BULLETIN OF THE EARTHQUAKE
RESEARCH INSTITUTE
Vol. 43 (1965), pp. 565-576

36. *An Estimation of Tectonic Stress from Compaction of Sedimentary Rock Strata.*

By Shozaburo NAGUMO,

Earthquake Research Institute.

(Read May 26, 1965.—Received June 30, 1965.)

1. Introduction

In the previous paper[1], compaction equation is derived for sedimentary rock by the theory of porous media. There, the change of porosity is expressed by an exponential function of external stress. The values of compaction coefficient are obtained from data of deep oil well by assuming that the external stress is due to the overburden stress of rock strata. However, it has been already noticed by several petroleum geologists[2] that porosity-depth relations are different to different places. The differences will be caused not only by rock facies, sedimentary environment[3] but also by tectonics of rock strata. Therefore, it will be natural to suppose that rock strata had been affected by a certain additional stress, besides its overburden stress, during the process of structural movement. Further, it will be supposed that the compaction of sedimentary rock also had taken place during this process. Thus, the purpose of this paper is to make a trial of estimating the amount of tectonic stress from the difference of porosity-depth relation.

2. Deduction of tectonic stress

As is shown in the previous paper, the compaction equation of porous media is given by

$$\begin{aligned} n &= n_0 e^{-\kappa(1-\beta)p} \\ \kappa &= (c_p - c_b)\ , \end{aligned} \tag{1}$$

where n porosity, n_0 porosity at $p=0$, p compressive stress, κ compaction

---

[1] S. NAGUMO, *Bull. Earthq. Res. Inst.*, **43** (1965), 339.

[2] H. ISHIWADA, *Private Communication.*

[3] KRUMBEIN and SLOSS, *Stratigraphy and Sedimentation* (Freeman, 1953), chap. 7, 11, and 12.

coefficient, β coefficient of stress partition into liquid, c_p pore compressibility, c_b framework compressibility.

The gradient of log $n \sim z$ curve is given by

$$\frac{d(\log n)}{dz} = -\kappa(1-\beta)\frac{dp}{dz} . \qquad (2)$$

This shows that the factors which affect the gradient of log $n \sim z$ curve are κ, β and dp/dz. Therefore, if κ and β take the same values at different places, the difference of the gradient is due to the difference of dp/dz. Therefore, when it is proved by other observed data that κ and β are equal, the difference of dp/dz will be obtained by the difference of the gradient of log $n \sim z$. Leaving the examination of such conditions to a later section, let us proceed to formulate the estimation of the tectonic stress from the factor dp/dz.

Since we have equated the sedimentary rock strata by the porous media, compressive stress p corresponds to the stress which is operating in the rock strata.

The stress that the rock strata of the earth's crust are bearing is thought to be devided into standard stress and supplementary stress as is clearly described by Anderson[4] and Hafner[5]. According to them, standard stress is a stress which is caused by the weight of horizontally layered uniform strata, and is the same in all direction, without shear stress. Let us call the other stress tectonic stress, instead of the use of supplementary stress, denoted by p_{tect}. The tectonic stress will be considered to be caused by such structural movements as uplift, subsidance, folding of rock strata, etc. Thus, by definition,

$$p = p_{\text{stand}} + p_{\text{tect}} . \qquad (3)$$

Because p_{stand} is due to its own-weight of horizontal rock strata, it is given by

$$p_{\text{stand}} = \rho_m g z , \qquad (4)$$

where ρ_m is a mean density to the depth z. The tectonic stress, which might be a cause of abnormal porosity change with depth, is thought to be caused by an uplifting movement of the earth's crust. Further, it will be supposed that the stress increases with depth. Let us assume,

---

4) E. M. ANDERSON, *The dynamics of faulting* (Oliver and Boyd, 1942).

5) W. HAFNER, *Bull. Geol. Soc. Amer.*, **62** (1951), 373.

therefore, that tectonic stress is proportional to depth,

$$p_{\text{tect}} = \alpha \rho_m g z \, , \tag{5}$$

where α is a proportional constant.

Then, by substituting (3), (4), and (5) into (1), we have

$$n = n_0 e^{-\kappa(1-\beta)\rho_m g(1+\alpha)z} \, . \tag{6}$$

When we compute compaction coefficient from well data, we do not know yet the amount of tectonic stress. Usually we apply equation (1) to the field data, and obtain compaction coefficient by assuming that the compressive stress is only standard, $p = \rho_m g z$. Let us denote compaction coefficient thus determined by κ', meaning apparent compaction coefficient,

$$n = n_0 e^{-\kappa'(1-\beta)\rho_m g z} \, . \tag{7}$$

Further, let us define standard compaction coefficient by κ_0 for the compaction of rock strata under the standard state in the sense of Anderson and Hafner. According to A. Matsuzawa[6], there is enough reason to suppose that the location of Kambara GS-1 is the place where the sedimentation has developed with monotonous subsidance near the center of the Kambara sedimentary basin. Therefore we may take the value of κ, obtained from the well Kambara GS-1 in the previous paper, as the standard compaction coefficient κ_0. Thus, the compaction formula (6) is expressed by

$$n = n_0 e^{-\kappa_0(1-\beta)\rho_m g(1+\alpha)z} \, . \tag{8}$$

From equations (7) and (8), the value of α is obtained by the relation

$$\alpha = \frac{\kappa'}{\kappa_0} - 1 \, . \tag{9}$$

When the value of α is obtained, the tectonic stress is determined by the equation (5). α is a factor which expresses the amount of tectonic stress by the unit of standard stress due to horizontally layered rock strata.

Therefore, tectonic stress is determined first by computing apparent compaction coefficient κ' from the well data, then by computing the value of α by the formula (9).

---

[6] A. MATSUZAWA, *Butsuri-Tankô*, **14** (1961), 194, and **15** (1962), 1.

3. Estimation of tectonic stress

Now let us make a trial of estimating the tectonic stress from the data of a deep oil well. In Fig. 1 is illustrated a semi-logarithmic plot

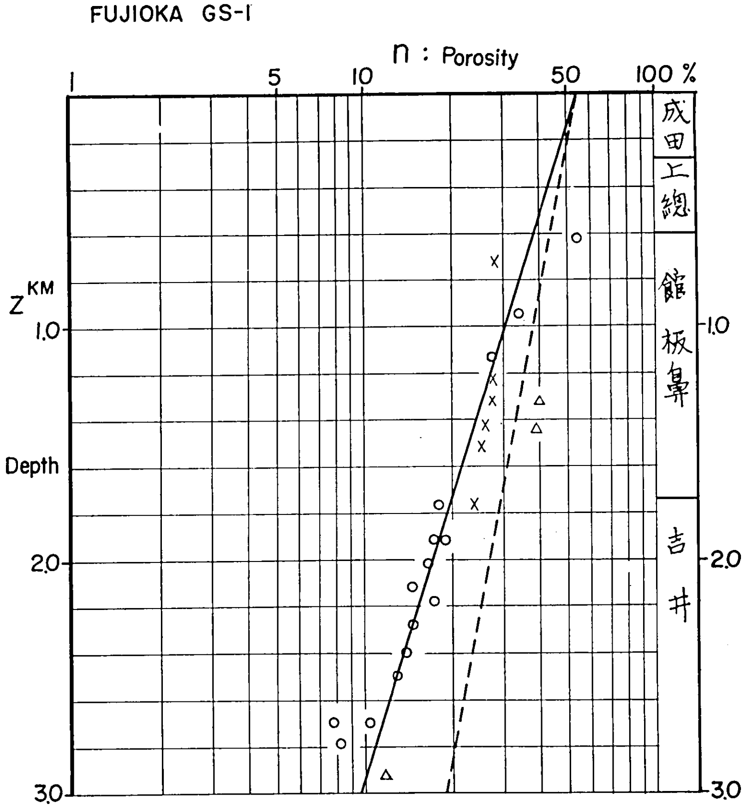

Fig. 1. Porosity-depth relation in the well Fujioka GS-1, in Gumma Prefecture, ○ : Mudstone, × : Sandstone, △ : Tuffacious stone, -- : Curve for the well Kambara GS-1.

of porosity versus depth measured for the drilled core sample of the well Fujioka GS-1 of Geological Survey of Japan. The well is located near the margin of the Kanto sedimentary basin. The heavy line in the figure represents the average increase of log n with depth for mudstone. Data for tuffacious stone and sandstone are excluded for its fitting, because they seem to belong to a different class of porous media. The dotted line in the same figure shows the average curve in the other well Kambara GS-1, of which location is near the centre of the Niigata sedimentary basin. The gradients of these curves are different. The values of the apparent compaction coefficient and surface porosity for the wells Fujioka GS-1 and the Kambara GS-1 are

$$\kappa'(1-\beta)=0.26\times10^{-8}\ (\text{C.G.S.}),\ n_0=0.55 \qquad \text{(Fujioka GS-1)}$$
$$\kappa'(1-\beta)=0.17\times10^{-8}\ (\text{C.G.S.}),\ n_0=0.57 \qquad \text{(Kambara GS-1)}$$

respectively. As stated in the previous paper, the value of compaction coefficient for Kambara GS-1 which is regarded as the standard compaction coefficient, κ_0, is

$$\kappa_0(1-\beta)=0.17\times10^{-8}\ (\text{C.G.S.})\ .$$

Therefore coefficient of tectonic stress α is obtained from the equation (9),

$$\alpha=\frac{\kappa'}{\kappa}-1=0.55\ .$$

Then the tectonic stress is from equation (5),

$$p_{\text{tect}}=0.55\ \rho_m gz=0.55\ p_{\text{stand}}\ .$$

Namely, the amount of tectonic stress which acted in the formation at the location of Fujioka GS-1 is estimated at about a half of the standard stress of the rock strata. The amount of its corresponding uplift is not so great since the value of the surface porosity is $n_0=0.55$, which is nearly the same as that of Kambara GS-1.

4. Discussion

As pointed out in 2, the gradient of log $n\sim z$ curve is affected by such factors as difference of compaction coefficients and the difference of liquid pressure within the rock strata even at the same horizon. In addition to these factors, the differences of depth from the maximum buried depth to the present depth, and the present dip of the rock strata are thought to affect the porosity-depth relation. Let us examine the effects of these factors.

Effect of uplift

A. Matsuzawa[7] has presented a view that the shale density is

---

[7] A. MATSUZAWA, *loc. cit.*, 6).

determined by the depth of the maximum burial. The large value of the shale density at the present shallower horizon indicates that the formation has once been buried to a deeper horizon, whose depth is represented by the value of porosity, and has subsequently been uplifted to the present level at a later stage of structural movement. There, the effect of compaction at the stage of uplifting movement is thought to be neglected. If this is the case the porosity depth relation becomes, from equations (1) and (6),

$$n = n_{H0} e^{-\kappa_0 (1-\beta) \rho_m g z} \tag{10}$$

$$n_{H0} = n_0 e^{-\kappa_0 (1-\beta) \rho_m g H_0} \tag{11}$$

where H_0 is the amount of uplift, z the present depth. As is evident in equation (10), the gradient of the log $n \sim z$ curve does not change from that of standard compaction. The only difference to the curve of the standard compaction is the value of the porosity n_{H_0} at the surface. The observed log $n \sim z$ curve should be the one which is shifted upward by the parallel transformation. These relations are schematically illustrated in Fig. 2. Therefore, it will be said that the difference in the gradient of log $n \sim z$ curve indicates that there is some other factor operating during the process of uplifting.

Effect of liquid pressure

As stated in the previous paper, the stress which causes the compaction of the sedimentary rock is the framework stress only, which operates on the framework of the porous media. Because the total stress is partitioned into framework stress and liquid stress, the amount of the framework stress is $(1-\beta)d\sigma$, β being a coefficient of stress partition into liquid, $d\sigma$ being the increment of total stress. Therefore, when the squeezing of liquid is difficult, the compaction exponent $\kappa(1-\beta)$ becomes small as the liquid pressure increases. Thus, the media is less compacted even under the same overburden pressure when the squeezing of liquid meets with difficulty. Therefore, the difference of apparent compaction coefficients may arise from the difference of the liquid pressure. We have assumed in the above argument that there is not much difference in the liquid pressure during the process of compaction between the well Kambara GS-1 and Fujioka GS-1. Since these two wells are located far apart in different sedimentary basins, and further, since the corresponding time rock unit does not always lie at the same depth, it is necessary to examine the validity of the above-mentioned assumption

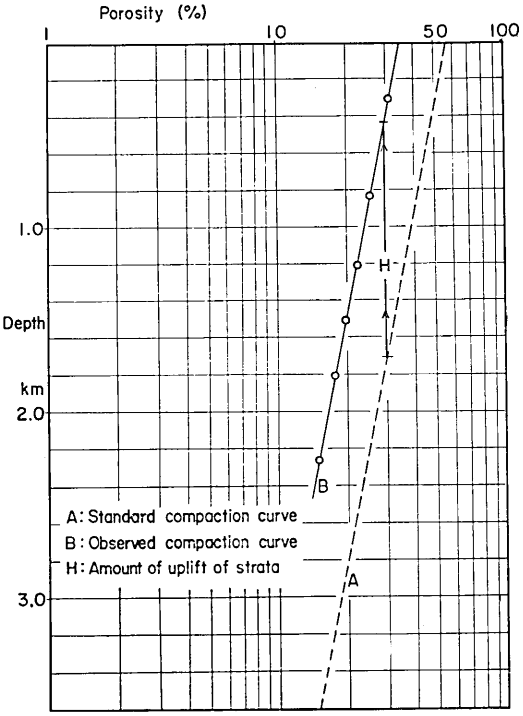

Fig. 2. Schematic representation of the effect of uplift of rock strata. When a rock strata is uplifted by the amount H during structural movement, the compaction curve is shifted from the standard one, A, upwards to the curve B. The gradient of $n\sim z$ curve does not change if there is no additional compaction during structural movement.

for the liquid pressure.

There may be many indirect methods of examination. For example, difference of rock facies, sand to shale ratio, the kind and amount of nonconformities might be used for such examination. However, the direct method will be the comparison of the liquid pressure itself at the present time. Unfortunately, the liquid pressure within the formation is not always measured at every level during the drilling of the oil well. However, as indicated by Hubbert and Rubey[8], the mud density which is used during the drilling is a very good means for the less accurate estimation of liquid pressure within the formation. The density of

---

[8] M. K. Hubbert and W. W. Rubey, *Bull. Geol. Soc. Amer.*, **70** (1959), 167.

drilling mud is controlled every day according to the condition of the formation. The mud density is usually kept only slightly greater than that which is necessary to retain the formation fluid. The log of drilling mud density is illustrated in Fig. 3. ⊙ mark is for Kambara GS-1, and × mark is for Fujioka GS-1. As is seen in Figure 3, we do not find any significant difference of mud density-depth relation between the two wells. Therefore, it will be safely concluded that there is no significant difference in liquid pressure between these two wells. Further, it will be concluded that the difference in the apparent compaction coefficient, which is obtained in 2, is not due to the difference of liquid pressure. The effect of liquid pressure may be a cause of differential compaction of sedimentary layer.

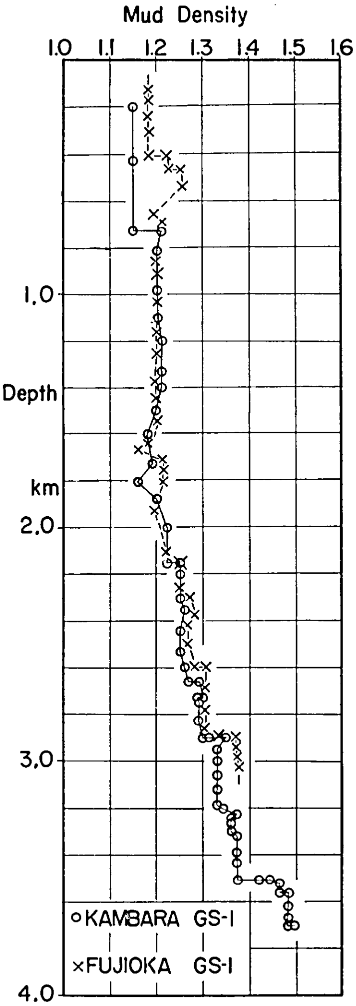

Fig. 3. Drilling Mud density versus depth curve.

Effect of compaction coefficient

As is clearly pointed out and proved by A. Matsuzawa[9], it is mudstone that is suitable for porosity-depth or porosity-stress analysis. This is because the porosity of other sedimentary rocks is affected by many other factors than pressure. For instance, in the case of sandstone, the effect of pressure is not so efficient for reducing the pore space, because of contacting resistance among small grains. The decrease of its porosity is mainly controlled by the properties of cementing materials and matrix in the pore. In the case of tuffacious stone, the grain densities are not regarded as constant because of closed pore and properties of solvent. Therefore, in the foregoing treatment of porosity-depth analysis, the data of mudstone is mainly used for the determination of log $n \sim z$ curve.

---

[9] A. MATSUZAWA, *loc. cit.*, 6).

As regards the difference of compaction coefficient of mudstone, it is assumed that there is no significant difference between the two wells. As stated in the previous paper[10], it is rather striking that the field data has proved the assumption that the compaction coefficient κ is kept constant through the process of compaction of mudstone. This fact will support the said assumption.

Effect of number of data

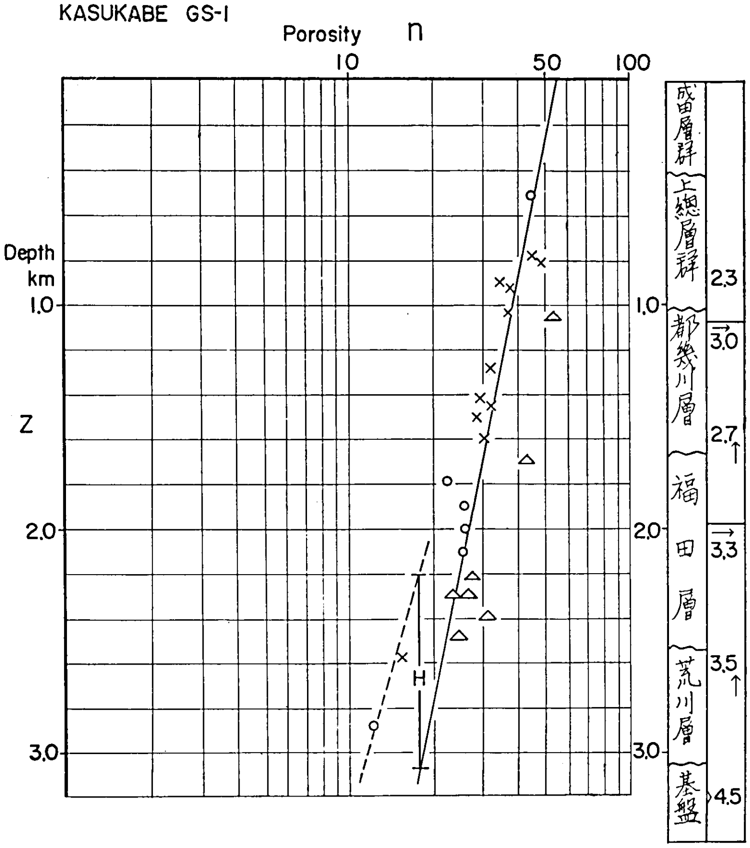

Fig. 4. An example of the effect of the amount of data. The lowest two observed data markedly deviate from the compaction curve (heavy line). The change of the gradient of $\log n \sim z$ curve for the lower horizon is not determined because of the insufficient amount of data. H represents the maximum amount of possible uplift under the assumption of upward parallel transformation of the curve.

---

[10] S. NAGUMO, *loc. cit.*, 1).

In addition to the above basic properties of log $n \sim z$ curve, sufficient observed data of porosity is required for identifying the change of the gradient of log $n \sim z$ curve. For instance, in the case of the well Kasukabe GS-1, which is illustrated in Fig. 4, the lowest two observed values at the depths of 2,900 m and 2,600 m are far apart from the average log $n \sim z$ line, which is fit for the shallower formations. These two values must be an indication of the uplift of the lower horizon under the nonconformities. However, because of the insufficient amount of observed data, it is not determined whether or not the uplifting movement is accompanied with additional compression of the strata. If the maximum amount of possible uplift is estimated by assuming the parallel upwards shifting of the log $n \sim z$ curve, it will be about 1.0 km.

Effect of inclination of strata

Since the depth is taken vertically downwards from the surface, the depth does not correspond to the true thickness of rock strata when the strata is inclined. If the dip of the inclined strata is θ, the true thickness which corresponds to the depth z is $z \cos \theta$, as is seen in Fig. 5. Therefore, if it is a case where the inclination of the strata is made after the accomplishment of compaction, the compressive pressure which determined the compaction is proportional $z \cos \theta$ instead of apparent depth z. Therefore, the effect of inclination of strata will appear so as to reduce the value of apparent compaction coefficient. The sense of this effect is opposite to the effect of liquid pressure.

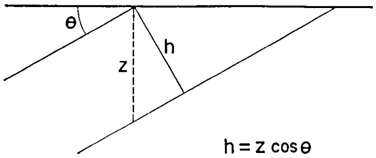

Fig. 5. Relation of thickness h and depth z

The above method is the only trial for the quantitative estimation of the tectonic stress from the compaction of sedimentary rock. Because of the limited amount of data at present available, the method can hardly be said to be proved, even though an example gives us a very interesting result. Therefore, it is hoped to continue to examine this method for many other data. When the quantity of tectonic stress within the formation is determined, the amount of tectonic force acting at the boundary surface will be estimated in accordance with the theory of elasticity. Further, such values of tectonic stress will contribute to the mechanisms of earthquake generation. These problems are left for further treatment at a future date.

5. Summary and conclusions

In this paper is presented a method of estimating the amount of tectonic stress from the compaction curve of sedimentary rock strata. Main results obtained are as follows:

(1) According to the theory of porous media, the gradient of log $n \sim z$ curve is affected by such factors as compaction coefficient of media, liquid pressure within the formation, and the amount of compressive stress.

(2) Tectonic stress, defined by the total stress minus standard stress, is obtained by the difference of the gradient of log $n \sim z$ curve if there are no significant differences in liquid pressure and compaction coefficient.

(3) The effect of liquid pressure within the formation is equivalent to the effect of tectonic stress. Therefore the difference of liquid pressure within the formation should be carefully examined when the comparison of the log $n \sim z$ curve is made.

(4) The effect of simple uplifting of rock strata results in the parallel upward shifting of log $n \sim z$ curve along the depth axis.

(5) An estimation of tectonic stress is made for the well Fujioka GS-1, whose location is near the margin of the Kanto sedimentary basin. The amount of tectonic stress is about 0.5 times the standard stress. This value seems to be a little smaller than that which is expected from the laboratory experiment of the failure of rock specimens.

Acknowledgements

The writer wishes to express his sincere thanks to Dr. H. Ishiwada of Geological Survey of Japan for his kind discussion on the present problem.

36. 堆積岩層の圧密による造構造応力の推定

地震研究所　南雲昭三郎

前回の論文において，堆積岩特に泥岩，頁岩の圧密現象を多孔性媒質理論によつて解析すると，$\log n$（n: 孔隙率）対深度曲線が直線になること，その勾配から圧密係数が求められるということを報じた．そこでは堆積岩層に作用する応力は水平な岩石層の自重によるいわゆる標準応力であるとした．しかし，すでに石油地質学者によつて気づかれているように$\log n-z$直線の勾配は場所によつて異なつている．この論文は，その勾配の差から堆積岩の圧密をもたらした造構造応力が推定できるものかどうか調べてみたものである．

多孔性媒質理論によると，$\log n-z$直線の勾配は，岩石の圧密係数，地層内の流体圧，地層に作用している圧密応力の大きさなどに依存することになる．それ故，岩石の圧密係数が等しく，また地層内の流体圧が等しい場合には圧密応力の大きさが求められることになる．地層に作用する圧密応力pは，いわゆる標準応力と呼ばれる水平な地層の岩石の自重による圧密応力Pstと，それ以外の応力—褶曲・断層などの地層の変形を生ぜしめるものとして造構造応力$Ptect$と呼ぶことにする—との和で表わされると考えられ，この造構造応力は，**Hafner**や**Sanford**の論文により，第1近似として深度と共に直線的に増加するものと考えられる．すると，$\log n-z$直線の勾配の差はこの造構造応力の差を表わすものということになり，実測資料から定量的にその大きさが求められることになる．計算式は第(7)式で表わされる．手続としては，まず実測資料に対して$\log n-z$直線を定め，その見掛けの圧密係数を定め，(9)式によつて造構造応力係数が求められ，(5)式によつて造構造応力の大きさが求められる．

例として信濃川中流沈降帯の蒲原GS-1号井における圧密曲線を標準とし，関東盆地の利根川中流沈降帯の藤岡GS-1号井の圧密曲線上に表われた造構造応力を推定してみたところ，造構造応力として，岩石自重による標準応力の約0.5倍という値を得た．この値は，実験室内における岩石の変形・破壊実験から予想される値と比べてみると少し小さいようである．

さらに$\log n-z$直線の関係するその他の因子の検討を行なつた．その結果，岩石の種類を泥岩・頁岩に限れば圧密係数はほぼ一定とみなされること，地層内の水圧の変化は造構造応力と同等の影響を及ぼすので，別途吟味されねばならぬこと，それには掘作時の泥水比重のログが役立つこと，いわゆる地層内の**Differential Compaction**はこの水圧に関係するであろうこと，過去の埋没深度と現在深度の差は$\log n-z$直線の深度軸に沿う平行移動で表わされること，地層の傾斜はみかけ圧密係数を小さくする方向へ影響することなどが分つた．

堆積岩の内部に作用する造構造応力の定量的推定は，弾性理論等の数理解析と相俟つて，地殻の境界面に作用する造構造応力の推定に関連し，さらに地震の発生機構にも関連してゆくものと考えられるが，それらの問題の究明は将来の問題として残されている．