Thermal Expansion Effects in Deep Sea Sediments
T.J.G. Francis
February, 1982
Internal Document No. 152

(This document should not be cited in a published bibliography, and is supplied for the use of the recipient only).
INSTITUTE OF OCEANOGRAPHIC SCIENCES

Wormley, Godalming,
Surrey GU8 5UB
(042-879-4141)

(Director: Dr. A. S. Laughton)

Bidston Observatory,
Birkenhead,
Merseyside L43 7RA
(051-653-8633)

(Assistant Director: Dr. D. E. Cartwright)

Crossway,
Taunton,
Somerset TA1 2DW
(0823-86211)

(Assistant Director: M. J. Tucker)
Thermal Expansion Effects in Deep Sea Sediments
T.J.G. Francis
February, 1982
Internal Document No. 152

Work carried out under contract to the Department of the Environment

This document should not be cited in a published bibliography except as "personal communication", and is supplied for the use of the recipient only.

Institute of Oceanographic Sciences,
Brook Road,
Wormley,
Godalming,
Surrey GU8 5UB
Summary

Because the thermal expansivity of pore water is much greater than that of the solid component, the physical properties of unlithified sediments are substantially modified by heating and subsequent cooling. The effects of heating and cooling on the density and void ratio are evaluated and hence the changes that can be expected in permeability are deduced. It is suggested that the heating/cooling cycle is not reversible but is likely to lead to sediment compaction. This phenomenon is called thermal tamping. Evidence for thermal tamping, brought about by the penetration of unlithified sediments by magma, has been obtained by Glomar Challenger drilling. The implications of thermally-induced density and permeability changes for the burial of high-level radioactive waste in the sediments of the ocean floor are discussed.
Introduction

Understanding how in-situ heating affects unlithified deep-sea sediments is important both for geological and practical reasons. Deep-sea drilling by the vessel Glomar Challenger over the past decade has revealed a number of places where magma has intruded sediment to form sills. The heat released by a large sheet of molten rock produces substantial physical and chemical changes on the sediments in its vicinity (e.g. Einsele et al., 1980). Burial of hot canisters of high-level radioactive waste within the sediments of the ocean floor has been proposed as one solution to the problem of disposing of this material (Hollister, 1977). The effects that a canister would have on the sediments surrounding it must be understood before such a solution can be fully evaluated.

This paper discusses the physical effects that a hot body is likely to produce when buried in unlithified sediments in great water depths. High temperatures are also likely to cause substantial chemical effects, speeding up diagenetic processes, but these are beyond the scope of the paper. In practice the physical and chemical effects would work together in modifying the original sediment.

Individual behaviour of the liquid and solid components

Before the response of the whole sediment to heating can be determined, it is necessary to summarise the behaviour of its liquid and solid components. The individual thermal behaviour of these components is straightforward and well understood.

The pressure-volume-temperature relations for sea water differ very little from those for pure water (Bischoff, 1980).
The specific volume of pure water as a function of temperature and pressure has been tabulated by Burnham, Holloway and Davis (1969). Saunders (1981) gives the equation of state relating the specific volume of standard ocean water (temperature 0°C, salinity 35‰) to pressure. Saunders' equation of state has been used to provide calibration factors for the values tabulated by Burnham et al. For a given pressure the calibration factor, which is correct at 0°C, is assumed to be constant, i.e. to apply over the whole range of temperature under consideration. The specific volumes and densities of sea water thus derived for the temperature range 0-400°C at pressures of 200 and 500 bar are listed in Table 1. The thermal expansion of sea water at these pressures is shown graphically in Figure 1, where the percentage volume expansion of sea water from its volume at 0°C is shown as a function of temperature. It is obvious that the volume thermal expansion coefficient, defined as \( \frac{1}{V} \left( \frac{dV}{dT} \right)_p \), is not a constant but increases with increasing temperature.

In contrast, the thermal expansion of most rock-forming minerals can be adequately described by a constant coefficient in the temperature range 0-400°C. Skinner (1966) has tabulated the thermal expansion characteristics of a wide range of such materials, based on measurements at atmospheric pressure over the temperature range 20°C-1000°C. Most rocks and common rock-forming minerals have a volume thermal expansion coefficient of about \( 3 \times 10^{-5} \), corresponding to a volume expansion of about 1% over the temperature range 0-400°C. A pressure of 500 bar would slightly reduce these values. The thermal expansion of one particular solid material, quartz, is shown in Figure 1 to illustrate the contrast in thermal expansivity between the solid and liquid components of the sediment. Quartz was chosen for this role, not because it is particularly important in deep ocean sediments, but because having a larger volume expansion coefficient than most minerals it can more conveniently be shown on the same graph as water.
It is reasonable to assume that the pore fluid of ocean floor sediments is, as far as its physical properties are concerned, indistinguishable from sea water. One can conclude therefore that the thermal expansivity of sedimentary pore water is some two orders of magnitude greater than that of the solid component. For the purposes of this paper, the expansion of the solid component of the sediment is regarded as negligible.

**Thermal expansion of a deep sea sediment**

The manner in which a sediment expands will to some extent be affected by the way in which heat is applied. The heating of sediment in-situ is unlikely to be a uniform process. Naturally it can occur when a sheet of magma intrudes to form a sill; artificially it is likely to be produced by the emplacement of a spherical or cylindrical body. In all cases strong temperature gradients are likely to exist, both during the development of the temperature field and in the steady state.

Two limiting cases to the way in which a sediment responds to heating can be conceived:

1. **Fully drained case.** The sediment matrix remains unchanged and the expanding pore water is accommodated by flowing away from the source of heat. In this case some increase in the pore pressure must occur in order to drive the flow of pore water, but the increase must be small in relation to the overburden pressure if the sedimentary fabric is not to be disrupted. The porosity of the sediment is unchanged, but the bulk density of the heated sediment is reduced because of the reduced density of the pore water. The bulk density $\rho$ is related to the solid particle density $\rho_s$ and the fluid density $\rho_f$ by

$$\rho = (1 - \phi) \rho_s + \phi \rho_f$$

where $\phi$ is the fractional porosity.
This expression can be used to calculate the density of the heated sediment since $\rho_f$ is known as a function of temperature (Table 1) and $\rho_s$ and $\phi$ are unchanged. The values obtained for a sediment of initial porosity 0.75 and grain density 2.7 g/cm$^3$ at an ambient pressure of 500 bar are given in Table 2 and plotted in Figure 2.

(2) **Undrained case.** In this case the pore water remains in place as it expands, disrupting the sedimentary matrix in the process. Considerable pore pressure must be developed if the sedimentary matrix is to be appreciably expanded. The pore pressure could even equal the overburden pressure, reducing the effective stress to zero and the sediment to the state of a liquid. However, the detailed analysis of sediment failure due to heating is beyond the scope of this paper. The bulk density of the heated sediment will be reduced both because of its increased porosity and because the density of the pore water is reduced.

If a volume of sediment $V$ weighs $W$ and the weights of the solid and fluid components are $W_s$ and $W_f$ respectively, then

$$V = \frac{W_s}{\rho_s} + \frac{W_f}{\rho_f} = \frac{W}{\rho}$$

hence

$$\rho = \frac{W}{W_s/\rho_s + W_f/\rho_f}$$

where in the undrained case $W$, $W_s$, $W_f$ and $\rho_s$ are constants. In the case of a sediment of initial porosity 0.75 and grain density 2.7 g/cm$^3$, the expression becomes

$$\rho = \frac{1.4633}{0.25 + 0.7883} \frac{\rho_s}{\rho_f}$$

Values obtained from this equation corresponding to an ambient pressure of 500 bar are listed in Table 2 and plotted in Figure 2.
The behaviour of a sediment in reality will fall somewhere between these two limiting cases. One would expect a highly permeable sand to behave in a fully drained manner (Case (1)). A uniformly heated, impermeable clay might tend to follow Case (2). As already mentioned, however, with \textit{in situ} heating on the ocean floor uniform heating is unlikely and strong temperature gradients are likely to exist. In the second case these would give rise to strong pore pressure gradients and it is difficult to envisage how the large pore pressures implicit in this case can be sustained. Pore water flow is likely to occur to relieve the pressure and collapse of the expanded sediment matrix back towards its original porosity would result.

Pore water flow will be facilitated by the increase in permeability which accompanies an increase in porosity. The increase in porosity corresponding to the Case (2) situation in Figure 2 is shown in Figure 3. The variation of permeability with porosity or void ratio has now been studied for a number of deep-sea sediments (Silva, 1977; Silva \textit{et al.}, 1980) (Figure 4). Measurements on some North Atlantic sediment samples are shown in Figure 5 (P.J. Schultheiss, private communication). The logarithm of the permeability of any particular sediment sample is approximately linearly related to the void ratio such that an increase in void ratio of unity corresponds to roughly an order of magnitude increase in permeability. Thus the porosity increase accompanying Case (2) thermal expansion (Figure 3) implies an increase in permeability of at least an order of magnitude. In other words, since increased pore pressure is accompanied by
increased permeability in the Case (2) expansion, the sediment acts as a safety valve to relieve the pressures developed.

In conclusion, although Case (2) behaviour may be the instantaneous or short term response of a sediment to heating, Case (1) is more likely to reflect its longer term behaviour. Nevertheless, Case (2) is worth considering in order to determine the maximum reduction in density that a sediment might undergo.

Thermal Contraction of a deep sea sediment - Thermal Tamping

It has been suggested in the previous section that thermal expansion of a deep-sea sediment is likely to be essentially a constant porosity process with pore water expansion accommodated by flow away from the source of heat. When a highly-permeable, coarse-grained sediment cools, this process is likely to be reversed. Water will flow back to fill the space created by the pore water contracting and the overall effect of the heating and cooling cycle will be nil. But for fine-grained, impermeable sediments reversibility seems unlikely. Thermal contraction of pore water will create a reduction of pore pressure which, if not compensated by the return flow, will lead to collapse of the sedimentary matrix. Any collapse of the matrix will reduce its permeability, making return flow of pore water more difficult and further collapse of the sediment more likely. Thus the overall effect of heating and cooling sediment will be to produce a more compacted, less permeable sediment - a process which can conveniently be called "thermal tamping". It is clear that thermal tamping will occur whenever thermal expansion is not reversible. The property of the sediments which makes reversibility unlikely is the void ratio - permeability relationship. Fine-grained sediments can be regarded as acting like a non-return valve, opening to allow increased pore water pressure to dissipate itself but closing to prevent pore
water flowing towards zones of reduced pore pressure. The process of thermal tamping is illustrated in geotechnical terms in Figure 6.

Assuming thermal tamping to be a 100% efficient process, the reduction in porosity or void ratio can be calculated as a function of temperature. If $V_s$ is the volume of the solid component and $V_v$ is the volume occupied by the fluid component of the original sediment, then the original void ratio is defined by

$$ e_{\text{orig}} = \frac{V_v}{V_s} $$

If heating the sediment to $T^\circ C$ from its ambient value causes the pore water to expand by $m\%$, then the volume, $V_v$ occupied by fluid at $T^\circ C$ becomes $\frac{V_v}{(1 + m/100)}$ on cooling back to $0^\circ C$. Thus the final void ratio on completion of the thermal cycle is given by:

$$ e_{\text{final}} = \frac{e_{\text{orig}}}{(1 + m/100)} $$

Expressed in terms of porosity, this formula can be written

$$ \phi_{\text{final}} = \frac{\phi_{\text{orig}}}{1 + (1-\phi_{\text{orig}}) m/100} $$

Since the ambient temperature at which the un lithified sediments of the ocean floor exist is close to $0^\circ C$, and since the thermal expansion of water is small in the range $0-10^\circ C$ anyway, values of $m$ can be taken directly from Figure 1. These values have been used to compute the reduction in void ratio which thermal tamping would bring about to a sediment with original void ratio 3.0 (porosity 75%) at an ambient pressure of 500 bar. The results of this calculation are shown in Figure 7. It is clear
that the higher the temperature to which the sediment is heated the greater the reduction in void ratio. Heating to 350°C causes a reduction in void ratio of about unity, corresponding to a decrease in permeability of approximately an order of magnitude.

Evidence for thermal tamping in deep-sea sediments

On Leg 64 of the Deep Sea Drilling Project, the vessel Glomar Challenger drilled four holes in the Guaymas Basin in the Gulf of California at sites where basaltic sills had penetrated highly porous sediments at shallow depths (Curray, Moore et al., 1979). The water depth at these sites is approximately 2000 m so that the ambient pressure in the vicinity of the sills at the time of their intrusion (within the last 400,000 years) was approximately 200 bar. A conspicuous effect which the intrusion had on the sediment was to reduce its porosity in the vicinity of the sills (Figure 8) (Einsele et al., 1980).

The formula relating sediment porosity to the expansion of the pore fluid for 100% thermal tamping can be used to calculate the percentage expansion of pore fluid which occurred. Taking the case of the sediment immediately above the sill at Hole 481A, the original porosity of the sediment is estimated at 0.7 and the final porosity is observed to be 0.3, giving the percentage expansion of pore fluid which occurred as 444%. At an ambient pressure of 200 bar this indicates that the temperature close to the sill reached about 370°C (Burnham et al., 1969) (offsacle on Figure 1). Although the temperature of the molten rock must have
been close to 1200°C, a value in the region of 370°C is reasonable because this is about the temperature at which water boils at 200 bar. The transition from liquid to gaseous phase at elevated pressure is less abrupt than at atmospheric pressure, and what particular phase the pore water is in is probably not relevant to the process of thermal tamping. However, the relatively rapid contraction of the pore water in the region of 370°C may have aided the process of thermal tamping. But the fact that the thermal tamping formula gives a sensible value for the temperature increase gives support to the reasoning behind it.

Thermal expansion effects around a buried canister of radioactive waste

The burial of a heat-generating canister within the sediments will modify their physical properties in a way which the ideas outlined in the previous discussion allow us to calculate. Immediately after emplacement the temperature field will develop around the canister, reaching an effectively steady state configuration in the order of a year (Hickox et al., 1980). Thereafter the temperature decays with the decay of the radioactive waste embedded in the canister, so that the temperature history immediately adjacent to the canister will be comparable to that shown in Figure 9. The precise shape of the temperature history curve and the peak temperature to which the canister wall rises depends on the inventory of radionuclides contained in the canister at the time of disposal, itself a function of the original loading of radionuclides in the solidified waste and the storage time to disposal. The peak temperature to which the canister wall is allowed to rise must be restricted if a canister lifetime in the range of 500 to 1000 years is to be achieved.
At the present time, peak wall temperatures in the range 100°C to 250°C are thought appropriate (Waste Form and Canister Task Group, 1981).

In order to understand the effect of thermally induced density changes in the sediment surrounding the canister, it is sufficient to rely on the peak temperature field developed around it. Making the following simplifying assumptions, this is easily calculated:

1. The canister is assumed to be a sphere of radius 0.35m, making it comparable in volume to the more realistic cylindrical canisters proposed (Waste Form and Canister Task Group, 1981).

2. The heat output of the canister, Q, is taken to have a constant value of 1000 W.

3. The thermal conductivity of the sediment, K, is taken as 0.85 Wm⁻¹K⁻¹ and assumed to be independent of the temperature. Measurement of the thermal conductivity of sediments as a function of temperature (Hadley et al., 1980) indicates that this is a good assumption up to 200°C and a reasonable one up to 400°C.

4. Hickox et al. (1980) have shown that thermally induced convection of the pore water is negligible and that conduction theory is sufficient to calculate the steady state temperature field around the canister.

5. The ambient temperature of the sediment prior to emplacement is taken as 0°C.

With the above assumptions, it is easy to show that the steady-state temperature of the sediment at radius r from the centre of the canister is given by

\[ T = \frac{Q}{4\piKr} \]
Temperature calculated from this expression for the values of \( Q \) and \( K \) given, is plotted against radius in Figure 10. Using the relationship of sediment density to temperature where the sediment expands with the pore water in situ (Case (2) in Figure 2), the corresponding density of the sediment as a function of radius has been obtained. This is also shown in Figure 10.

The "Burp" effect

One phenomenon which it has been suggested might affect a hot canister buried in deep-sea sediments is the so called "Burp" effect. Heat from the canister, it has been proposed, would reduce the density of the sediment to such an extent that not only would a convective upwelling of sediment occur but that this same upwelling might carry the buried canister back to the sea bed. For such an effect to be possible, the effective density of the canister and surrounding sediment must be less than the density of the unaffected sediment. The sediment density calculated from the temperature field (Figure 10) allows this effect to be examined quantitatively. Since the density shown in Figure 10 is a lower limit to the actual density that might occur, this examination will err on the safe side.

Consider a spherical shell of heated sediment and outer radius \( r \) surrounding the canister of radius \( r_0 \). Assuming that the canister remains fixed within the shell of heated sediment a Buoyancy Force can be defined that will tend to move the complete spherical body up or down:

\[
\text{Buoyancy Force} = \text{Weight of Sphere of Unaffected Sediment (radius } r) - \text{Weight of Canister (radius } r_0) - \text{Weight of Shell of Heated Sediment (radius } r_0 \text{ to } r)
\]
A positive Buoyancy Force will tend to move the canister upwards, a negative one to make it sink. In order to appreciate whether the Buoyancy Force developed is ever big enough to actually move the canister, it must be converted into a stress which can be compared with the strength of the sediment. A Buoyancy Stress can be obtained simply by dividing the Buoyancy Force by the cross-sectional area of the sphere:

$$S = \frac{F}{\pi r^2} = \frac{1}{\pi r^2} \left( \frac{4}{3} \pi r^3 \rho_i - \frac{4}{3} \pi r^3 \rho_c - \int_{r_0}^{r} 4\pi r^2 \rho \, dr \right)$$

This expression has been evaluated numerically taking values of $\rho$ from Figure 9, $\rho_i = 1.463 \text{ g cm}^{-3}$ and $\rho_c = 3.0 \text{ g cm}^{-3}$ (c.f. Base Case Scenario, Systems Analysis Task Group Report, 1981). The Buoyancy Stress thus derived is plotted as a function of radius in Figure 11. It is clear from this figure that beyond a radius of about 1m the combined volume of canister and heated sediment is positively buoyant. The maximum buoyancy stress developed, however, is small, about 0.6 kPa. In contrast the shear strength which the sediment can be expected to have at a burial depth of 30m (Base Case Scenario, Systems Analysis Task Group Report, 1981) is about 30 kPa (Silva, 1977). Since positive buoyancy is only developed beyond about 1m radius and the maximum buoyancy stress at about 2m radius, where the sediment is unlikely to be weakened either by temperature
or by the mechanical effects of emplacement, positive buoying of the canister upwards seems very unlikely.

As one would expect, the peak buoyancy stress (-7 kPa) is developed at the canister wall itself and is negative. Since this is also where the temperature is greatest and where one might expect the sediment to be most weakened, this stress may even exceed the strength of the sediment and cause the canister to sink. Furthermore, the mean density taken for the canister (3.0 g cm\(^{-3}\)) is a minimum value, in order to maximise any positive buoyancy effect. A denser canister would create greater negative stresses than -7 kPa and be more likely to sink.

In conclusion, the "Burp" effect in which a hot canister is carried upwards in a mass of reduced density sediment of its own making seems highly unlikely. The canister is much more likely to sink.

**Conclusions**

1. A hot body buried in deep sea sediments will substantially modify the physical properties of the sediments adjacent to it. These changes arise because the thermal expansivity of the pore water is considerably greater than that of the solid components of the sediment. Neglecting any chemical changes which the heat source might promote, the following physical changes can be expected.

2. Heating up the sediment will reduce its density by an amount which depends on the degree to which expanded pore water can flow away. The maximum possible reduction in sediment density at any point can be calculated if the maximum temperature to which that point has been subjected is known.
Cooling of the sediment is unlikely to be simply the reverse of heating, but could lead to collapse of the sediment matrix if pore water cannot flow back fast enough. This process, which has been called "thermal tamping", would create a compacted shell of sediment surrounding the body once it has cooled. The permeability of the sediment within this shell will be less than that in the unaffected sediment.

The processes outlined above have important implications for the burial of hot canisters of radioactive waste beneath the ocean floor.

The density reduction that could be produced in the sediment by a canister of the volume and heat output proposed is too small for the "Burp" effect to be plausible. The canister is much more likely to sink.

Thermal tamping will enhance the ability of the sediment to retain the radionuclides once the canister has corroded away. With the temperature history adjacent to the canister shown in Figure 9 most of the thermal tamping would occur within 100 years of burial. On this basis a canister life of 500-1000 years may not be necessary.

The higher the temperature to which the canister wall is allowed to rise the more effective the thermal tamping is likely to be. This would favour either a higher loading of radionuclides within the canister or a shorter storage period prior to disposal.
(8) Thermal tamping will also be more effective at shallower sites, since the thermal expansivity of water decreases with pressure (Figure 1). In this respect, therefore, a 4000m disposal site would be marginally more effective than a 6000m one.

(9) Thus thermal tamping introduces new considerations to be taken into account in optimising the conditions for the sub-seabed disposal of high-level radioactive waste. An experimental investigation of the effects of temperature cycling on deep-sea sediments under in situ conditions is needed to confirm the existence and magnitude of thermal tamping.

Acknowledgements

I thank Peter Schultheiss and Hugh St. John for helpful discussions. This research has been carried out under contract for the Department of the Environment, as part of its radioactive waste management research programme. The results will be used in the formulation of Government policy, but at this stage they do not necessarily represent Government policy.
<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Specific Volume (200 bar)</th>
<th>Density (200 bar)</th>
<th>Specific Volume (500 bar)</th>
<th>Density (500 bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.9639 cm$^3$/g</td>
<td>1.037 g/cm$^3$</td>
<td>0.9518 cm$^3$/g</td>
<td>1.051 g/cm$^3$</td>
</tr>
<tr>
<td>40</td>
<td>0.9725</td>
<td>1.028</td>
<td>0.9619</td>
<td>1.040</td>
</tr>
<tr>
<td>80</td>
<td>0.9926</td>
<td>1.007</td>
<td>0.9814</td>
<td>1.019</td>
</tr>
<tr>
<td>120</td>
<td>1.0216</td>
<td>0.979</td>
<td>1.0084</td>
<td>0.992</td>
</tr>
<tr>
<td>160</td>
<td>1.0600</td>
<td>0.943</td>
<td>1.0433</td>
<td>0.958</td>
</tr>
<tr>
<td>200</td>
<td>1.1087</td>
<td>0.902</td>
<td>1.0866</td>
<td>0.920</td>
</tr>
<tr>
<td>240</td>
<td>1.1730</td>
<td>0.853</td>
<td>1.1409</td>
<td>0.877</td>
</tr>
<tr>
<td>280</td>
<td>1.2624</td>
<td>0.792</td>
<td>1.2104</td>
<td>0.826</td>
</tr>
<tr>
<td>320</td>
<td>1.4045</td>
<td>0.712</td>
<td>1.3060</td>
<td>0.766</td>
</tr>
<tr>
<td>340</td>
<td>1.5281</td>
<td>0.654</td>
<td></td>
<td></td>
</tr>
<tr>
<td>360</td>
<td>1.7734</td>
<td>0.564</td>
<td>1.4483</td>
<td>0.690</td>
</tr>
<tr>
<td>380</td>
<td>8.0359</td>
<td>0.124</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td></td>
<td></td>
<td>1.6890</td>
<td>0.592</td>
</tr>
</tbody>
</table>

Table 1. Specific volume and density of sea water (salinity 35%) in the temperature range 0-400°C at 200 and 500 bar (derived from Burnham et al., 1969 and Saunders 1981).
<table>
<thead>
<tr>
<th>Temperature</th>
<th>Case (1)</th>
<th>Case (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°C</td>
<td>1.463 g/cm³</td>
<td>1.463 g/cm³</td>
</tr>
<tr>
<td>40</td>
<td>1.455</td>
<td>1.451</td>
</tr>
<tr>
<td>80</td>
<td>1.439</td>
<td>1.429</td>
</tr>
<tr>
<td>120</td>
<td>1.419</td>
<td>1.400</td>
</tr>
<tr>
<td>160</td>
<td>1.394</td>
<td>1.364</td>
</tr>
<tr>
<td>200</td>
<td>1.365</td>
<td>1.322</td>
</tr>
<tr>
<td>240</td>
<td>1.333</td>
<td>1.273</td>
</tr>
<tr>
<td>280</td>
<td>1.295</td>
<td>1.215</td>
</tr>
<tr>
<td>320</td>
<td>1.250</td>
<td>1.144</td>
</tr>
<tr>
<td>360</td>
<td>1.193</td>
<td>1.051</td>
</tr>
<tr>
<td>400</td>
<td>1.119</td>
<td>0.925</td>
</tr>
</tbody>
</table>

Table 2. Effect of thermal expansion on the density of a sediment at 500 bar. Initial porosity of sediment 0.75; grain density 2.7 g/cm³. Case (1) applies when pore water flows away leaving porosity unchanged. Case (2) applies when pore water expands in-situ.
References


Figure Captions

Figure 1. The thermal expansion of water/seawater at 200 and 500 bar. The expansion of quartz, measured at atmospheric pressure, is shown for comparison. As a general rule the thermal expansivity of sedimentary pore water is two orders of magnitude greater than that of the solid component.

Figure 2. The effect of thermal expansion on the density of a sediment at an ambient pressure of 500 bar. Initial porosity of sediment 0.75; grain density 2.7 g/cm$^3$.

Figure 3. Increase of porosity with temperature when pore water remains in place as a sediment expands. The values correspond to the Case (2) situation in Figure 2.

Figure 4. Permeability versus void ratio for various deep-sea clays (from Silva et al., 1980).

Figure 5. Permeability versus void ratio of some North Atlantic sediments (personal communication from P.J. Schultheiss).

Figure 6. The process of thermal tamping expressed in geotechnical terms on a consolidation plot. 0: Normally consolidated sediment. 1: Pore water expansion decreases effective stress. 2: Drainage re-establishes initial $p'_o$. 3: Pore water contraction increases effective stress. 4: Drainage re-establishes $p'_o$ at reduced void ratio.

Figure 7. Thermal tamping. The reduction in void ratio of a sediment, originally close to 0°C, when heated to a given temperature and then allowed to cool back to its original temperature. Original void ratio 3.0; ambient pressure 500 bar.
Figure 8. Sill-induced reduction of porosity (hatched areas) in Guaymas Basin drill sites. The dashed line indicates the porosity/depth relationship that would be expected in the absence of intrusions (after Einsele et al. 1980).

Figure 9. The temperature history adjacent to a waste canister buried in the sediments of the ocean floor (after Russo, 1980).

Figure 10. The steady state temperature field around a spherical canister of radius 0.35m, heat output 1000 W, embedded in sediment of thermal conductivity 0.85 W m\(^{-1}\) K\(^{-1}\) (dashed line). The solid line shows the corresponding sediment density, assuming that the sediment expands with the pore water in situ (Case (2) in Figure 2).

Figure 11 The Buoyancy Stress of a spherical canister and surrounding shell of sediment as a function of radius. The density of the canister is 3.0 g cm\(^{-3}\) and its radius 0.35m. The density of the surrounding sediment is shown in Figure 10. See text for definition of Buoyancy Stress. For comparison, the shear strength of a typical oceanic sediment at 30 m burial depth is about 30 kPa (Silva, 1977).
Figure 1
CASE 1  EXPULSION OF PORE WATER WITH SEDIMENT MATRIX UNCHANGED I.E. CONSTANT POROSITY

CASE 2  EXPANSION OF PORE WATER IN SITU

Figure 2
Figure 4
Figure 5

- (H) MARL 52% CaCO₃
- (V) MARL 50% CaCO₃
- ▲ (V) MARL 64% CaCO₃
- (V) RED PELAGIC CLAY

(H) HORIZONTAL FLOW
(V) VERTICAL FLOW
Figure 6

VOID RATIO e

EFFECTIVE STRESS (LOG P')

1 2 0 4 3
10

P_0'

1 10 100
VOID RATIO AFTER THERMAL CYCLE TO TEMPERATURE GIVEN

Figure 7

VOID RATIO AFTER THERMAL CYCLE TO TEMPERATURE GIVEN

1.5

2.0

2.5

3.0

3.5

100

200

300

400

TEMPERATURE °C

FRACTIONAL POROSITY

0.65

0.70

0.75
Figure 10
Figure 11