentation rate observed just below the top of the seal but the lack of sealing within the overlying pulse of sedimentation at 80 to 110 mbsf makes this explanation problematic. Between 170 mbsf and 240 mbsf the fluid pressure is equal to the reduced lithostatic pressure, i.e., the effective stress is equal to zero, and the sediments are in a condition of incipient fracture. Overpressured fluids could therefore be actively leaking through the seal at the present time. However, it seems unlikely there has been significant leakage through the seal in the past, because the leaked gas would have sealed and overpressured the overlying sediments.

It is unlikely that a mechanism other than gas capillary sealing is responsible for the overpressuring at ODP Site 975. There is no indication of diagenesis or pore plugging by inorganic or organic precipitation. There are no abnormal or unusual variations in porosity (other than the increase under the seal which would increase permeability, not reduce it). Gas capillary sealing is directly indicated by the observation of gas in the logs and the cores, and we can think of no reasonable alternative to gas capillary sealing for overpressuring at ODP site 975.

Our analysis raises the question of whether gas generation or disequilibrium compaction was the main cause of overpressuring. If the conclusion that there has been little leakage of gas or water through the seal since its formation is correct, disequilibrium compaction alone may create the observed overpressure, but the introduction of gas is required to cause a dramatic reduction in permeability, which then allows maintainance of the overpressures.

Conclusions

The main conclusions reached in this paper are: 1. The overpressure profile observed at ODP Site 975 cannot be easily explained by disequilibrium compaction alone because the intrinsic permeabilities of the shallow, porous sediments alone are too high to allow overpressures to develop; the introduction of a very low permeability barrier is required to explain the fluid pressure and the porosity profiles observed. 2. The seal could presently be leaking because fluid pressure between 170 and 250 mbsf is near lithostatic. 3. The seal must have formed within 30 meters of the sea floor for the high porosities found just below the seal to be preserved. The seal could not have formed at its present depth because compaction cannot be reversed by the later generation of overpressures. 4. From the known sedimentation rate and the current depth of the seal, the seal formed approximately 2 million years ago. 5. The striking association of gas spikes in the density log below the top of the seal in a zone of cyclic alternation of nannofossil ooze and clay horizons suggests the sealing is capillary. Gas capillary sealing in a seal interval containing ~10 thin sandy layers in contact with finer grained sediments could produce the required capillary blockage. 6. The lack of overpressures in the 145 meters between the seal and the sea floor make it unlikely that much gas and water has leaked through the seal as it was buried. We believe the shallow seal at ODP Site 975 is an unusually clear and accessible example of a kind of seal that may commonly bound overpressured compartments in a broad depth range in sedimentary basins, accretionary prisms, and indeed almost anywhere that layered sediments have accumulated and gas (or non wetting fluids) have been generated.

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