Compaction Curve with Consideration of Time and Temperature Effects for Mudstones

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ABSTRACT: A compilation of compaction curves shows that the curves vary widely (porosity-burial depth), especially at the depth shallower 2000 m. There is no unique physical or mathematic expression of mudstone compaction. In this study, we have considered the burial depths (shallower 2000m), where the process of mechanical compaction dominate, and point out on time and temperature effects influencing variations of mudstone compaction curves. We revised and reconstructed the existing, widely referred, mudstone compaction curves using a correction of clay mineral dehydration and thermal correction based on time and temperature effects, respectively. The results show that the mudstone compaction curves seem to improve matching with one another. These corrections are possible toward establishment of a standard compaction curve of mudstones.

1. INTRODUCTION

Mudstone compaction has been studied for many years. A compilation of compaction curves which have been published by Mondol *et al.* (2007) showed the discrepancies among the cited data. Mudstone compaction has related to the oil and gas migration, especially shale gas which is trapped in shale (or mudstone) formation and one of the most rapidly expanding trends in oil and gas exploration and production today. Also by using compaction curves, prediction and detection of overpressure zones are one of the most important contributions to the petroleum exploration.

We intend to give an answer to the doubts of discrepancies in mudstone compaction curves as shown in Figure 1, especially the depth shallower 2000 m dominated by mechanical compaction. Time (Geologic time) and temperature were studied as major factors influence the mudstone compactions. In order to coming out these effects, we classified the data depending on geologic ages and geothermal gradients. The data which were plotted on porosity-burial depth vary with geologic ages and geothermal gradients. Furthermore, with respect to clay mineral dehydration and fluid expansion in mudstones caused by time and temperature effects, respectively, can be corrected by equations which was proposed by Keith and Rimstidt (1985).

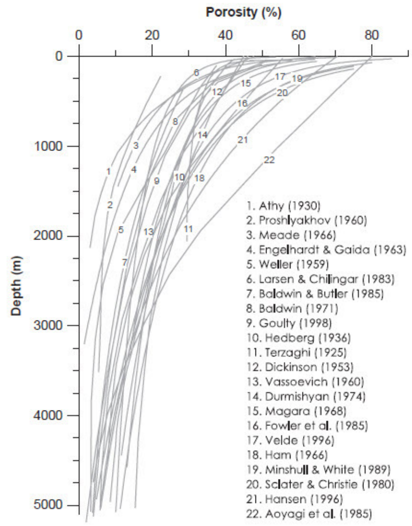

Figure 1 Compilation curves of mudstone compactions from Figure 1 in Mondol *et al*., 2007

Table 1 Data information

No.	Location	Max. Depth (m)	Geothermal gradient (°c\km)	Geologic Time Age	Amount of data	Reference
1	Oklahoma basin	2,000	~ 25	Pennsylvanian-Permian	368	Athy (1930; p.12)
2	Maracaibo basin	2,000	~ 16	Tertiary	37	Hedberg (1936; p.254)
3	Colombia basin	2,000	12-23	Cretaceous	33	Johnson (1950; p.337)
4	Akita basin	3,000	30-60	Miocene	143	Aoyagi et al. (1979; p.41)
5	Makran basin	5,000	~ 35	Tertiary	25	Fowler et al. (1985; p.429-430)
6	Central California	300	13.8-22	Pliocene-Pleistocene	35	Meade (1966; p.1086)
	Maracaibo basin	3,000	~ 16	Tertiary		
	Po valley basin	2,000	~ 18.8	Miocene-Pliocene		
7	N Pacific	50	~55	Pleistocene	138	Velde (1996; p.196)
	Barbados	460	~15	Eocene-Holocene		
	Antarctic	300	~ 52	Pliocene-Pleistocene		
	Sulu Sea	1,000	~ 127	Miocene-Pleistocene		
	Po Valley	2,500	~ 18.8	Pliocene-Holocene		
	Niigata basin	4,500	~ 30	Miocene-Holocene		
	E Atlantic	300	25-50	Pliocene-Holocene		
	Indian Ocean	1,300	30-50	Tertiary		

We revised and reconstructed data plots of mudstone compactions after time and temperature corrections. The reconstructed plots match well with one another than shown by original plots. It is possible that these studies will be able to establish mathematic expression of compaction and propose a standard curve of mudstone compactions.

2. DATA COLLECTIONS

The porosity and density are theoretically related and known as the indicators of the compaction of sediments. Time and temperature factors play important roles in controlling the density and porosity of mudstones during mechanical compaction. In this study, we compared, revised, and reconstructed the published porosity-burial depth data from several locations, geologic ages, and geothermal gradients. The data used in this study are listed in Table 1 along with location, maximum depth, geothermal gradient, geologic time, amount of data, and reference.

2.1 Information of porosity acquisitions

In cases of data No. 1, 2 and 3, porosities were estimated from density data as followed:

$$\phi = \left[1 - \left(\frac{\mathit{Bulk\ density}}{\mathit{Absolute\ density}}\right)\right] \cdot 100 \qquad (1)$$

where bulk density is the density of thoroughly dried rock, i.e. pore space free of liquids, and absolute density (or called grain density) is the density of constituent particles of a rock, i.e. rock substance free from pore space. However, they are different way to obtain the density data. The bulk density of data No. 1 was acquired by weighing a sample in mercury with a Jolly balance and a sufficient mass being suspended to submerge the sample. While, the data No. 2 used Melcher method and pycnometer method in order to measure bulk density and absolute density, respectively. In case of the bulk density data No. 3 came from wireline measurements of wells in Colombia. In addition, we assumed the absolute density of data No. 1 and 3 remains constant and equal 2.762 g/cm^3 (Fowler *et al.*, 1985) for calculating in Eq. (1).

The porosity data No. 4 were from the core samples obtained at 16 wells in Akita oil field, Japan. The natural densities of the samples were measured within a few hours, just after taken from wells, and then were converted to porosity data by that assuming specific gravity of the present sea water as 1.025, thus the average specific gravity of the grain is 2.65, as followed:

$$\phi = \frac{\rho_g - \rho}{\rho_g - \rho_l} \qquad (2)$$

where ρ is the natural density, ρ_g is the grain density, ρ_l is the density of pore water, and ϕ is the porosity.

The porosity data No. 5 were estimated by seismic velocity data using an empirical relationship derived by Hamilton (1978). First the seismic velocity was converted to bulk density (ρ_s), and then the bulk density was converted to porosity (ϕ) by using following equation

$$\rho_s = \phi\rho_w + (1-\phi)\rho_g \qquad (3)$$

a grain density (ρ_g) of 2.762 g/cm^3 and a pore water density (ρ_w) of 1.050 g/cm^3 are assumed from measurements on Deep Sea Drilling Project (DSDP) site 222.

The data No. 6 were taken as averages from the trends graphically reported in the cited publications (Meade, 1963; Storer, 1959; Hedberg, 1936). All data converted from density data which acquired from laboratory test. For data No. 7, the porosity data obtained from several basins as shown in Table 1. Almost all data were taken from Ocean Drilling (ODP) and DSDP. The porosity data were acquired from consolidation test in laboratory. The laboratory test is for porosity measurements as a void ratio and the compacting force as pressure exerted by the solids. The porosity (ϕ) is related to void ratio (e) by Eq. (4).

$$e = \frac{\phi}{(1-\phi)} \qquad (4)$$

In this study we omitted porosities above 60% because, since most of the previous studies did not deal with sediments of porosity above 60% near the surface (Velde, 1996) and there is little information about initial porosity ranging from 70% to 90% which is available from natural sediments. In addition, clay-water system is not perfectly elastic and volume recovery is never complete, thus an initial porosity of 70 - 90% may be reduced to porosity of 60% (Hedberg, 1936).

2.2 Basin information

The basin information of Oklahoma basin in data No. 1 stated that all the samples studied were taken from areas of structural deformation and some of compaction may have resulted from vertical and lateral pressures in the earth's crust. The samples were acquired from wells in the Mervine, South Ponca, Thomas, Garber, and Blackwell fields. The sediments range from Permian age to base of Pennsylvanian age with no intervening unconformity. While, the data No. 2 was obtained from the Geological Laboratory of Venezuela Gulf Oil Company. These data came from the study of core samples of Tertiary mudstones from wells drilled in the large geosynclinal basins of Venezuela. The samples were taken from a deep test in undisturbed and essentially horizontal Tertiary strata far removed from areas of major tectonic disturbance and the strata consisted in large part of mudstones which were free from appreciable sand impurity. In addition, absence of major unconformities in the section makes it possible to assume that the existing overburdens are maximum overburdens. In the case of the data No. 3 obtained from several wells of Mesozoic mudstones in Colombia.

The geologic information of data No. 4 referred to Miyazaki (1966). The samples were taken from Akita oil field and range from the mudstone of the Sasaoka formation to the black shale of the Funakawa formation. In fact, the density distribution on each well seems to be pretty normal. Each well is situated near the crest of gentle anticline, where can be recognized no structural disturbances in sediments.

The data No. 5 were taken from abyssal plain sediments in the Makran accretionary prism of northwest Indian Ocean where the oceanic Arabian plate is subducting shallowly northwards beneath the continental Eurasian plate. The abyssal plain sediments were stated that they are undeformed sediments and very little erosion takes place. According to they do not exhibit major internal deformation, thus they do not undergo tectonic consolidation.

There is little information on composited data No. 6. The sediments are all Cenozoic. Most of the sediments consist of clastic, inorganic, and terrigenous detritus. One of the composited data is the data in Venezuela basin which was already discussed above (Data No. 2), while other data are Po Valley basin of Storer (1959) and central California basin of Meade (1963).

The basin histories of data No. 7 stated that the samples were not affected by diagenesis and were critical to any interpretation of general sedimentary compaction phenomenon in ocean basins as it was the beginning stages of particle re-arrangement which must necessarily condition later stages of volume reduction which are only due to pressure.

3. TIME EFFECT

With respect to seismic work, it is known that, in argillaceous sediments, velocities of seismic wave general increase with rock density, and also increases of seismic velocities increase with geologic age (Weatherby and Faust, 1935). Furthermore, increase in seismic velocity with depth means that the terms of sediments dewatering can be gained, if the seismic velocities are converted to porosities.

Burst (1969) studied on relationships of porosity and time. He found that porosity declines as a function of geologic time, but his plot was not clear because he did not plot ranges of porosities and the depth was not specified. Hence, we selected specific depths, i.e. 3000 ft, 4000 ft and 5000 ft, in the porosity-time plots of Burst (1969) based on Manger (1963)'s data as shown in Figure 2. We found that the porosity declines as a function of geological time as same as Burst (1969).

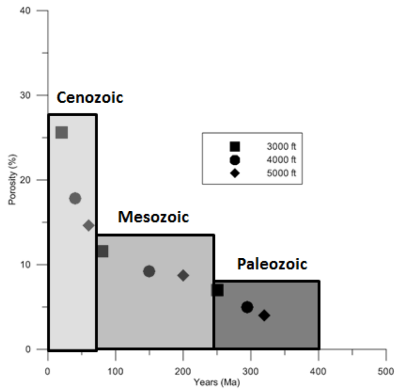

Figure 2 Porosity and geological time relationship. Modified from Burst (1969)

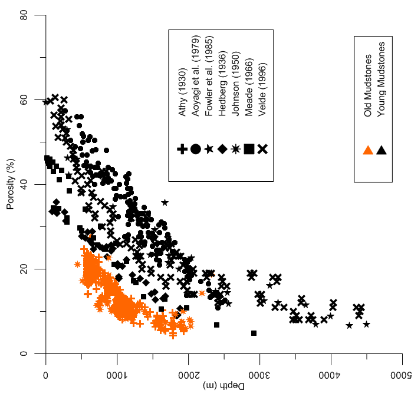

Figure 3 Porosity-burial depth plots classified by geologic ages

To find out the time effect which influences the mudstone compactions on our data, we classified the existing mudstone compaction data using geologic time. Hence, the data can be divided into two groups. First group is old mudstones (Paleozoic and Mesozoic ages) which are high porosity reductions represented by Data No. 1 and 3. Second group is young mudstones (Cenozoic age) which are low porosity reductions represented by data No. 2,4,5,6, and 7 as shown in Figure 3.

Time effect influencing on mechanical compactions of mudstones are much clear by showing in Figure 4. The approximate depths of 550 m and 1500 m were specified, the graph shows that porosity declines with increasing time at constant depth (or overburden pressure). Consequently, we can conclude that burial depth or effective stress is certainly one of the main controlling factors of compaction of mudstones, but that it cannot be a single factor to explain the compaction curves.

Influence of time on mechanical compaction was due to complete dehydration of many clay lattices in old sediments under normal compaction, while partial dehydration has occurred on young sediments (Van Olphen, 1963). Secondary compression (porosity decrease not caused by effective stress) and erosion are possible reasons for high porosity reduction in the old mudstones, compared with young mudstones.

4. TEMPERATURE EFFECT

Even though temperature is a main factor in the chemical processes in deep part of mudstone compactions, but the evidences of Magara (1978) showed that it also influences the shallow part dominated by the mechanical compaction, if sedimentation and burial continued in the geological past, the under-compacted section would be influenced by the aquathermal effect.

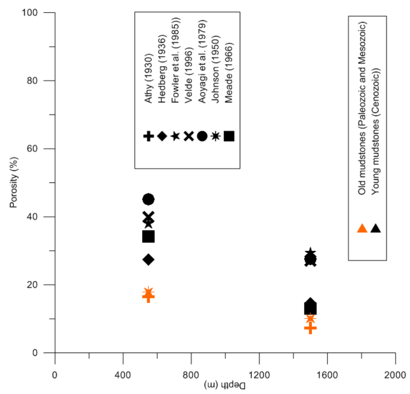

Figure 4 Time effect on porosity-burial depth plots at depth ~550 m and ~1500 m

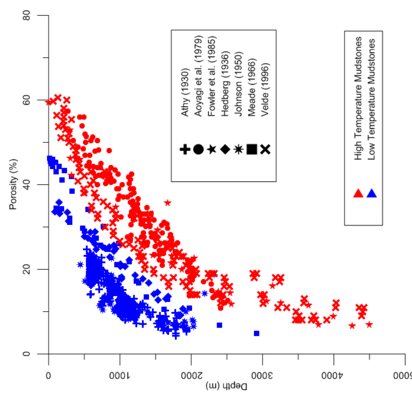

Figure 5 Porosity-depth plots classifying with geothermal gradient

Another point of view is the theory of consolidation proposed by Terzaghi (1943). He stated that loss of water (consolidation) of sediments corresponds to absorption of water (Fluid expansion) to increase of heat. In addition, fluid expansion is in accord with a second stage of de-watering processes which was studied by Burst (1969). He stated that when heat accumulations is sufficient to mobilize the interlayer water, one of the two remaining interlayers is discharged into bulk system. Hence, the fluid expansion of high geothermal environments lead to the de-watering processes will be slower than the areas which have normal geothermal environments.

In this study, we studied on temperature effect using geothermal gradient of each location as listed in Table 1, and then we divided the geothermal gradient into two groups as plotted in Figure 5. The first group is the geothermal gradient higher than 30 °c/km known as high temperature mudstones, and another group is the geothermal gradient lower than 30 °c/km which is low temperature mudstones. Geothermal gradient influences the fluid pressure in the formation. Low porosity reduction is due to the increase in geothermal gradient. Consequently, the low porosity reduction can be considered as fluid expansion of de-watering processes of rocks.

5. POROSITY CORRECTIONS

Keith and Rimstidt (1985) proposed the models to correct the porosity during compaction with considerations of time and temperature effects. According to there are no evidences about information of erosions in old mudstones, thus in this study we assumed that the scatters of porosity data during compaction are caused by time and temperature effects regarding clay mineral dehydration and thermal expansion. We applied their models to correct our porosity data considering different clay mineral dehydration is caused by different time and fluid expansion is caused by temperature increasing in order to establish a standard compaction curve for mudstones.

5.1 Time correction

According to Van Olphen (1963), many clay lattices in Paleozoic and Mesozoic ages appear to have been dehydrated completely under normal compaction, while partial dehydration has occurred on young sediments (Cenozoic age). Hence, it is possible that porosity scatters of mudstone compactions, especially in mechanical compaction, are caused by different ages (Time effect).

We applied the porosity correction for clay dehydration proposed by Keith and Rimstidt (1985). The expelled fluid related to smectite to illite transformations varying with time and depth, and the smectite in a sedimentary package were to transform, presumably its porosity would increase by 15% (Burst, 1969). We applied the correcting equation of Keith and Rimstidt (1985) to convert porosities in old mudstones to young mudstones.

Time step (Δt) of smectite to illite transformations moves through a depth interval (Δz) with velocity (v_r) as

$$\Delta z = v_r \Delta t \tag{5}$$

Hence, in this study time step (Δt) between Cenozoic to Paleozoic age and Cenozoic to Mesozoic age are 485 Ma and 185 Ma, respectively. We used the velocity of smectite to illite transformations (v_r) moves through a depth interval (Δz) following Keith and Rimstidt (1985) as $1\text{x}10^{-5}$ m/year. Consequently, we found that the smectite to illite transformations during Cenozoic to Paleozoic age and Cenozoic to Mesozoic age occurred in the depth interval (Δz) of 4850 m and 1850 m, respectively.

Using the above depth correction, the corrected porosity is given by

$$\phi_a = \phi + \left(\frac{d\phi}{dz}\right)_{sm-ill} \cdot \Delta z \tag{6}$$

where ϕ_a is the corrected porosity, $\left(\frac{d\phi}{dz}\right)_{sm-ill}$ is porosity changing with changing depth caused by the smectite to illite transformation. Keith and Rimstidt (1985) evaluated $\left(\frac{d\phi}{dz}\right)_{sm-ill}$ in his work based on porosity increasing by 15% of Burst (1969), which is equal to $2.1\text{x}10^{-3}$ m^{-1}.

Eq. (6) was applied for converting the porosities of old mudstones. The high porosity reductions of the old mudstones caused by complete dehydration of smectite to illite transformations comparing with partial dehydration of young mudstones were corrected by the smectite-illite dehydrations varying with depth to the porosity data in old mudstones (Paleozoic and Mesozoic ages) of data No. 1 and 3. The results show that the corrected porosities were higher than the original data as shown in Figure 6.

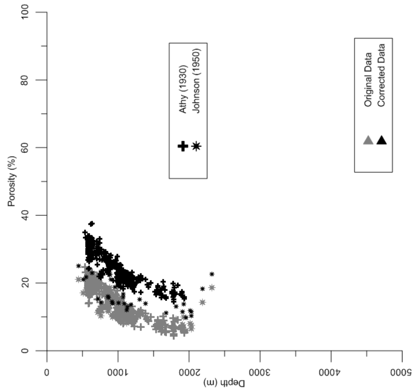

Figure 6 Time corrections of old mudstone compactions

5.2 Temperature correction

Magara (1978) found that amount of water expelled by compaction decreases with burial depth, but the subsurface temperature tends to expand volume of water (fluid expansion). In addition, the fluid expansion is in accord with increases of expelled water in a second stage of de-watering processes, which was studied by Burst (1969). Hence, the fluid expansion of high geothermal environments lead to the de-watering processes will be slower than the areas having normal geothermal environments.

We applied an equation for thermal correction proposed by Keith and Rimstidt (1985). They showed that the specific fluid volume change with depth, which is expressed as

$$V_{sp} = 2.6x10^{-8}z + 9.5x10^{-4} \tag{7}$$

where V_{sp} is the specific volume of fluid and z is the burial depth. In addition, the change of porosity with depth changing caused by thermal expansion $\left(\left(\frac{d\phi}{dz}\right)_{therm}\right)$ is expressed by specific fluid volume change with depth as:

$$\left(\frac{d\phi}{dz}\right)_{therm} = \left(\frac{\phi}{V_{sp}}\right) \cdot \frac{dV_{sp}}{dz} \tag{8}$$

where $\frac{dV_{sp}}{dz}$ is the change of specific fluid volume with depth changing.

Finally, according to a depth interval (ΔZ), thus the adjusted porosity is given by

$$\phi_a = \phi - \left(\frac{d\phi}{dz}\right)_{therm} \cdot \Delta Z \tag{9}$$

We corrected the porosities as we converted porosities of high temperature environments to normal temperature environments using Eq. (9). Because of the depth interval (ΔZ) of our high temperature mudstone data is around 5000 m, thus we believed that during 5000 m the specific fluid volume is changed by high temperature environments following Eq. (7) and (8). The porosity data which were corrected for temperature effect include data No. 4, 5 and 7. We reconstructed the porosity-burial depth plots as shown in Figure 7. The results show that the corrected porosities were lower than the original porosities. However, this correction might have some errors because the parameters referred by Keith and Rimstidt (1985), 40 °c/km as geothermal gradient, while in this study we used these parameters representing several geothermal gradients higher than 40 °c/km.

6. DISCUSSIONS AND CONCLUSIONS

Time and temperature factors influence variations of mudstone compaction curves, especially on mechanical compaction (shallower 2000 m). In this study the data can be divided into three groups based on time and temperature factors (Figure 8). The first group is the data of young (Cenozoic age) and high temperature mudstones. The second group is the young and low temperature mudstones, while the third group is the old (Paleozoic and Mesozoic ages) and low temperature mudstones.

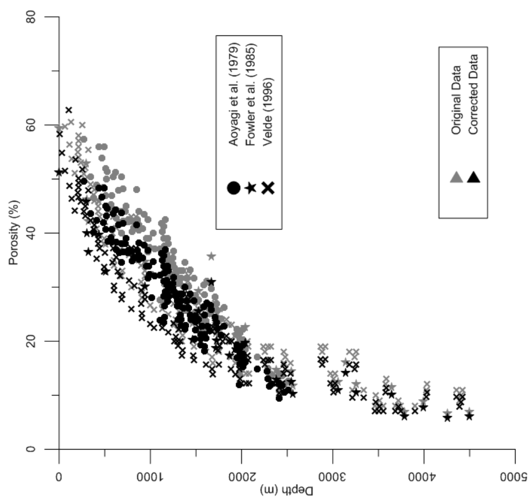

Figure 7 Temperature corrections of high temperature mudstone compactions

High porosity reductions of old mudstones caused by time effect are possible to relate to the different clay mineral dehydrations. Similarly, low porosity reductions of high temperature mudstones caused by temperature effect are possible to relate to fluid expansion. Consequently, we corrected and reconstructed the porosity-burial depth plots using the equations proposed by Keith and Rimstidt (1985), and the reconstructed plots show in Figure 9.

The graphs seem to improve matching with one another than compared with original plots and a trend curve represents the corrected curves toward a standard curve of mudstone compactions, especially during mechanical compaction (~500-2000 m), that we proposed in this work. The standard curve fits with exponential equation. For example, this curve is represented by $\phi = 45e^{-0.45z}$ where ϕ is the porosity and z is the burial depth (km). These corrections might have some errors because we assumed and used some parameters referred by Keith and Rimstidt (1985). The parameters were not acquired to represent each basin. However, we believe that this study will be a guideline toward establishment of a standard compaction curve for mudstones.

The standard curve of compaction for mudstones will be very useful to apply for prediction and detection of overpressures and basin modeling works. The overpressure zones can be roughly evaluated before an exploration, if time and temperature of basins are known based on this guideline. Furthermore, in basin modeling works, reconstruction of basin geometries normally use default compaction curves and default thermal properties, the parameters which influence on compaction curves, i.e. time and temperature, are normally not considered in basin analysis. Consequently, the standard curve of compaction will be useful to improve accuracy in basin modeling works.

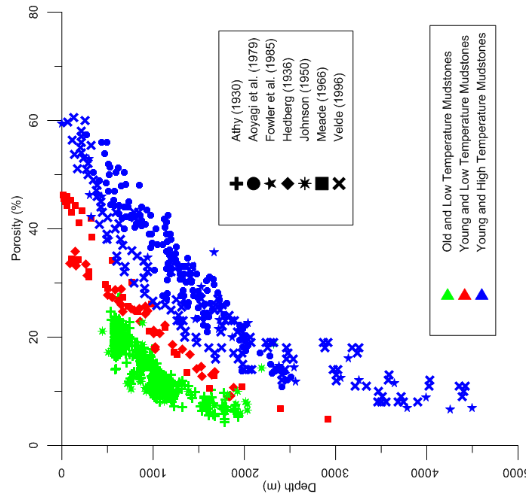

Figure 8 Divided groups of mudstone compactions based on time and temperature factors

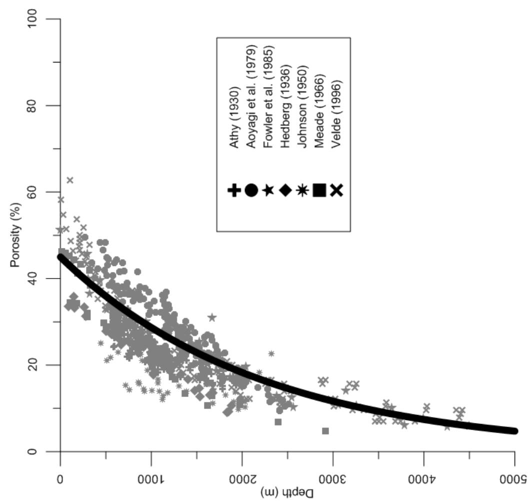

Figure 9 Porosity-depth plots after time and temperature corrections

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