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Porosity Loss in Chalk Facies Sediments by Physical Compaction or by Cementation - Consequences for P-wave Modulus

The P-wave modulus and porosity of samples from North Sea chalk reservoirs were compared to data from the Ocean Drilling Program. The ODP classifies pelagic calcareous sediments as uncemented "ooze", "chalk", "clay", "claystone" and "mixed sediments" or as cemented "limestone" and "mixed sedimentary rock". Here the porosity and the P-wave modulus are discussed for these sediments.

INITIAL SEDIMENT

Results show that sea bottom porosity varies between 55% and 80% depending on sorting. Sorting of pelagic calcareous sediments depends on mixing between nannofossils (mud), clay, and microfossils.

RECRYSTALLIZATION

Upon deposition, sediment particles are not in equilibrium with the pore water and recrystallization (Ostwald ripening) probably takes place because calcite surfaces dissolve and/or grow in constant interchange with calcium- and carbonate- ions from the solution. Recrystallization involves simultaneous dissolution and precipitation processes, and thereby the degree of recrystallization depends on time and temperature as well as particle size, shape and roughness. The overall result of the recrystallization is larger, smoother and more regular crystals, but recrystallization as such does not cause porosity loss.

PHYSICAL COMPACTION

Physical compaction is the main factor causing porosity loss in carbonate ooze, chalk and mixed sediments upon burial. Chemical compaction along stylolites are insignificant in the studied ooze, chalk, and mixed sediment sections. Clay rich lithologies may reach porosities below 10% by physical compaction, whereas clay poor ODP chalk cannot even be compacted to 30% porosity. Recrystallization causes the calcite crystals to be more equant, and may in this way promote mechanical compaction of ooze and mixed sediments. Where the rate of mechanical compaction is low relative to recrystallization, the recrystallization leads to formation of contact cement, which, when strong enough, halts mechanical compaction. This commonly happens after compaction to around 50% porosity, where further physical compaction requires increasing rate of stress addition. Internally derived contact cementation thus retards or prevents porosity loss. For physical compaction to proceed where contact cement has formed, the effective burial stress must increase rapidly, either by a sudden change to larger burial or by release of pore pressure.

In hydrocarbon bearing North Sea chalk, microfossils may be filled with cement and mud particles mature to equant shape while the mud matrix itself remains uncemented as a consequence of "hydrocarbon lubrication". Uncemented North Sea chalk with mature mud may have porosities near 20% where the effective burial stress is large enough. In several North Sea fields the effective burial stress is so low that porositities of 40%-50% are maintained.

CEMENTATION

Chalks in the deep sea indurate to limestones over a short depth interval, where the porosity declines, indicating that the induration is not only due to formation of contact cement. It is possible that limestone form when hot calcium-rich pore water advects from the basalt and causes thorough recryatllization and deposition of externally derived cement. An internal source for the cement, e.g. from stylolites is not excluded but must be subordinate as evidenced by the low $\delta^{18}O$ values in the limestone. Cementation may result in porosities of less than 10% irrespective of clay content, however some cemented samples may have porosities as high as 50%.

In the central North Sea, the Chalk Formation has low porosities, where hydrocarbons are not present, and the chalk probably is below the "cementation front". So even if the presence of hydrocarbons facilitates compaction, it also prevents cementation, so that porosity is maintained in hydrocarbon bearing intervals.

SUMMARY OF POROSITY REDUCING FACTORS

1. In the first few hundred meters of burial, carbonate ooze looses porosity by mechanical loading, and is recrystallized, normally without formation of contact cement.
2. When the rate of porosity loss by mechanical compaction becomes slower than recrystallization, contact cement starts forming and the ooze indurates to chalk. Porosity loss progresses through mechanical compaction.
3. When the contact cement becomes too strong relative to the weight of the overburden, porosity reduction by mechanical compaction stops, and the chalk maintains its porosity, while recrystallization causes the chalk to coarsen, so that grains and pores grow.
In calcareous sediments with lower carbonate content, the formation of contact cement is hampered by the non-calcite phases, and porosity loss by mechanical loading may continue.
4. Limestone forms, where hot calcium bearing fluids advect into the chalk (or ooze), and the calcite crystals grow as pores diminishes.
In calcareous sediments with lower carbonate content, the minerals are segregated, and calcite grains cannot form contact cement.

EFFECTIVE MEDIUM MODEL

The P-wave velocity of a water saturated sediment depends on the relative proportion of water and sediment particles, the chemical composition of the pore water and the mineralogical composition of the particles. It also depends on the effectiveness of the contact between the sediment grains. In order to address the question of predicting sediment composition from P-wave velociy, the P-wave velocity, v_P, may first be recalculated to P-wave modulus, M:

$$M = v_P^2\rho$$

where ρ is the bulk density.
M is an elastic property describing the stress-increment relative to strain-increment under linear elastic uniaxial confined conditions:

$$M = \delta\sigma / \delta\varepsilon$$

where ε is the axial strain. By using the elastic modulus of the components of a mixture it is possible to predict the limits for the modulus of the mixture from simple mechanics. A mixture cannot be stiffer than the limit defined by Voigt (1910) or softer than the limit defined by Reuss (1929). For homogeneous mixtures, Hashin and Shtrikman (1963) defined a narrower upper bound than Voigt. For sediments, a maximal porosity is obtained at sedimentation at the sea bottom, the critical porosity, ϕ_c. The Hashin Shtrikman upper bound for the mixing of sediment particles and water may thus be narrowed by using ϕ_c as an end point for the mixing (Nur et al., 1998).

For sediments, the Reuss bound corresponds to particles in suspension, whereas one may envisage the modified upper Hashin bound of Nur et al., as representing sediments, where the particles are in closest packing. The area in between the bounds must thus be occupied by sediments with less than perfect contact between particles. I here present a new model where ϕ_c is defined as the sea bottom porosity, and the space between the Reuss bound and the upper modified Hashin-Shtrikman bound is filled by curves, each representing a constant degree of grain contact, which I will call iso-frame curves (IF). They are calculated as upper modified Hashin-Shtrikman curves, but in stead of mixing the mineral phase and water, I mix the mineral phase and suspensions in varying proportions. Each suspension loose water along the curve, but do not enter the framework. Each curve should thus represent a constant degree of induration (IF). For the model, I use the elastic moduli of pure phases as given in Table 1.

Table 1. Densities, ρ, and Elastic Moduli for Pure Phases. Bulk Modulus K, Shear Modulus G and P-wave Modulus M. Data for Water are Calculated Under the Assumption of a Temperature of 25°C, an Ambient Pressure of 0.1 MPa, and a Salinity of 3.5 % (citations in Mavko et al. 1998).

	ρ [g/cm^3)	K [GPa]	G [GPa]	M [GPa]
Calcite	2.71	71	30	111
Clay	2.55	25	9	37
Quartz	2.65	37	45	97
Water	1.02	2.3	0	2.3

APPLICATION OF MODEL TO DATA

Data were extracted from the Ocean Drilling Program (ODP) Initial Reports from Leg 130 and 165 to Leg 184 as well as from two North Sea chalk fields. As a first step all data with carbonate content above 50 wt% of the solid phase were chosen and the lithology from visual core description noted. Of these, data with non-pelagic lithology and data from aragonite bearing intervals were discarded. As a second step, water saturated bulk density, ρ, and porosity, ϕ, from the index property tables and P-wave velocities, v_P were sampled from same core section as the accepted carbonate data. These data are thus collected within a maximal interval of 1.5 m. Only v_P data measured on the split core in the horizontal direction (relative to in situ position) were used. By using split-core data, the data can be directly referred to chemical data and lithology as described on the core. The two sets of data were merged so that all carbonate data with no corresponding P-wave velocity or density data were excluded. Where available, pore water chemistry (data from same core), and age as defined by nannofossils and foraminifers, were noted.

The full data set was split into six in order to be able to discern the influence from diagenesis, sorting, and mineralogy: 1) ooze with more than 75% calcite. 2) Chalk with more than 75% calcite. 3) clay, mixed sediments, and claystone with more than 75% calcite. 4) ooze, mixed sediments, clay, and chalk with 50%-75% calcite. 5) limestone with more than 75% calcite. 6) limestone and sedimentary rock with 50%-75% calcite.

The ODP ooze samples with more than 75% calcite spans a porosity range from 75% to 25%. Some of the data are below the Reuss bound and must be erroneous. The ooze samples are rarely indurated to more than IF = 0.1 (Figure 1). The large variation in porosity must partly be due to varying degree of compaction, partly to differences in sorting. Mixing of nannofossils and hollow microfossils in ooze (and chalk) results in a relatively high P-wave modulus for a given porosity as compared to a pure nannofossil (mudstone) sediment.

The ODP chalk samples with more than 75% calcite span an equally wide porosity range, but have higher M than the ooze samples. As a rule, ODP chalk samples have IF-values below 0.6. The IF = 0.6 may be a limit for compaction of deep sea chalk. The wide scatter of data may reflect samples with different sorting of microfossils and coccoliths, and I have added conceptual compaction trends for three different textures (Figure 1).

North Sea chalk samples are nearly pure calcite. Samples with mudstone texture fall along a mudstone trend in a M - ϕ plot (Figure 1). Samples of wackestones with filled microfossils fall along a less porous trend (Røgen et al. 2000). The North Sea chalk apparently compact to lower porosities and higher IF-values (up to IF = 0.8) than the deep sea chalk (Figure 1). This is probably a consequence of hydrocarbons retarding the formation of contact cement and a high degree of recrystallization promoted by the long time since deposition of the Cretaceous sediments. The relatively high temperature relative to effective burial in the overpressured Central North Sea will also promote recrystallization.

Un-cemented samples with a significant content of non-carbonates should include samples with the poorest sorting, so that their lower limit in a M - ϕ plot may define a "poor sorting trend" (Figure 2). The samples may compact to porosities as low as 5% and IF = 0.9. This is probably a consequence of poor sorting but may also reflect a retardation of formation of contact cement.

Limestone and mixed sedimentary rocks may have lost porosity by cementation due to an external source, or they may have stiffened at constant porosity due to internally sourced contact cementation. The hole data swarm of calcite rich as well as calcite poorer limestones and mixed sedimentary rocks generally fall in the range IF = 0.4 - 0.9 in a M - ϕ plot (Figure 3). They are thus shifted upwards along the M-axis relative to the uncemented lithologies (Figure 1, 2). High porosity limestones may have internally derived cement. The porosity is so high that there is hardly room for externally derived material.

Whereas mechanical compaction unequivocally reduces porosity with or without velocity increase, the primary consequence of cementation is a stiffening of the frame, which may or may not be accompanied by porosity loss.

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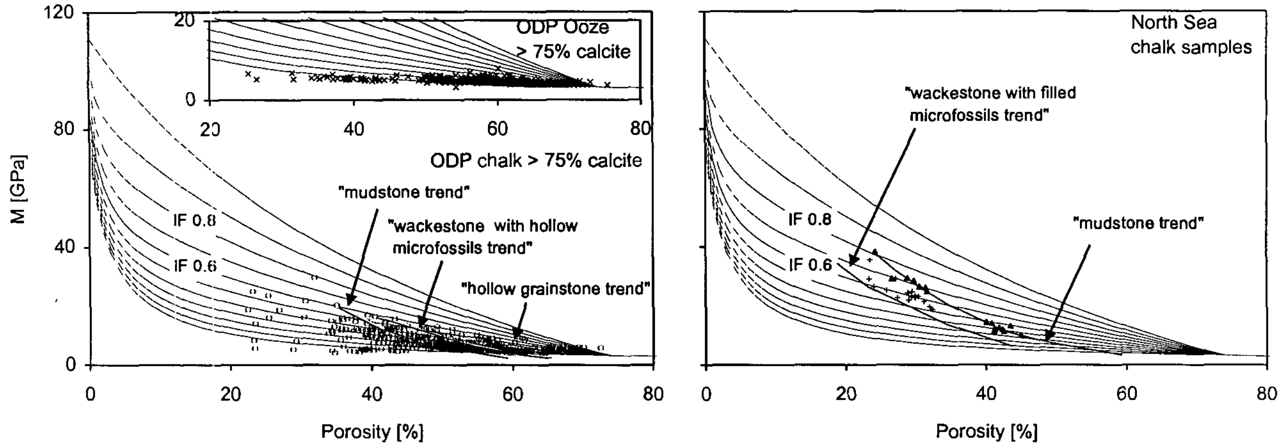

Figure 1. ODP data left: ooze (x-es) and chalk: (o-es).

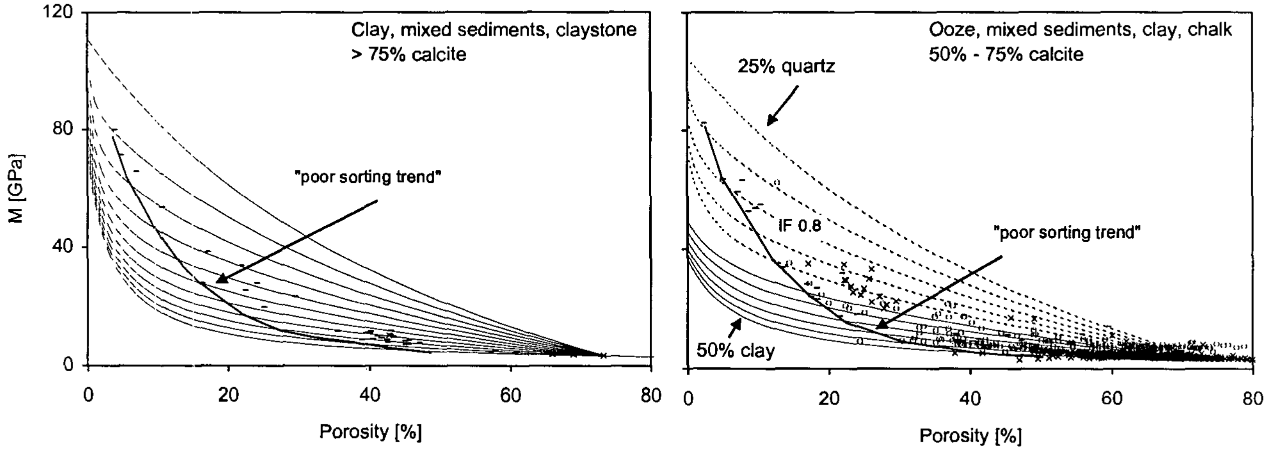

Figure 2. ODP data: clay and claystone (bars), ooze and mixed sediments (x-es), chalk (o-es).

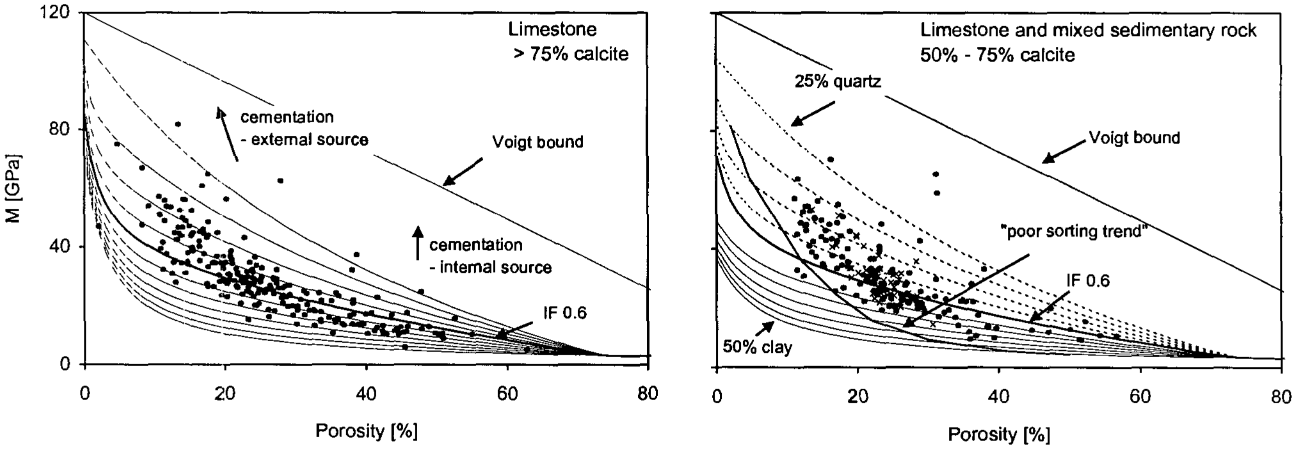

Figure 3. ODP data: limestones (dots) and mixed sedimentary rocks (x-es).

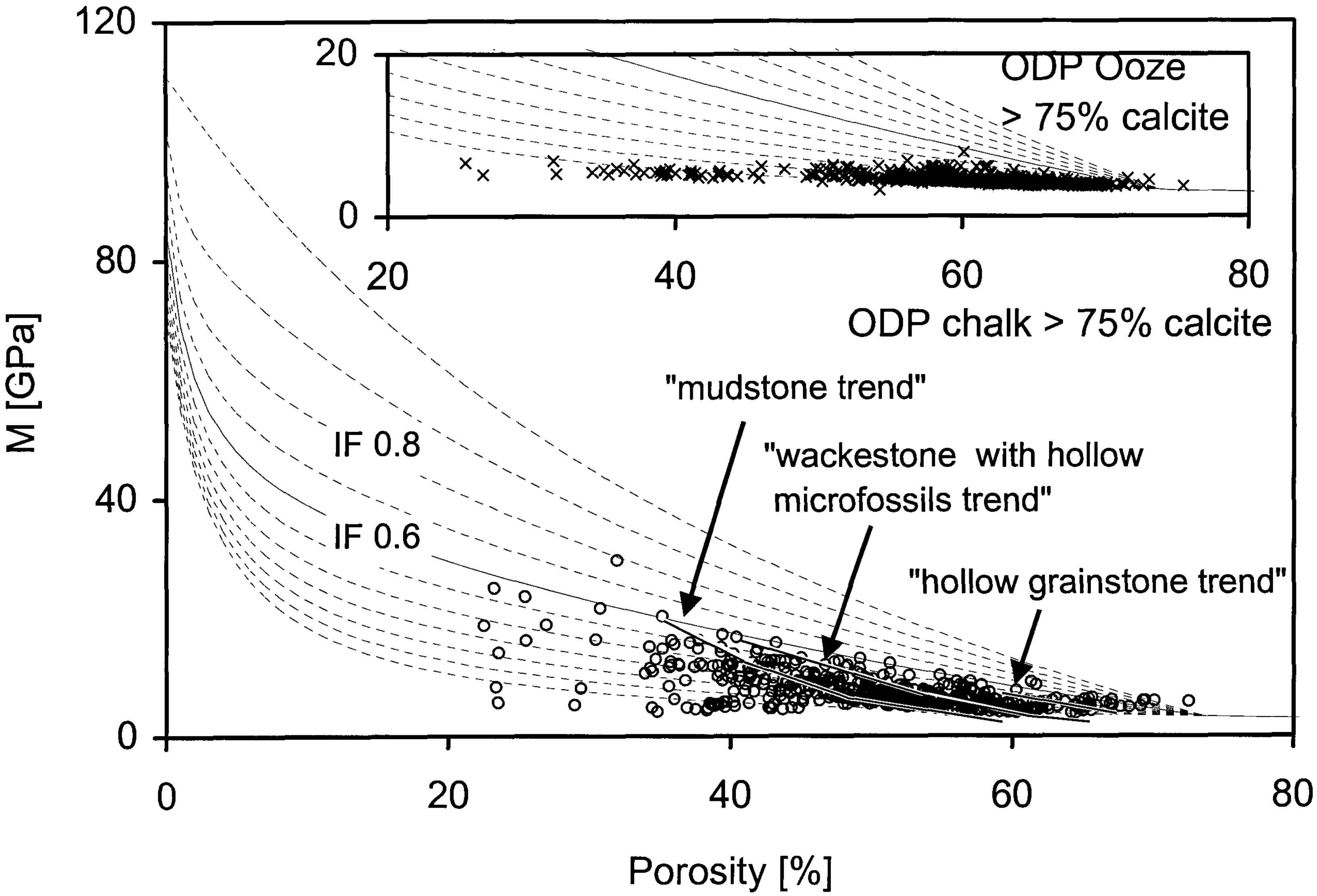
120
80
40
0
M [GPa]
0
20
40
60
80
Porosity [%]
IF 0.8
IF 0.6
"mudstone trend"
"wackestone with hollow microfossils trend"
"hollow grainstone trend"
20
0
20
40
60
80
ODP Ooze
> 75% calcite
ODP chalk > 75% calcite

Figure 1-1

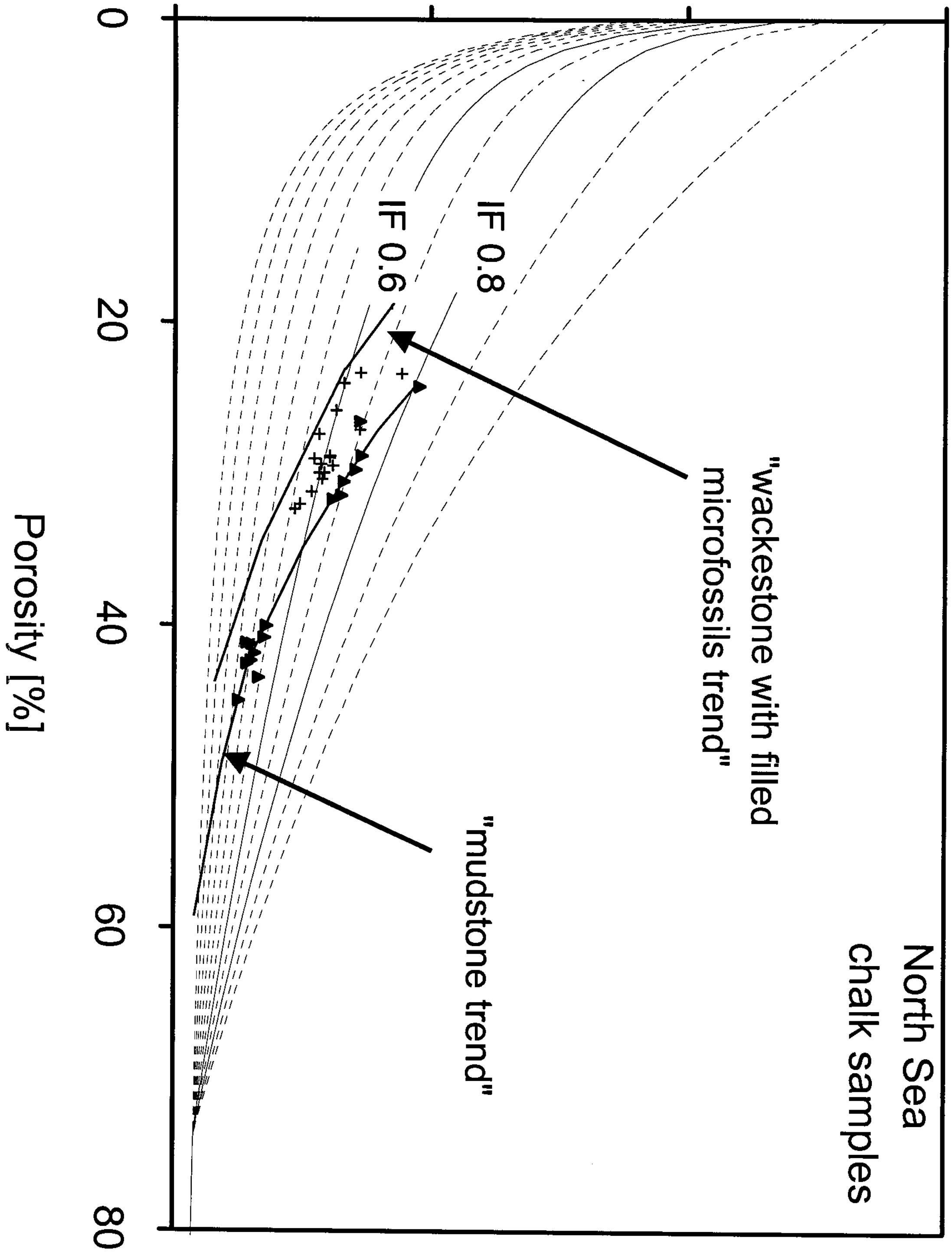
North Sea
chalk samples
"wackestone with filled
microfossils trend"
"mudstone trend"
IF 0.8
IF 0.6
0
20
40
60
80
Porosity [%]

Figure 1-2

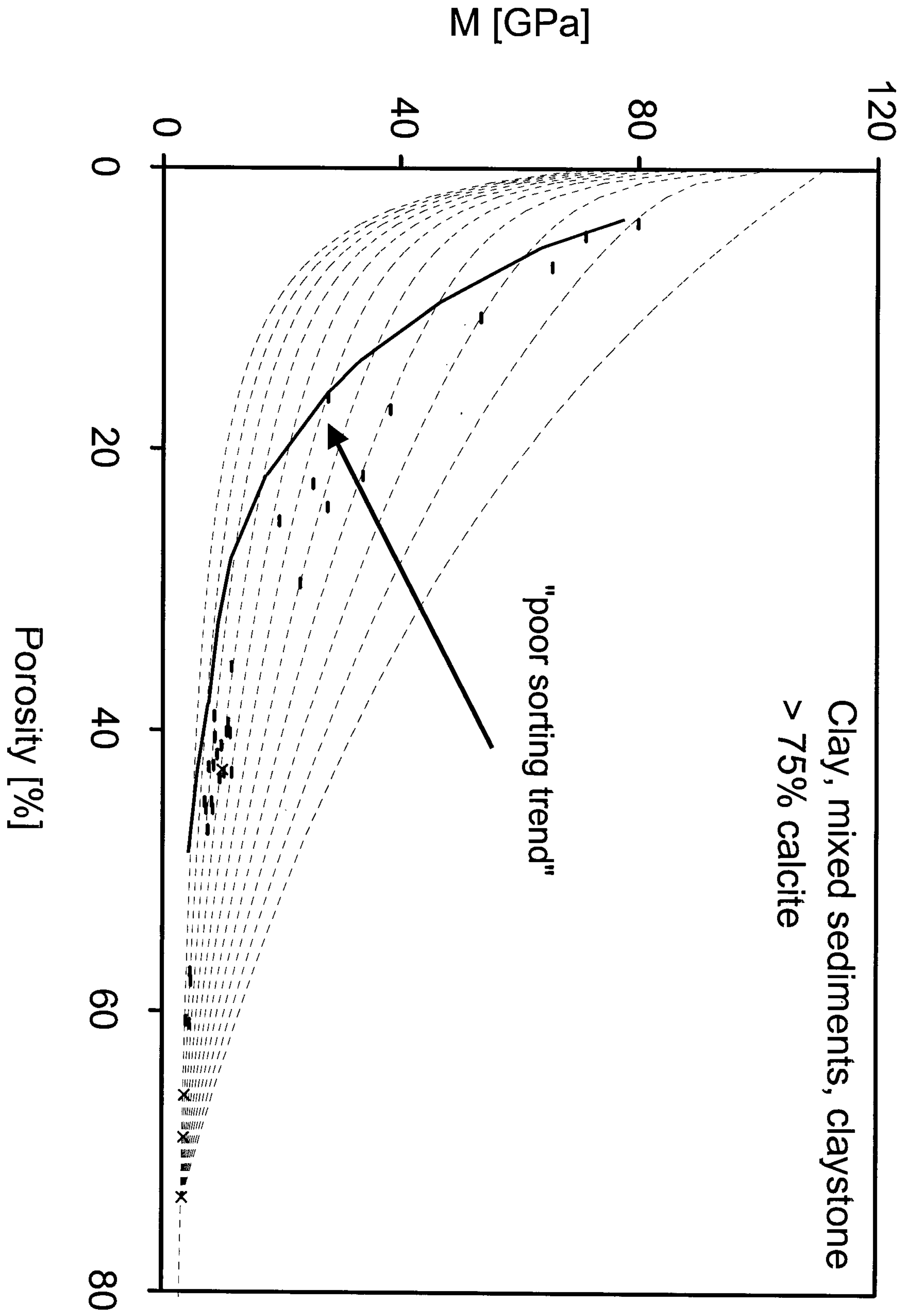
Clay, mixed sediments, claystone
> 75% calcite
"poor sorting trend"
M [GPa]
0
40
80
120
Porosity [%]
0
20
40
60
80

Figure 2-1

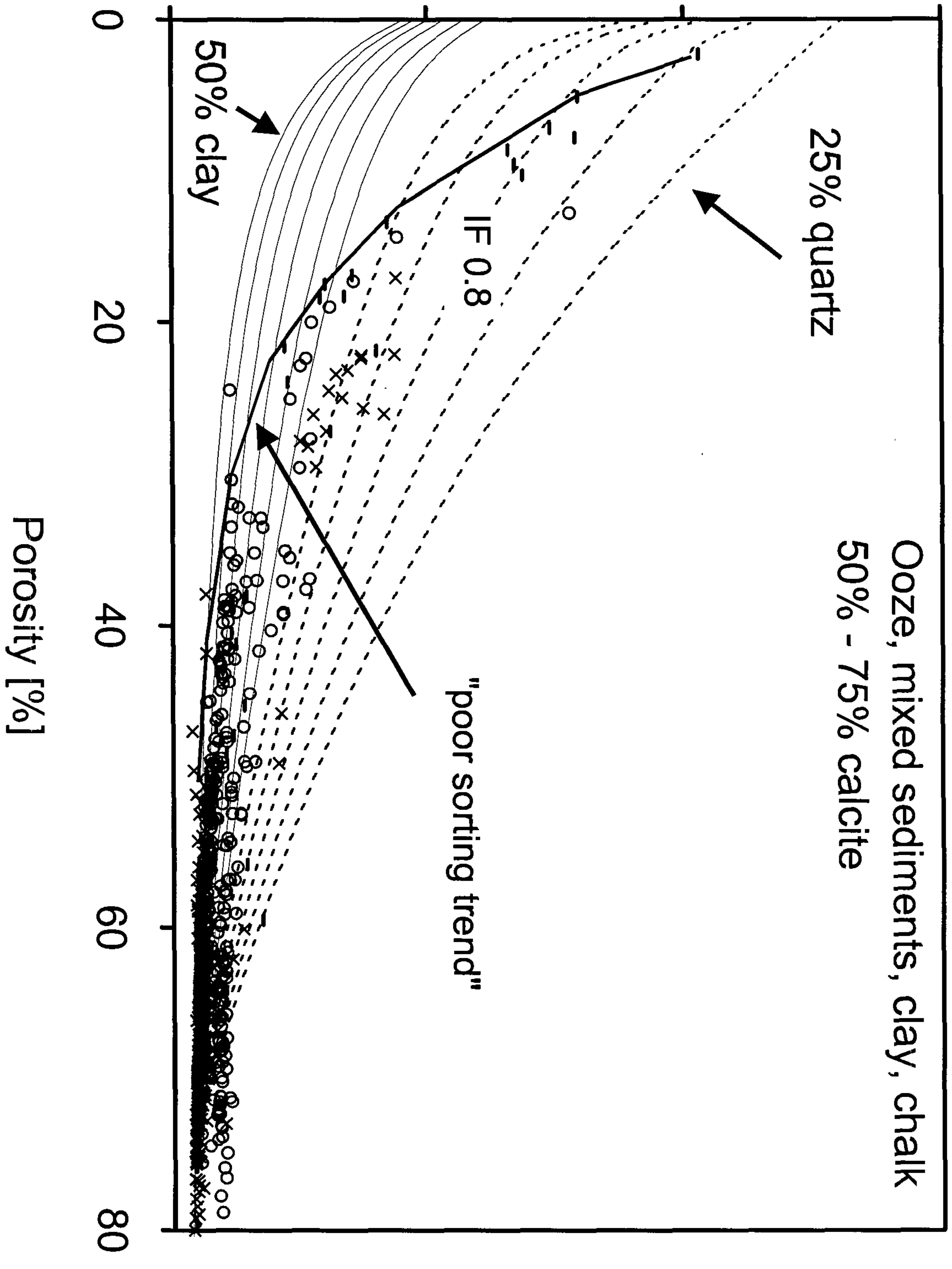
Ooze, mixed sediments, clay, chalk
50% - 75% calcite
25% quartz
IF 0.8
"poor sorting trend"
50% clay
0
20
40
60
80
Porosity [%]

Figure 2-2

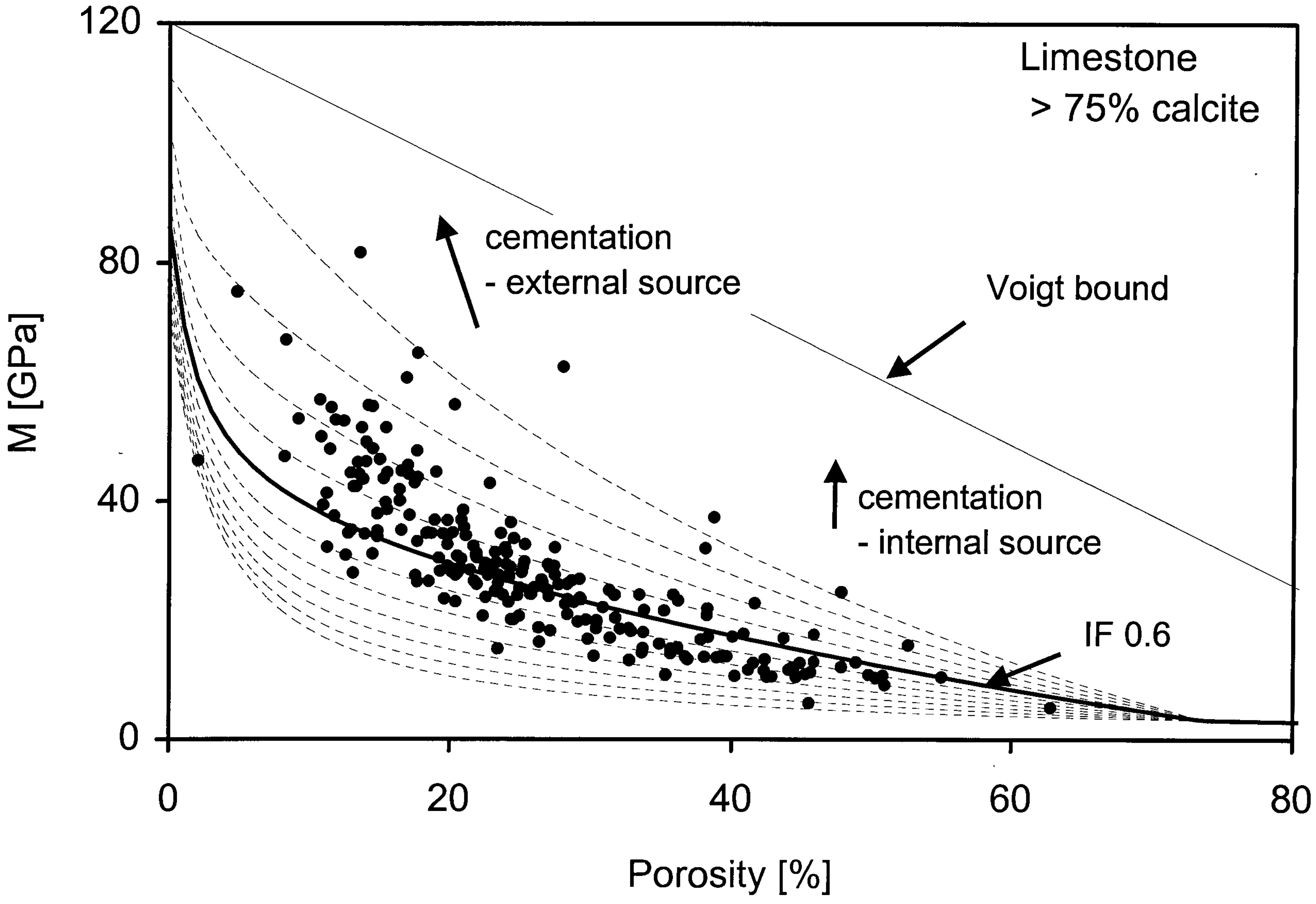
Limestone
> 75% calcite
cementation
- external source
Voigt bound
cementation
- internal source
IF 0.6
M [GPa]
120
80
40
0
0
20
40
60
80
Porosity [%]

Figure 3-1

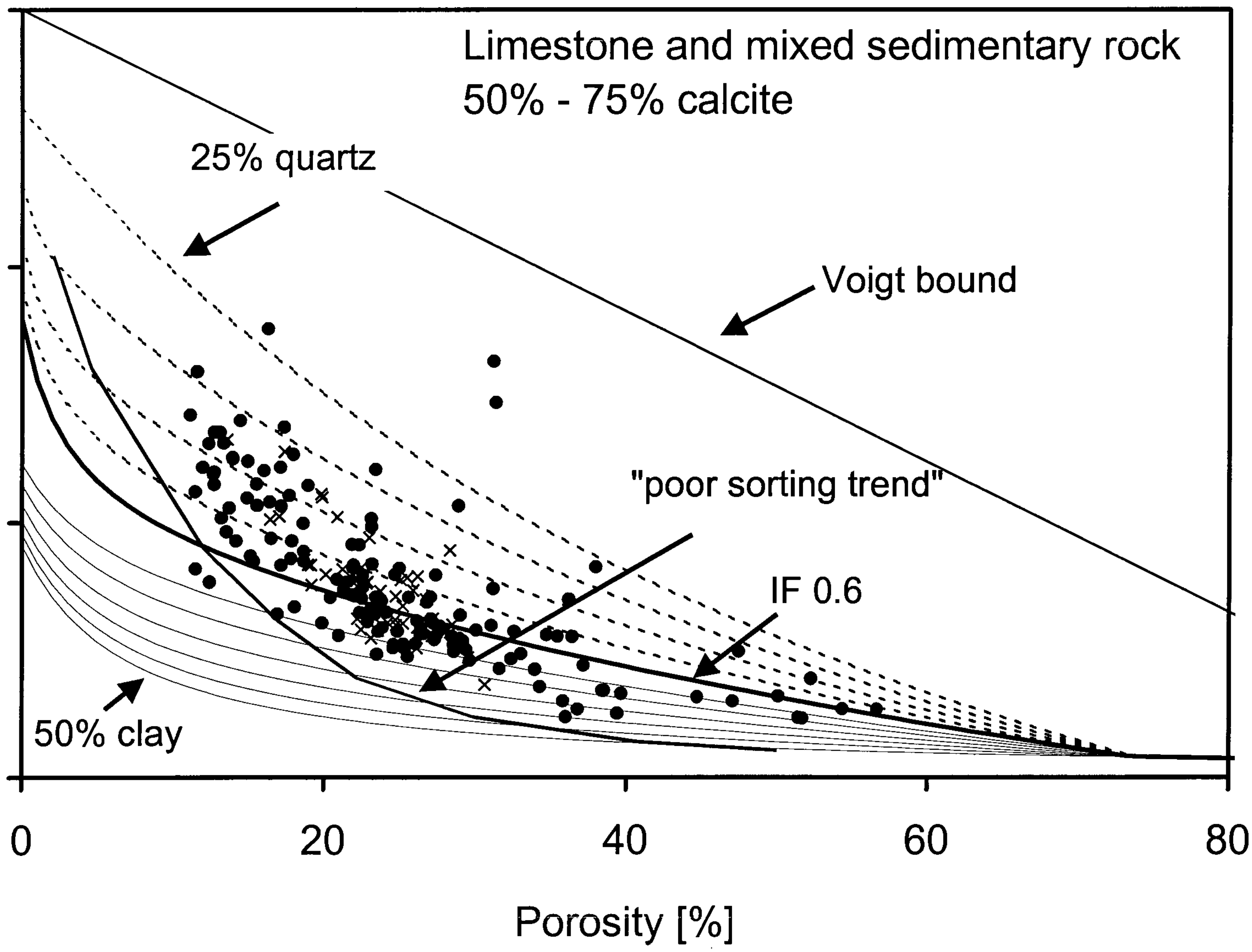
Limestone and mixed sedimentary rock
50% - 75% calcite
25% quartz
Voigt bound
"poor sorting trend"
IF 0.6
50% clay
0
20
40
60
80
Porosity [%]

Figure 3-2