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Thermal Expansion Effects in Deep Sea
Sediments

T.J.G. Francis

February, 1982

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NATURAL ENVIRONMENT RESEARCH COUNCIL

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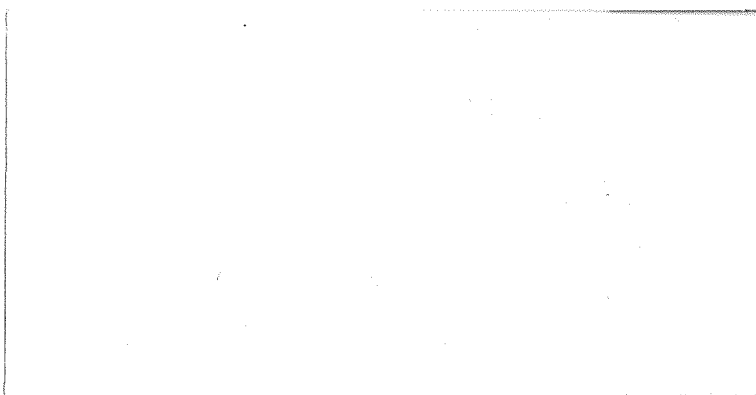Bidston Observatory,
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Summary

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 $35^c/cc$) 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 $\frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_p$, 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°-1000°C. Most rocks and common rock-forming minerals have a volume thermal expansion coefficient of about 3×10^{-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 ρ is related to the solid particle density ρ_s and the fluid density ρ_f by

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

where ϕ is the fractional porosity.

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This expression can be used to calculate the density of the heated sediment since ρ_f is known as a function of temperature (Table 1) and ρ_s and $\emptyset$ 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

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

where in the undrained case W, W_s, W_f and ρ_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

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

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 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 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

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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

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

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 $\dfrac{V_v}{(1 + m/100)}$ on cooling back to $0^{\circ}C$. Thus the final void ratio on completion of the thermal cycle is given by:

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

Expressed in terms of porosity, this formula can be written

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

Since the ambient temperature at which the unlithified 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 2000m 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) (offscale 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 $Wm^{-1} K^{-1}$ 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

$$T = \frac{Q}{4\pi Kr}$$

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:

Buoyancy Force = Weight of Sphere of Unaffected Sediment (radius r)

        - Weight of Canister (radius r_0)

        - Weight of Shell of Heated Sediment (radius r_0 to r)

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$$\text{or} \quad F = \frac{4}{3} \pi \, r^3 \rho_s - \frac{4}{3} \pi \, r_o^3 \rho_c - \int_{r_o}^{r} 4\pi r^2 \rho \, dr$$

where ρ_s = density of unaffected sediment

ρ_c = mean density of canister

ρ = density of heated sediment = $\rho(r)$

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:

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

This expression has been evaluated numerically taking values of ρ from Figure 9, ρ_s = 1.463 gcm^{-3} and ρ_c = 3.0 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

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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.

(3)   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 wihtin this shell will be less than

that in the unaffected sediment.

(4)   The processes outlined above have important implications for the

burial of hot canisters of radioactive waste beneath the ocean

floor.

(5)   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.

(6)   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.

(7)   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.

Temperature	200 bar		500 bar	
	Specific Volume	Density	Specific Volume	Density
0°C	0.9639 cm³/g	1.037 g/cm³	0.9518 cm³/g	1.051 g/cm³
40	0.9725	1.028	0.9619	1.040
80	0.9926	1.007	0.9814	1.019
120	1.0216	0.979	1.0084	0.992
160	1.0600	0.943	1.0433	0.958
200	1.1087	0.902	1.0866	0.920
240	1.1730	0.853	1.1409	0.877
280	1.2624	0.792	1.2104	0.826
320	1.4045	0.712	1.3060	0.766
340	1.5281	0.654		
360	1.7734	0.564	1.4483	0.690
380	8.0359	0.124		
400			1.6890	0.592

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)

Bulk Density

Temperature	Case (1)	Case (2)
0°C	1.463 g/cm^3	1.463 g/cm^3
40	1.455	1.451
80	1.439	1.429
120	1.419	1.400
160	1.394	1.364
200	1.365	1.322
240	1.333	1.273
280	1.295	1.215
320	1.250	1.144
360	1.193	1.051
400	1.119	0.925

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/cm^3. Case (1) applies
when pore water flows away leaving porosity unchanged.
Case (2) applies when pore water expands in-situ.

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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^oC, 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

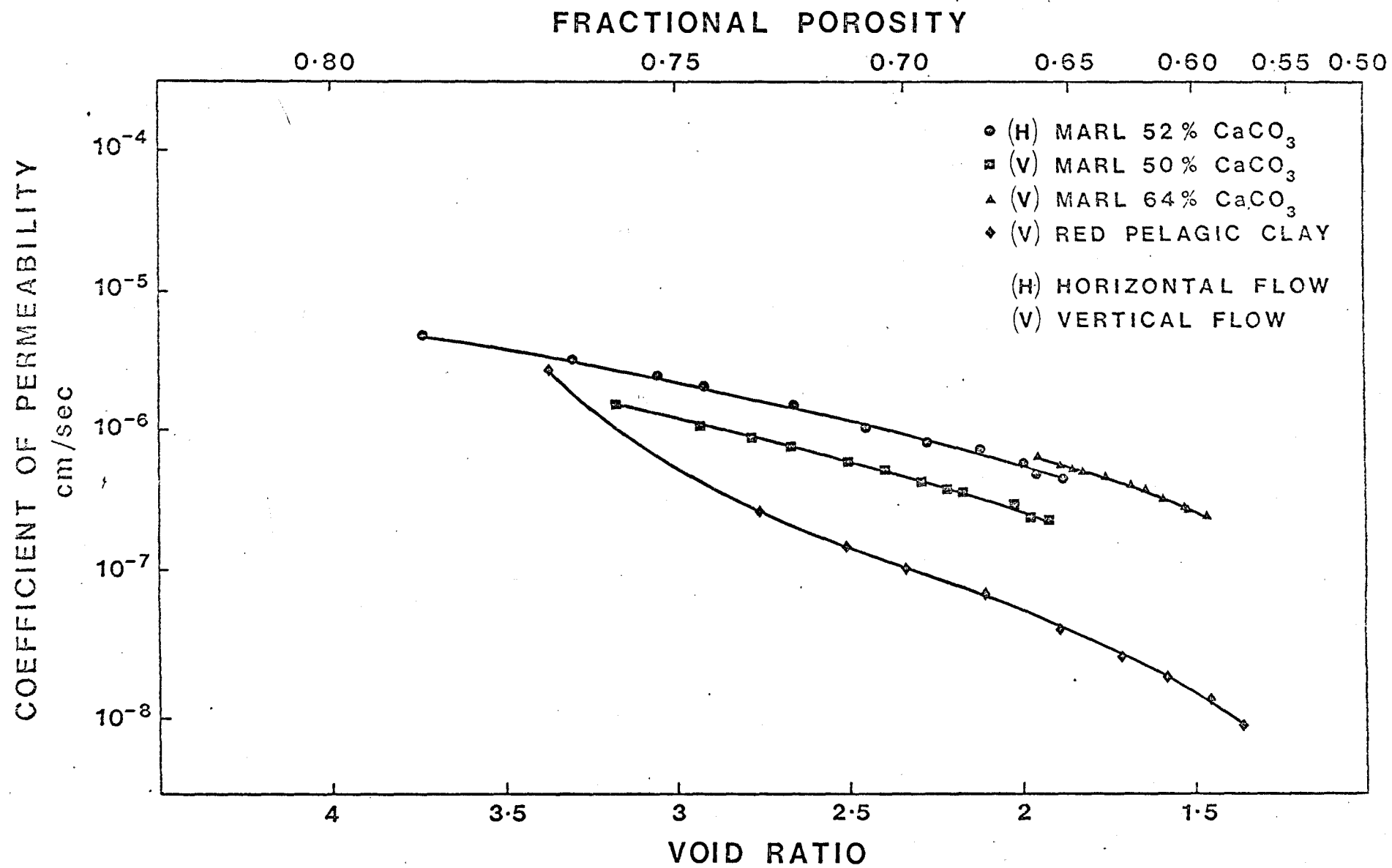sediment at 30m burial depth is about 30 kPa (Silva,
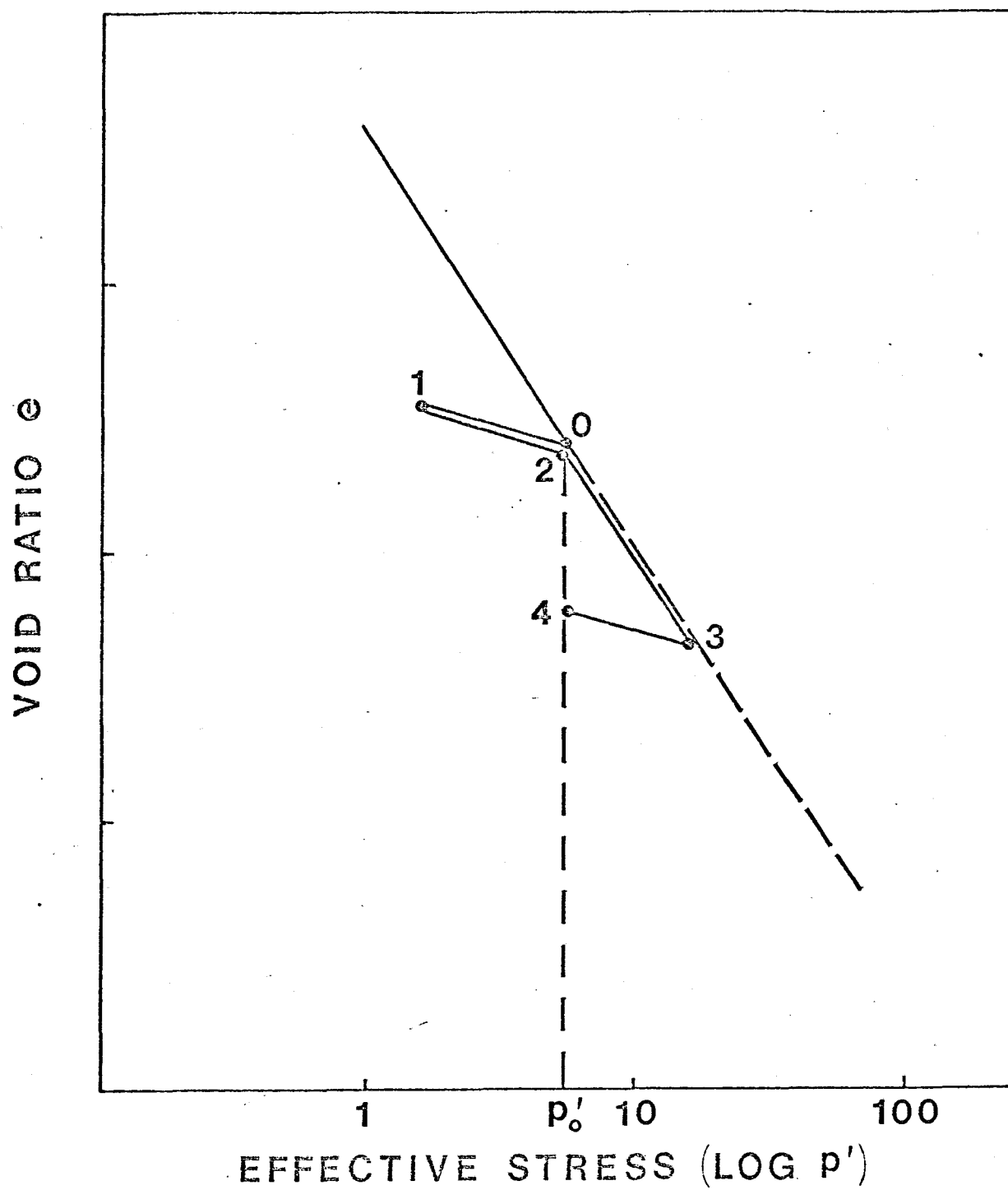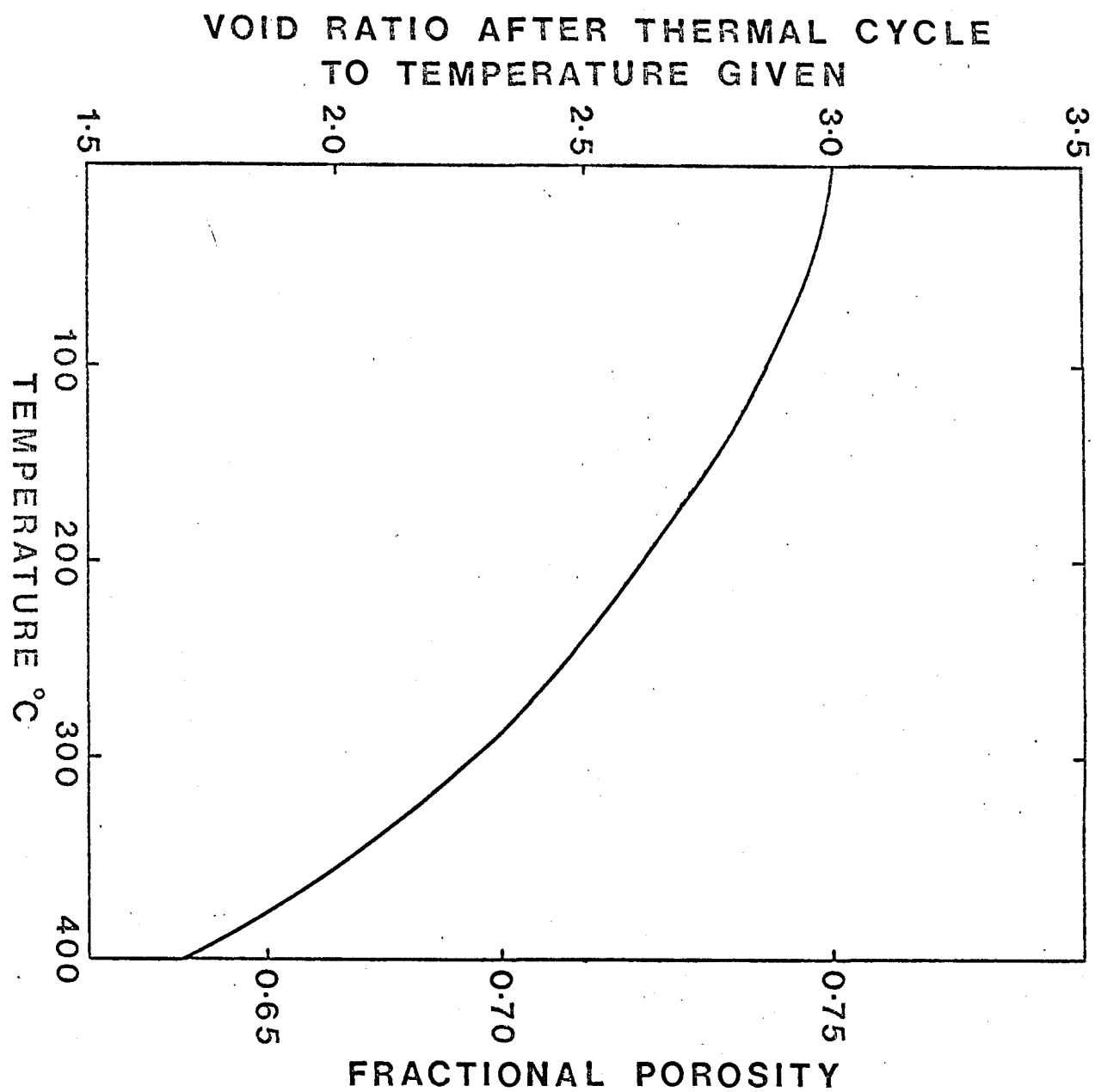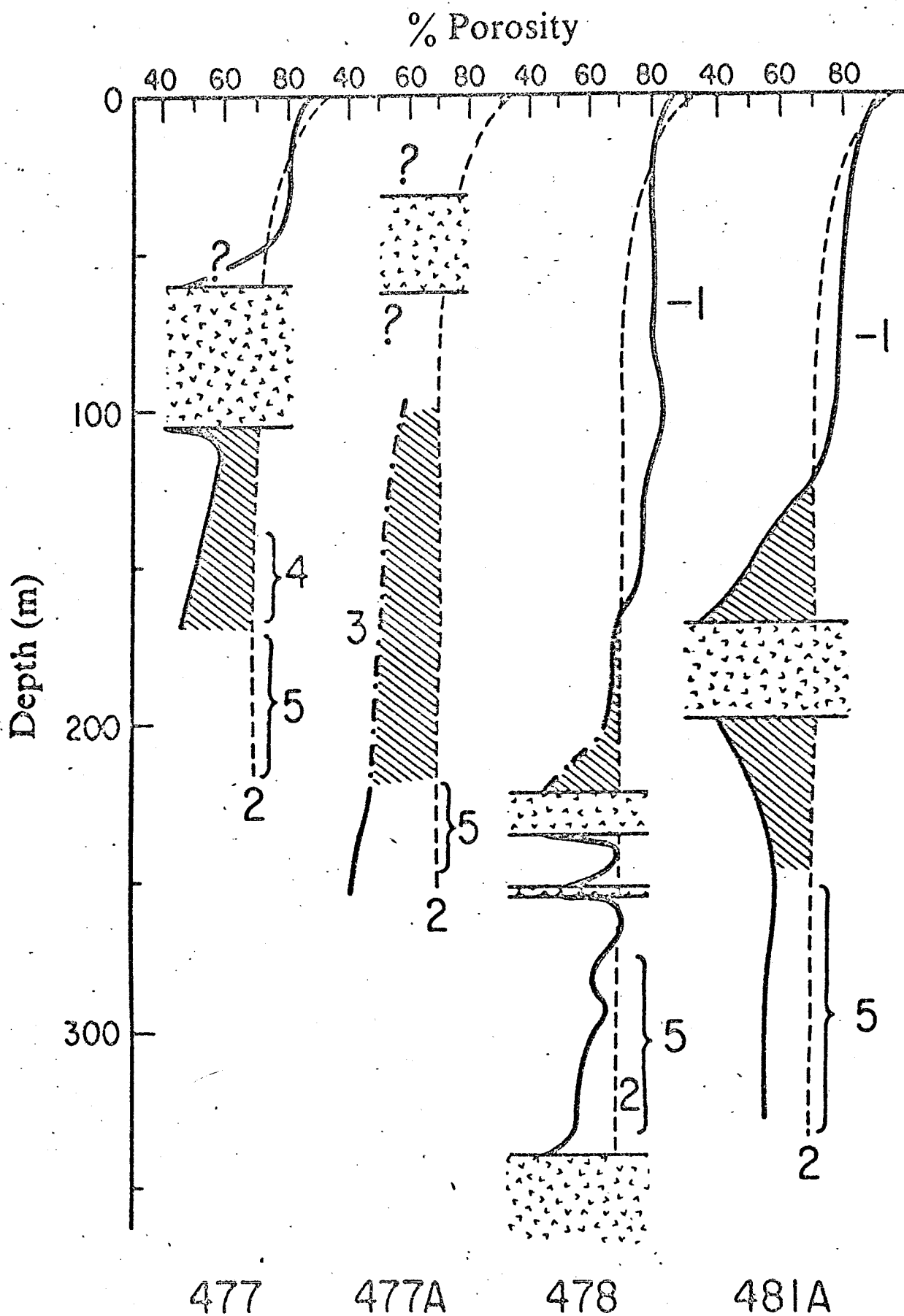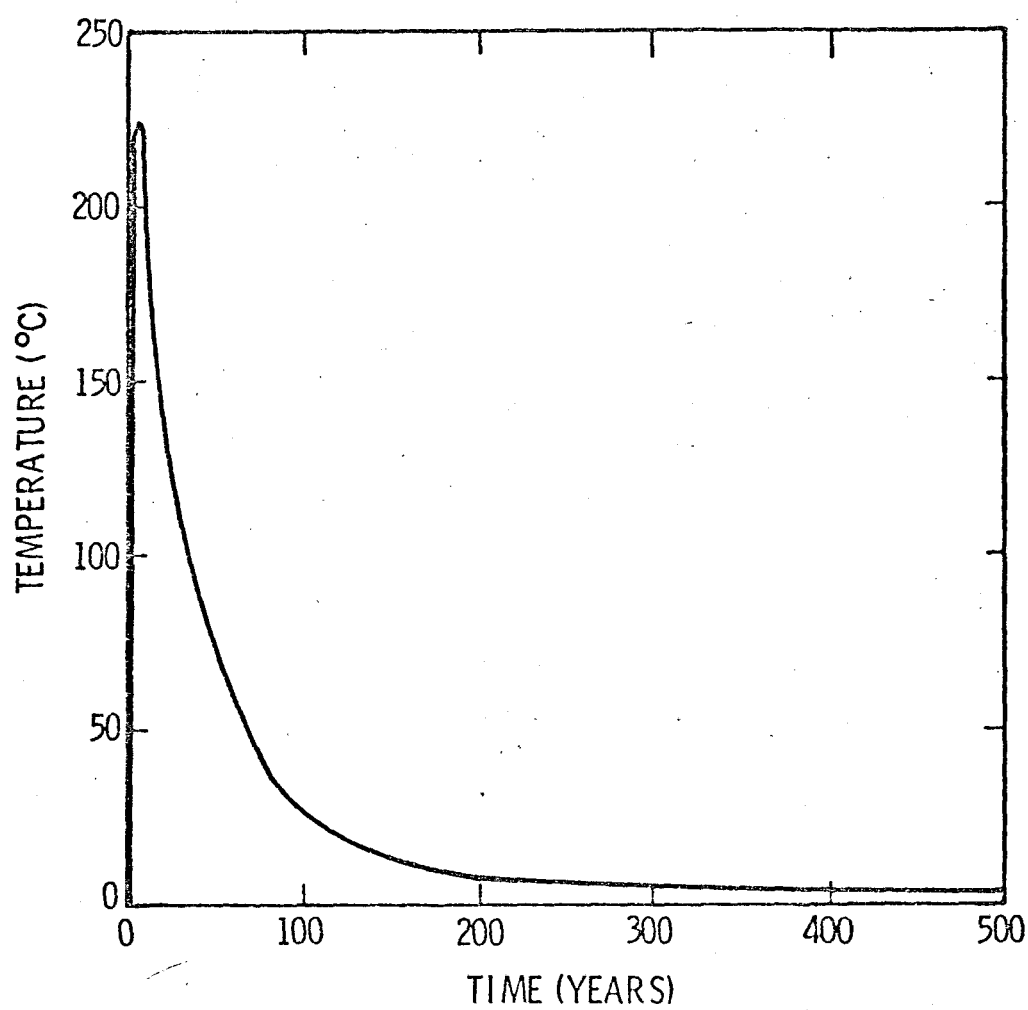
1977).
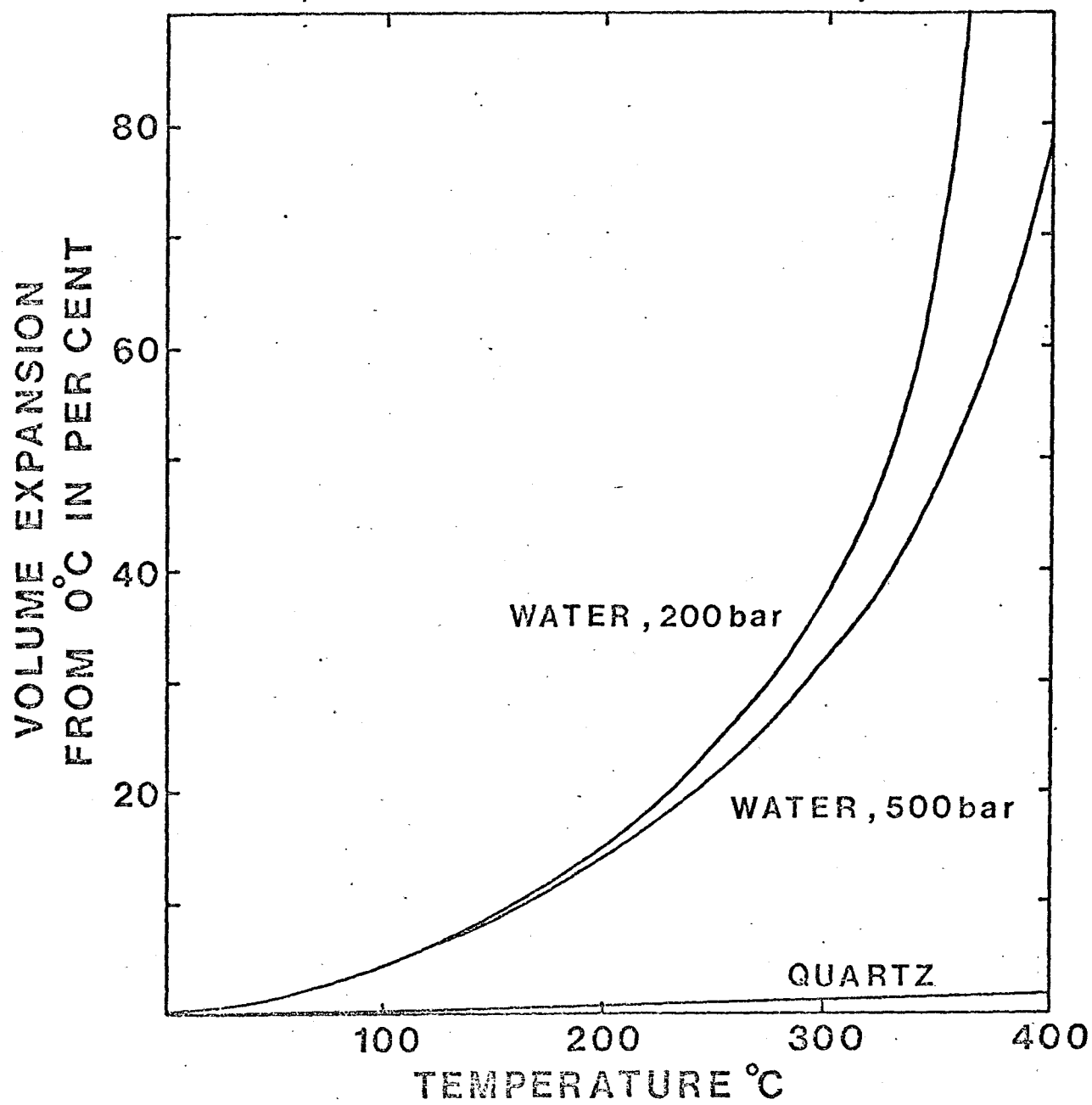
Figure 1
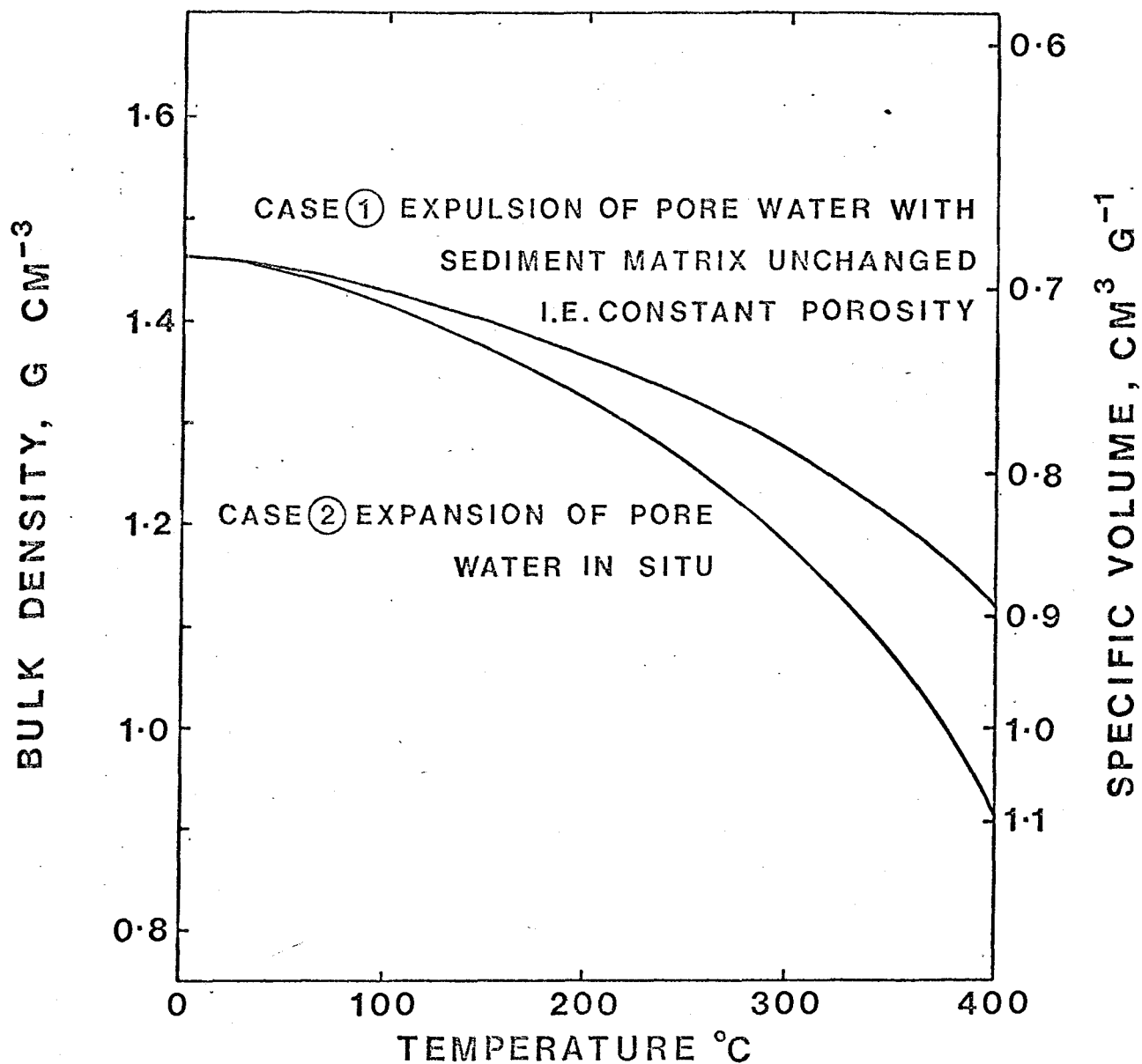
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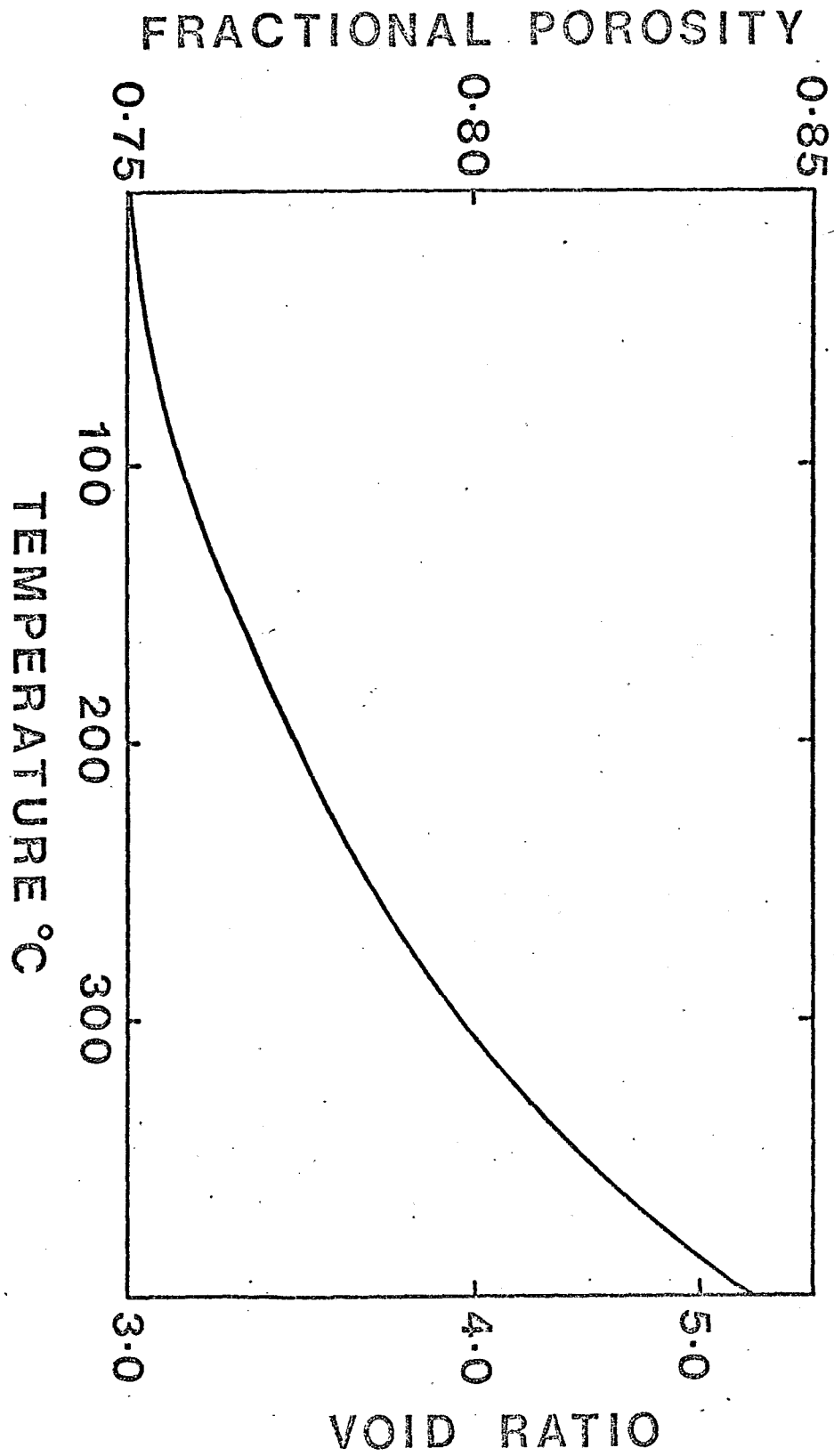
Figure 3
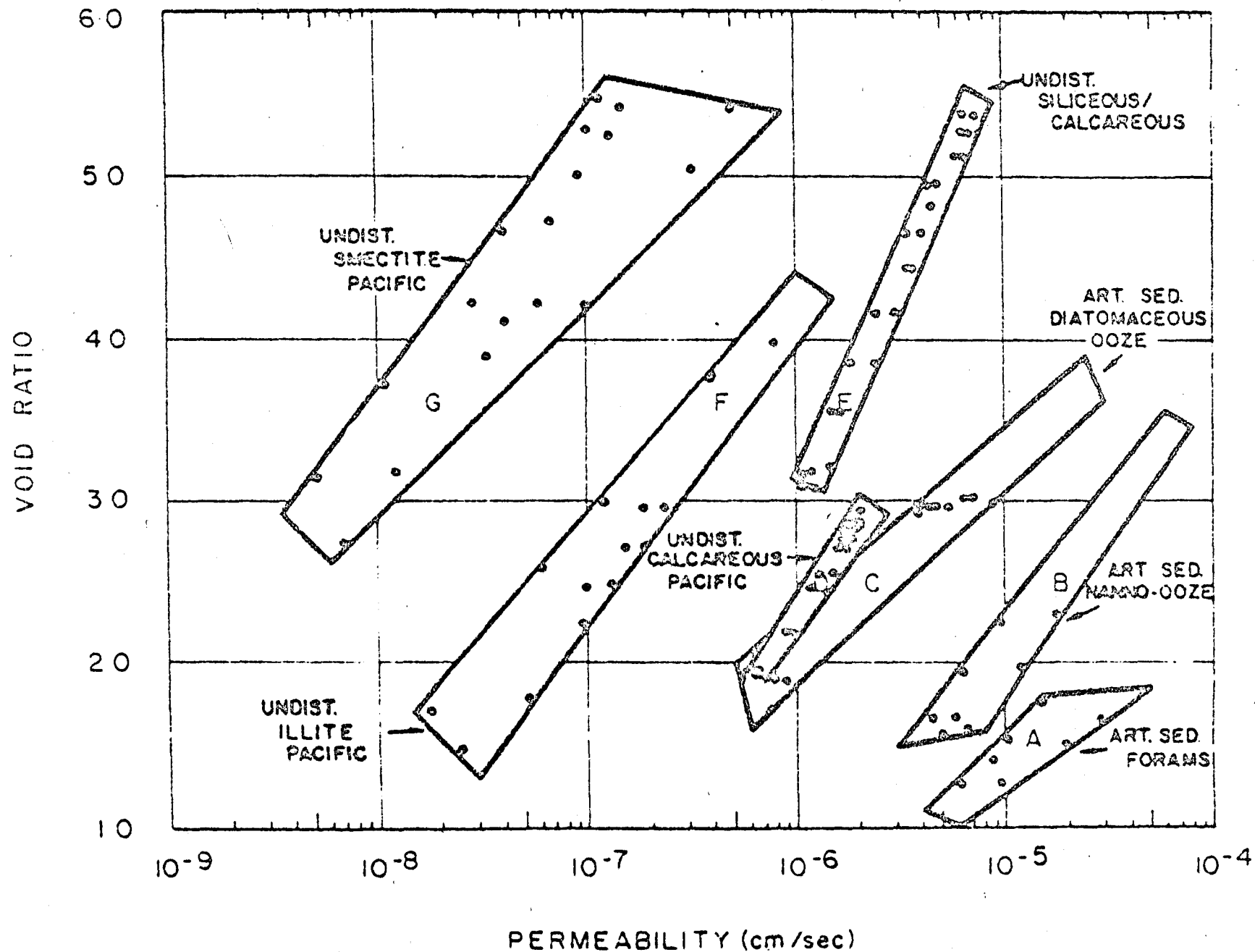
Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11