Three decades of geopressures : insights and enigmas

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Three Decades of Geopressures – Insights and Enigmas

by P. E. Gretener [1] and Feng, Zeng-mo [2]

with 8 figs and 4 tabs

Preliminary Preprint (subject to revisions)

Abstract

In this paper we review and analyze observations made on geopressures. We find that a number of viable pressure generating processes have been suggested. The relative merits of these mechanisms are hard to evaluate since most of them are beyond rigid quantitative assessment due to many intangible factors. The occurrence of maximum geopressures at depths exceeding 7,000 m (23,000 ft) demonstrates, however, that these pressures can be generated at great depth. Yet, one must not lose sight of the fact that normal pressures can also be found at any depth level. Geopressure generation efficiency depends on both the generation power and the effectiveness of the fluid flow restriction. Without effective fluid flow restriction even the most vigorous generating mechanisms can only lead to geopressure events of very limited duration. Such events may well leave a permanent record in the form of synsedimentary deformations but they will not provide pressure anomalies directly observable throughout geological time. Fluid flow restriction takes precedence over pressure generation in controlling the longevity of the anomalies. Geopressures can be generated at any depth level but it is the distribution of the aquifers, aquitards, and aquicludes within the sedimentary cover that determines the position of the geopressured zones.

Zusammenfassung

In diesem Artikel versuchen wir den gegenwärtigen Stand der Forschung über abnormale Porenwasserdrucke darzustellen. Wir konzentrieren uns vor allem auf die Sedimentserie und die möglichen Auswirkungen auf die Erdölsuche und die Erdölgewinnung. Die Erdölindustrie hat klar gezeigt, dass sowohl abnormal hohe wie normale Porenwasserdrucke bis zu den grössten erbohrten Tiefen (9000 + m) vorkommen. Man darf aber nicht vergessen, dass die Ideen und Konzepte des erhöhten Porenwasserdruckes allgemeine Gültigkeit haben in der Geologie, wie dies z. B. die russische Tiefbohrung (12 km) auf der Kola Halbinsel zeigt.

Viele Kernfragen des erhöhten Porenwasserdruckes sind auch heute noch umstritten und harren auf eine endgültige Klärung. Es scheint jedoch, dass die Verteilung dieser abnormalen Drucke in erster Linie eine Frage der Permeabilitätsverteilung im Untergrund ist. Die abnormalen Drucke erscheinen in der Form von Linsen, die sowohl vertikal wie horizontal beschränkt sind, sich aber oft über weite Distanzen hinziehen. Sie sind häufigst, wenn auch nicht ausschliesslich, in jungen Sedimenten zu finden. In Evaporitprovinzen, mit ausgedehnten Salzlagern – dem besten natürlichen Dichtungsmaterial –, können sich abnormale Porendrucke über lange Zeiten erhalten, und zudem extreme Werte erreichen.

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1. Preface

Thirty-three years have gone by since GEORGE DICKINSON first opened the discussion on the phenomenon that has most commonly become known as «geopressures». DICKINSON, usually cited as publishing in 1953, presented his observations initially in 1951 to the 3rd World Petroleum Congress in The Hague, the first large international gathering of geologists after the 2nd World War. Since that time we have witnessed an explosion of interest in this subject, and yet it remains discomforting to see a great deal of disagreement on the validity and applicability of basic principles and concepts.

In 1980 PLUMLEY introduced his paper with the following sentence: «The causes of abnormally high subsurface fluid pressures continue to be elusive despite literature evidence of a widespread attack upon this problem by the petroleum research community». Now, four years later, not much has changed. Opinions on fundamental aspects of geopressuring remain sharply divided. For an example, one may follow what we prefer to call the «aquathermal pressuring controversy» (CHAPMAN, 1980, 1982; BARKER and HORSFIELD, 1982; DAINES, 1982; SHARP 1983).

Part of the problem may be caused by the fact that the terminology has never been clarified and no uniform usage has emerged. It is our intent to make a contribution towards the understanding of processes involved and we do not wish to get embroiled in a debate on semantics, terminology, and classification. In order not to add to the existing confusion we have decided to give a «List of Symbols» and a «Glossary». We do not expect our definitions to meet with universal approval, but we do believe that they will eliminate possible misinterpretations and save us from needless controversy over what we consider to be mute points.

Particularly troublesome is the usage of the terms «seal» and «isolation» and additional comments may be in order. For us there is no such thing as a «perfect seal». A seal is perfect by definition, and as such, a rarity in nature. Isolation, the way we see it, can be both sudden or gradual, and also perfect (complete) or partial. The term, therefore, does require a qualifier. In general isolation will be both gradual and partial. In model studies isolation is often assumed to be both instantaneous and perfect. In nature this is rarely the case and it must be taken as a crude approximation of the actual situation.

In this paper we direct our attention to abnormal pressures which are higher than normal values. We do recognize that subnormal pressures (also abnormal) do exist but they do not form the primary target of this paper.

In order not to mislead the reader with undue precision, all our depths and depth-conversions are given in round numbers.

2. Brief Historical Review

When in 1951 GEORGE DICKINSON delivered his paper «Geological Aspects of Abnormal Reservoir Pressures in the Gulf Coast Region of Louisiana, U.S.A.» to the 3rd World Petroleum Congress, I, the senior author, was there. I dutifully collected his preprint, which contained the critical pressure-depth chart as a one square foot fold-out. Needless to say I was blissfully ignorant of the wide-ranging ramifications this paper was to have on the geological research of the coming decades. Pressure, stress, and all that goes with it, were nebulous concepts in those days and certainly did not figure in the standard geological curriculum.

DICKINSONS's analysis can be described as follows:

The total overburden stress (S_Z) is given by:

$$S_z = \bar{\rho}_b \cdot g \cdot z \qquad (1)$$

where: $\bar{\rho}_b$ is the average bulk density of the water bearing sediments
g is the gravitational acceleration
z is the depth

The pore fluid pressure in an open system (p_n) is given by:

$$p_n = \bar{\rho}_f \cdot g \cdot z \quad (2)$$

where: $\bar{\rho}_f$ is the average brine density
g is the gravitational acceleration
z is the depth

The gradient of the total overburden stress and the pore pressure gradient are given by:

$$dS_z/dz = \bar{\rho}_b \cdot g \quad (3)$$

$$dp_n/dz = \bar{\rho}_f \cdot g \quad (4)$$

In his paper DICKINSON (1953) chose $\bar{\rho}_b = 2.31 \times 10^3$ kg/m³ which yields the very convenient:

$$dS_z/dz = 1.0 \text{ psi/ft} = 22.5 \text{ kPa/m} \quad (5)$$

For the average brine density he selected $\bar{\rho}_f = 1.07 \times 10^3$kg/m³ which leads to:

$$dp_n/dz = 0.465 \text{ psi/ft} = 10.5 \text{ kPa/m} \quad (6)$$

Over the past 30 years both these values, derived for the U.S. Gulf Coast, have become generally accepted. One must be aware, however, that both are subject to variations of a few percent, as already pointed out by DICKINSON (1953). For very young and shallow sediments the average bulk density may well be somewhat lower than the one shown and for older sediments in interior basins that density may be up to 10% higher than the one chosen.

The two lines given by equations (5) and (6) are shown on DICKINSON's plot (1953, Fig. 2) and they bracket all the pressure values recorded. Many of the pressures, however, do not fall on the 0.465 psi/ft line, i. e. they are not normal. One should realize that the term «normal pressure» refers to a standard of reference, that considers the total sedimentary sequence as an unconfined acquifer, rather than a normality of occurrence. Some of the pressures plotted by DICKINSON give pressure-depth ratios that approach 0.9 psi/ft (20 kPa/m). Obviously the sedimentary sequence is not always an open system. However, one must not lose sight of the fact that the plot also shows normal pressures prevailing to the maximum recorded depth of 16,000 ft (4,900 m). DICKINSON (1953) thus clearly demonstrated that for many cases we have:

$$p_a > p_n \quad (7)$$

where: p_a abnormal fluid pressure (geopressure)
p_n normal fluid pressure

In 1959 HUBBERT and RUBEY published their classic paper entitled «Role of Fluid Pressure in Overthrust Faulting». It was HUBBERT and RUBEY's intent to shed some light on the enigma of overthrust faulting. In doing so they may well have achieved some secondary goals which in the long run may turn out to be of far greater importance. In particular they have introduced the geological fraternity to the concept of effective stress as formulated by TERZAGHI (1936, see also SKEMPTON, 1960) which states:

$$S_z = \sigma_z + p$$
$$\text{or} \quad \sigma_z = S_z - p \qquad (8)$$

where: S_z is the total overburden stress as defined in equation (1)

p is the pore pressure as in equation (2)

σ_z is the effective overburden stress

The above equation (8) makes it apparent that under conditions of high pore pressure the rock becomes stress-relieved and in the limiting case where $p = S_z$ the rock is totally destressed, i. e. in a stress state of no burial ($\sigma_z = 0$).

HUBBERT and RUBEY (1959, p. 142) also defined the very useful parameter (λ):

$$\lambda = p/S_z \qquad (9)$$

This factor indicates the fraction of the total overburden stress that is carried by the fluid pressure. The parameter is dimensionless. Unfortunately when choosing the value for S_z as in equation (5), the pressure-depth ratio (PDR), using English units, becomes numerically equivalent to the parameter λ in psi/ft. It is this latter that is most often given in the literature. In view of the fact that S_z never deviates much from the DICKINSON value we can say: $\lambda \sim$ PDR. One must keep in mind that in the SI system the PDR will range from less than 10 kPa/m to more than 23 kPa/m and it will not at all be related to λ which must be found by application of equation (9).

To our knowledge this parameter has never been named. Since it will figure repeatedly in this paper it seems expedient to label it. In this paper we shall refer to it as the stress relief factor (SRF) since it indicates the fraction of the total overburden stress supported by the formation fluid, or simply pore pressure.

For normal hydrostatic conditions we have:

$$\lambda_n = 0.465 \qquad (10)$$

Considering that subsurface waters may range from fresh water to very heavy brines we may assign the following limits:

$$0.43 < \lambda_n < 0.48 \qquad (11)$$

For the case of geopressures we have:

$$0.5 < \lambda_a < 1.0 \qquad (12)$$

For the case of subnormal pressures we have:

$$0 < \lambda_a < 0.43 \qquad (13)$$

Some authors (e. g. TKHOSTOV, 1963; THOMEER and BOTTEMA, 1961) prefer to give the excess pressure as a ratio using the hydrostatic or normal pressure (p_n) as a standard. They give:

$$PR = p_a/p_n \quad (14)$$

where: PR is the pressure ratio (our terminology).

Another important contribution to the subject matter was made in 1965 by HOTTMAN and JOHNSON. These authors demonstrated how abnormally high fluid pressures can be recognized on sonic and resistivity logs of wells drilled in the U.S. Gulf Coast. In the realm of geopressures such logs will deviate from the normal depth trend for shales and thus give a warning that high pressures have been encountered. This is particularly important in cases where porous beds, that would allow the well to take a kick, are absent.

In the early 1960's the city of Denver was rocked by numerous small earthquakes causing minor damage. Needless to say, the population of this major city got quite upset over these occurrences. In a stroke of genius EVANS (1966) pointed his finger straight at Uncle Sam. While the American and international public is quite willing to hold Uncle Sam responsible for all the ills that befall us, it nonetheless seemed preposterous to accuse him of triggering earthquakes. Even the scientific community felt that the authority for such happenings was still reserved for the higher court, commonly believed to preside in the heavens. To anybody having studied the HUBBERT and RUBEY (1959) paper the case was perfectly clear. EVANS (1966) simply provided the most exciting, also involuntary, in situ experiment to their theory. The U.S. army was pumping waste fluids through the Denver Arsenal well into the basement rocks beneath the Denver basin. The virgin stress conditions were evidently such that the increased pore pressure was sufficient to activate a dormant fault, just as the «HUBBERT and RUBEY Theory» would have it. EVANS was later vindicated by the U.S.G.S experiments at Rangely (RALEIGH 1972). The possibility that earthquakes might be interfered with by man is a concept which to this day boggles the mind. But no doubt the possibility exists and in fact has already been exploited in the popular press by ALISTAIR MCLEAN in his «Goodbye California». The moral of this story for the concept under review: geopressures favour structural instability.

In 1967 POWERS proposed the smectite-illite transformation as a pore pressure generating mechanism. This case is still in court, more about it in section 4. BARKER (1972) suggested the mechanism that has become known under the name of «aquathermal pressuring». Again the effectiveness of this process is much debated (sec. 4). Most recently the geochemists have entered the scene and added the kerogen-hydrocarbon transformation to the list of pressure generating mechanisms (MOMPER, 1978; DU ROUCHET, 1981). PLUMLEY (1980), amongst others, has made it plain that compaction disequilibrium cannot be the only process leading to abnormally high fluid pressures and other causes must be considered (sec. 4.1). However, after 33 years there is no agreement as to what contributes what; what, if any, are the major processes of pore pressure generation, and the whole concept of geopressures is clearly far removed from any quantitative solution. We shall attempt to carry on this history of pore pressure with an effort to illuminate matters at least in a qualitative way.

There is still a tendency to consider this subject the exclusive domain of HC explorationists. Already in 1969 GRETENER attempted to show the universal applicability of these ideas to geology as such. HUBBERT and RUBEY (1959) and EVANS (1966) showed applications in structural geology. Other authors demonstrated its use in explaining synsedimentary deformations. The high mobility of largely solid magmas (mushes) finds a logical explanation and even such exotic phenomena as closed system Pingos fit into the concept.

3. Generalizations about Geopressures

In this section we make an attempt fo find any common features for the phenomenon of geopressures. DAHLSTROM (1970) stated: «Another source of confusion has been the failure to discriminate between the *fundamental* and the *incidental*». This is the «signal-to-noise» concept of the geophysicists transferred into the geological domain. The question which we are asking here is: «Are there any systematic factors associated with the occurrence of geopressures that can be recognized by certain trends (fundamentals) or are geopressures merely the consequence of the accidental interplay of many factors beyond the scope of a methodical study?»

The search for common elements in geopressure occurrences is complicated by the fact that reported pressures are based on different types of data. Some are derived from log-deviations (sec. 5.1) or deduced from mud weights. In either case it is appropriate to refer to *indicated pressures*. Others are the result of drill stem tests or reservoir observations, i. e. actually *measured pressures*. Unfortunately in many, if not most, cases it is unclear what type of data form the basis of the reported pressure values.

3. 1 Depth of Geopressures

DICKINSON (1953) shows abnormally high reservoir pressures (p_a) from 7,000 to 15,000 ft (2,000 to 4,500 m). In this interval pressure-depth ratios (PDR's) approach 0.9 psi/ft (20 kPa/m). TKHOSTOV (1963, p. 80, Fig. 14) plots formation fluid pressures from Russia and other parts of the world. Geopressures exist as shallow as 500 m (1,500 ft) and as deep as 6,500 m (21,000 ft). Maximum PDR is usually near 1.0 psi/ft (22.7 kPa/m), but locally may exceed this value (FERTL, 1976, p. 336). LEPINE and WHITE (1973) report on geopressures from Australia and New Guinea. Sizable excess pressures are recorded from 4,000 to 14,000 ft (1,200 to 4,300 m) with maxima near 1.0 psi/ft (22.7 kPa/m). FERTL (1976) shows a number of pressure-depth plots that fit the above observation. HUNT's plot (1979, p. 240) combines some of FERTL's values with some Russian data. High geopressures are found from 2,000 to 17,000 ft (600 to 5,200 m). KINCHELOE and SCOTT (1974) give a stress relief factor of about 0.7 for depth of 31,441 ft (9,580 m).

3. 2 Geographical Distribution of Geopressures

Geopressures are a global phenomenon as FERTL (1976) points out. Scanning the literature one does detect a preference for the continental margins and young orogenic belts. In those cases we have conditions of either ongoing, continuous and rapid sedimentation, or recent (Tertiary/Cretaceous) rapid loading by tectonic processes. In section 4 we shall see that the idea of recent, rapid and substantial burial favours almost all views held on the generation and maintenance of geopressures and thus this trend does little to discriminate between competing ideas.

Geopressures are, however, not restricted to these areas. They have also been reported from stable platforms and interior basins (see e. g. KINCHELOE and SCOTT, 1974; THOMEER and BOTTEMA, 1961).

3. 3 Age Distribution of Geopressures

FERTL (1976, p. 325) states: «These abnormal pressures can be present in shale/sand sequences and/or massive evaporite-carbonate sections, and abnormally pressured formations are known to range in the geologic time scale from the Cenozoic era (Pleistocene age) to as old as the Paleozoic era (Cambrian age).» This statement is basically correct but it bears further scrutiny.

Reported geopressures do indeed range from the Ordovician Arbuckle sandstone (KINCHELOE and SCOTT, 1974; ROWLAND, 1974) to the Plio-Pleistocene reservoir rocks of the Ventura field (WATTS, 1948). The data listed by TKHOSTOV (1963, p. 98 – 111) indicate that geopressures are more prevelent in Mesozoic and younger rocks than in the Paleozoic. THOMEER and BOTTEMA (1961, p. 1725) report very high geopressures in the Permian of NW Germany, a case which seems to defy the rule. However, these pressures are found under a regional blanket of salt 1,400 ft (400 m) thick. This constitutes an exceptional seal and accounts for the unusual nature of this observation. A similar situation exists in the Mississippi interior salt basin where Jurassic rocks are under maximum geopressure (PARKER, 1974).

Once again the fact that geopressures are more common in young sediments than in old ones does not provide much of a clue. It simply confirms the well known fact that seals are rare in nature and fluid flow restrictions will permit restoration of equilibrium provided sufficient time is available.

3. 4 *The Onset of Geopressures*

The change from a normal to an abnormal pressure situation is usually referred to as the transition zone (STUART, 1970). This transition zone is extremely variable. It may be sharp, or even abrupt where salt is involved, or it may be very gradual. An excellent example has been reported by SHOULDICE (1971) from the west coast of Canada. Two wells within the same basin (Tofino basin) about 50 km (30 mi) apart show a very different onset of geopressures. In one well the formation fluid pressure begins to deviate from its normal value at a depth of about 3,000 ft (1,000 m) an rises progressively to a PDR value of 0.8 psi/ft (18.1 kPa/m) at the total depth of 12,000 ft (3,700 m). In the other well a sharp deviation from the normal value occurs at 4,000 ft (1,200 m) reaching a PDR value of near 0.9 psi/ft (20.4 kPa/m) at 4,600 ft (1,400 m). It must be noted that the pressures reported by SHOULDICE are indicated pressures. A similar situation is shown in DICKINSON's (1953) early publication. On his Figure 6 (p. 420) a number of wells show a transition zone starting at about 8,500 ft (2,600 m) with a PDR value of about 0.8 psi/ft (18.1 kPa/m) at 11,000 ft (3,400 m), while one well increases from 0.6 psi/ft (13.7 kPa/m) at 12,800 ft (3,900 m) to 0.85 psi/ft (19.4 kPa/m) at 13,200 ft (4,000 m).

STUART (1970) shows the top of the geopressures displaced by faults. The obvious implication is that these faults are viewed as restrictions to fluid flow. This results in a highly variable depth-to-geopressures in a very local area.

Where salt forms the caprock (MOSTOFI and GANSSER, 1957), the concept of the transition zone fails altogether. Above the salt the pore pressure environment may be (but need not be) normal; below the salt high and possibly maximum geopressures seem to be the rule. As the drill passes from the impervious salt into the underlying beds the transition is instantaneous.

In short the onset of geopressures is highly variable, indicating that many poorly predictable factors are involved.

3. 5 *Maximum Value of Geopressures*

It has been reasoned (TERZAGHI, 1950; HUBBERT and RUBEY, 1959; THOMEER and BOTTEMA, 1961) that for a *regional* condition of geopressuring the value of the formation fluid pressure cannot exceed that of the total overburden stress. At this point the overburden is in a state of floatation (TERZAGHI, 1950, p. 92) and any further increase in the fluid pressure would simply «lift the lid». Thus we can write:

$$P_{a(max)} = S_z \tag{15}$$

The above value is referred to in the literature as the geostatic, lithostatic, or petrostatic pressure. It is gratifying to find that published data do indeed support the above prediction. The above value may be marginally exceeded in the crest of a HC reservoir with a large HC column, since this of course constitutes a purely local condition. Also under such circumstances hydraulic fracturing of the caprock is likely to occur which in turn limits the fluid pressure.

The fact that we observe and predict $p_{a(max)} = S_z$ cannot be interpreted that the total overburden stress is the source of the geopressures as stated by Stuart (1970, p. 80). The total overburden stress represents the maximum constraining power rather than the maximum generative force. This distinction is important and will be discussed further in section 4.

3. 6 *Abnormally Low Densities and High Porosities Associated with Geopressures*

There can be no question that in the U.S. Gulf Coast some of the overpressured sediments, in particular many of the sales, have low densities and high porosities which are anomalous for their present depth of burial. At one time this was thought to be a universal condition, an idea that in the face of current evidence must be abolished. Since this question is also intimately related to the ideas on geopressure generation and maintenance, it will be discussed in more detail in section 4.

3. 7 *Geopressures and Temperatures*

It has been pointed out by many authors that the onset of hard geopressures in a clastic sequence is accompanied by an increase in the geothermal gradient (see e. g. Lewis and Rose, 1970). Since the top of the geopressures is usually associated with a loss of the carrier beds, i. e. the sandstones, the shale/sand ratio increases dramatically. Shale is a much poorer thermal conductor than sand which easily explains the observed increase in the geothermal gradient (Gretener, 1981, p. 45).

Since many geopressures occur at great depth they are also associated with high temperatures. It is, however, wrong to relate geopressures in general to high temperature regions. In temperature, like in pressure, it is customary to give the temperature-depth ratio which corresponds to an overall average temperature gradient ($\overline{\Delta T / \Delta z}$). In the Gorgan Plain of Northern Iran, where very high geopressures have been observed (Jaafari and Ghadimi, 1971), the average temperature gradient is 50° C/km (2.8° F/100'), a very high value for a sedimentary basin (Gretener, 1981, p. 58). However, in the Mississippi interior salt basin with equally high geopressures, the gradient is normal at 30° C/km (1.7° F/100'). The same is true for the Anadarko basin where in No. 1 Rogers at a record depth of 9,580 m (31,441 ft) the stress relief factor is estimated to be in excess of 0.7 and the average geothermal gradient is about 25° C/km (1.4° F/100').

A conclusion to the effect that geopressures occur preferentially in high temperature areas is unwarranted at this time.

3. 8 *Geopressures and the Occurrence of Gas*

When scanning the literature one cannot help noticing the persistent reports of gas associated with high geopressures (Thomeer and Bottema, 1961; Jaafari and Ghadimi, 1971; Lepine and White, 1973; Kincheloe and Scott, 1974; and others). This is not to say that gas is always present in commercial quantities, but at least some gas flow seems to be almost universally present in high pressure zones. Hedberg (1974) has also pointed to the frequent occurrence of methane in overpressured shales, often directly observable on the surface within mud volcanoes.

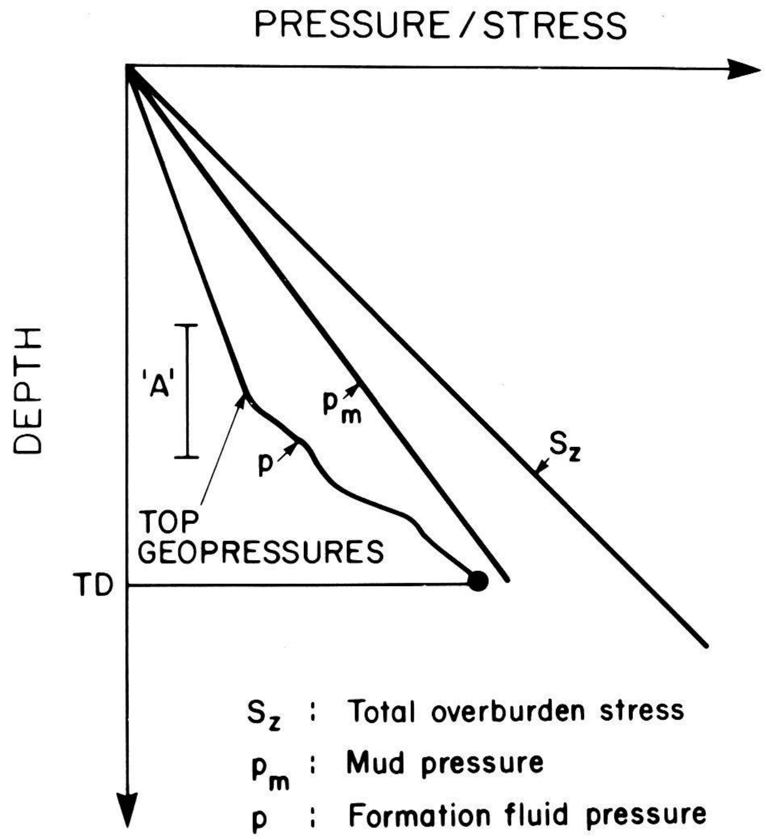

Figure 1 A well terminated in the transition zone when drilling became dangerous and expensive. The pressure-depth curve shown here is the result of limited data and does not depict the full subsurface condition.

3.9 *Distribution of Pore Pressure with Depth*

Many of the published pressure-depth curves look as shown in Figure 1. Such a plot leaves one with the impression that geopressures once encountered will persist to infinite depth at least as far as the HC explorationist is concerned. We do not believe that this is the case. As one enters the transition zone drilling becomes increasingly cumbersome, dangerous, and above all, expensive. The result is abandonment of the well at the total depth (TD) position indicated on Figure 1. Thus, the picture obtained is a result of the data available rather than a true portrayal of reality. We believe that geopressures occur in the sedimentary section as wedges and lenses; in some cases these may be very extensive both laterally and vertically. There is strong evidence in the literature to support the view of geopressure reversals as being the rule rather than the exception (THOMEER and BOTTEMA, 1961, p. 1728 – 1729; PARKER, 1974, p. 72; KINCHELOE and SCOTT, 1974, p. 30; NYEIN et al., 1977, p. 68; MEISSNER, 1978, p. 211; VAN DEN BARK and THOMAS, 1981, p. 2361). The extent and position of these geopressure lenses and wedges is controlled by the distribution of fluid flow restrictions. One would anticipate a return of the pore fluid pressure to normal conditions to occur at the sediment-basement interface, with the upper part of the brittle and fractured crystalline basement acting as an open system with lateral communication to the surface. Some support for this idea is found in the Arsenal well NE of Denver (EVANS, 1966, p. 18, Fig. 7) where in fact a subnormal fluid pressure with $\lambda \sim 0.35$ was found in the top basement rocks.

Table 1
Occurrence of $p_a \sim s_z$

Depth m	Depth ft	Age	Lithology	Area	Source
7,000	23,000	Jurassic	salt/carb	Mississippi	PARKER, 1974, p. 72
5,500	18,000	Jur/Cret	anh/carb/sh	N. Iran	JAAFARI & GHADIMI, 1971, p. 1165
4,100	13,600	?	?	Hungary	HUNT, 1979, p. 240
500 – 3,500	600 – 11,000	Mesoz/Ter	–	world-wide	TKHOSTOV, 1963, p. 80
1,400 – 3,000	500 – 10,000	?	–	New Guinea	LEPINE & WHITE, 1973, p. 157
2,100	7,000	Tertiary	–	Iran	HUBBERT & RUBEY, 1959, p. 156
500/3,000	1,600/9,800	Permian	salt/carb	NW Germany	THOMEER & BOTTEMA, 1961, p. 1725

Table 2
Deepest normal pressures

m	ft	Age	Area	Source
4,900	16,800	Tertiary	U.S. Gulf Coast	DICKINSON, 1953
3,800	12,000	Pliocene	Kara-Dag	TKHOSTOV, 1963
3,400	11,100	Jurassic	Ozek-Suat	TKHOSTOV, 1963
5,500	17,900	Jurassic	Mississippi	PARKER, 1974
7,400	24,200	Mississippian	Anadarko OK	KINCHELOE & SCOTT, 1974 *

* just a sharp ingression to 0.48 within a large overpressure zone.

Table 3
oldest geopressure

m	ft	λ	Age	Lithology	Area	Source
9,580	31,441	0.75	Ordovocian	shale/ss/carb	Anadarko OK	KINCHELOE & SCOTT, 1974
7,150	23,500	0.9	Mississippian	shale/ss/carb	Anadarko OK	KINCHELOE & SCOTT, 1974
3,000	10,000	1.0	Permian	salt	NW Germany	THOMEER & BOTTEMA, 1961
7,000	23,000	1.0	Jurassic	salt	Mississippi	PARKER, 1974
4,900	16,110	0.85	Mississippian	sh/ss/carb	Anadarko OK	ANON., 1984

P. S. TKHOSTOV (1963, p. 98 – 101) lists 43 reservoir pressures of Devonian and Carboniferous age from various parts of Russia without a single serious overpressure ($\lambda > 0.5$).

3. 10 *What, if anything, do Geopressures have in Common?*

Reading through section 3 is a bewildering experience. About the only self-evident conclusion that emerges is: Geopressures are a complex phenomenon. In Tables 1, 2 and 3 another attempt is made to sort out the evidence that currently can be found scattered in the literature. Table 1 indicates that maximum or near maximum geopressures can be found at any drillable depth in the sedimentary sequence. Table 2 shows that the same can be said about normal fluid pressures. Thus geopressures can, but need not, be developed at any depth within the sedimentary cover. For Table 1 we recognize from the discussion in subsection 3.5 that these are in situ geopressures that have been developed at their present depth or at a greater depth in cases where later uplift has occurred. Table 1 thus clearly indicates that geopressures can be produced at great depth regardless of what theoretical considerations or mathematical models suggest.

Table 3 gives testimony that geopressures of substantial magnitude can occur in ancient rocks. Whether they have existed and survived in those rocks throughout their history or whether they have only recently been introduced, is yet another question.

Thus it seems we are left with little hard evidence about the origin of geopressures. They do seem to become more prevalent at depths in excess of 3,000 m (10,000 ft) and young rocks are their favored habitat. There can be little doubt that conditions of recent, rapid, and substantial burial (equivalent to rapid heating) are advantageous to the generation of geopressures.

4. Thoughts on Geopressure Generation and Maintenance

4. 1 *Pore Pressure Generating Processes*

A number of processes have been suggested for the generation of high formation pressures. No agreement exists at this time about the relative merits of these mechanisms. For a list of these processes one may consult GRETENER (1982, p. 5). When we choose to investigate the following six mechanisms we clearly express a personal bias which is also directed toward those processes applicable to the sedimentary sequence. The processes under consideration include: rapid loading (RL), clay transformation (CT), kerogen transformation (KT), aquathermal pressuring (AP), osmotic pressuring (OP), and tectonic pressuring (TP). In addition, one must be aware that geopressures can migrate into sections removed from their place of origin (migrated pressures) and, in areas of complex history with both phases of burial and erosion, geopressures may be uplifted (transplanted geopressures).

Rapid loading (compaction disequilibrium) was for a long time considered the prime, if not the only, process leading to geopressures. The mechanical compaction – in particular of clays – requires the application of a load AND the escape of the pore water. When the fluid escape lags the application of the load, high pore pressures develop as shown by the TERZAGHI model found in every soil mechanics text (see e.g. DUNN et al., 1980, p. 122).

As is the case for all geopressure generating mechanisms, the process of rapid loading is entirely relative. It is possible to generate excess pressures even in an environment of high rates of fluid escape, provided the loading process is extremely fast. The most outstanding case is the impact loading of coarse river gravels by a landslide. Under those conditions it is possible to generate an excess fluid pressure in the gravels and temporarily fluidize the material (PAVONI, 1968). However, this represents a «geopressure event» and not a lasting «geopressure condition». In order to have geopressures persist over geological time spans the presence of fluid flow restrictions of sufficient quality is an absolute necessity.

BRADLEY (1975) suggested that rapid loading can only operate at shallow depth where compaction in un- or semi-consolidated mud rocks is fast. This led to what we like to call the «BRADLEY-DICKEY controversy» (BRADLEY, 1976; DICKEY, 1976). DICKEY maintained that as long as a rock can undergo compaction the process is basically viable. There is truth on both sides of the argument. Mechanical compaction no doubt is most effective at shallow depth and gets progressively assisted or displaced by other diagenetic processes at greater depth. However, if fluid flow restrictions develop early in the process of burial, mechanical compaction gets severely delayed and will be effective to much greater depth than under normal conditions. In order to appreciate this argument one must only compare the classic compaction curves of ATHY, HEDBERG and DICKINSON (see RUBEY and HUBBERT, 1959, p. 175, Fig. 2). There is no doubt that these profound variations must not only be attributed to various degrees of compaction disequilibrium but also to variable shale lithology, the latter being a very poorly defined quantity.

The process of rapid loading is certainly viable for the creation of geopressures. Its effectiveness will diminish with depth in a manner that may vary considerably for different geological provinces and it seems impossible to assign a specific maximum depth below which this process will be inoperative. It is also important to realize that stress relief factors with a value near unity can only be produced by rapid loading if perfect isolation is accomplished at shallow burial. This has been much overlooked but has been pointed out by RUBEY and HUBBERT as early as 1959 (p. 183, Table 2).

In 1967 POWERS made the point that the smectite-illite transformation may lead to high pore processures. According to POWERS (1967) the structured water next to a clay surface has a higher density than the ordinary pore water. Conversion from one to the other during clay dehydration will thus lead to a volume expansion. This in turn must lead to excess fluid pressures when drainage is either inhibited or prevented. However, ANDERSON and LOW (1958) found that the structured water is not of higher but rather of slightly lower density than the bulk water. FOSTER and CUSTARD (1980) have, therefore, suggested that clay dehydration is accompanied by an abrupt loss of permeability which in turn leads to geopressure formation. Another suggestion (see PLUMLEY, 1980, p. 417) envisages a loss of strength in the clay package during dewatering with a concomitant transfer of the overburden load from the matrix to the pore fluid. Neither of these scenarios is dependent on a density difference between interlayer water and pore water. Obviously the clay mineralogists have yet to settle what exactly happens during this transformation. The fact that geopressures often occur near the clay dehydration zone allows us to «keep the process on the books». Clay dehydration, like all diagenetic processes is temperature dependent and occurs between 90 and 110°C (200 – 230°F) according to BURST (1969, p. 80) which in the U.S. Gulf Coast places the «action» at a depth of about 8,000 to 13,000 ft (2,400 to 4,000 m). According to BRUCE (1984, p. 675) the temperature range for the smectite-illite transformation varies considerably for different geological provinces and in general covers a larger temperature range than given by BURST (1969). It seems that some of the factors affecting this transformation are not yet fully understood. In regards to the potential as a geopressure generating mechanism, BRUCE (1984, p. 682) states his opinion clearly: «Observed relations of smectite diagenesis and abnormal pressure indicate that smectite-illite transformation is a principal mechanism for development of abnormal pore pressure in the Tertiary section of the United States Gulf Coast».

MOMPER (1978) and DU ROUCHET (1981) amongst others, have pointed out that the kerogen-to-hydrocarbon transformation is bound to cause excess fluid pressures. MOMPER (1978, p. B – 44) states: «All generated fluids contribute to the overpressuring but, at peak oil generation, the bitumen may be the greatest source of pore pressure increase because the volume increase due to liquid formation in the system is considerable. A net increase of as much as 25 % over the original OM volume is estimated in effective source systems, depending on the initial concentration of OM and its convertibility to liquids». One of the best examples to demonstrate the validity of this suggestion has been published by MEISSNER (1978, p. 211, Fig. 5) who shows a sharp overpressuring in the rich source rock of the Williston Basin, the Bakken shale. Clearly this is a basically viable process whose effectiveness is beyond precise calculations since it depends on such unknowns as: the total amount of mature source rocks, the richness of these source rocks, the type of kerogen being converted, the vertical extent of the oil window, etc. Taking both the oil and gas windows one can say that this process operates in the temperature range of about 100 to 220° C (210 to 430° F). As in the case of the clay transformation this process is restricted to a definite depth range, a range that depends on the average geothermal gradient. In cool areas the vertical range is wider and located deeper than in hot areas.

In 1972 BARKER, quantifying a concept recognized as early as 1932 by VERSLUYS, pointed out that heating of a closed porous rock system must lead to excess pressures. This has become known as «aquathermal pressuring». Basically the process cannot be argued with. However, in view of the small volume changes associated with it, the associated fluid restriction must approach that of a seal and as a result the effectiveness of aquathermal pressuring has come under dispute. For the pros and cons of this controversy the reader is referred to the papers by: CHAPMAN (1980; 1982), BARKER and HORSFIELD (1982), DAINES (1982), and SHARP (1983). This process is independent of depth but depends on the heating rate which in turn is a function of the burial rate and the geothermal gradient (GRETENER and CURTIS, 1982, p. 1125).

Osmotic pressuring has been discussed by HANSHAW and ZEN (1965). Where semi-permeable shale membranes separate carrier beds of appreciably different salinity it is possible to create sizable overpressures. HANSHAW and ZEN (1965, p. 1383, Fig. 3) show that for reasonable salinity contrasts and otherwise ideal conditions, excess pressures of 10 to 20 MPa (1,500 to 3,000 psi) may result. This process also defies forecasting, being dependent on incidental factors, and it is certainly not a function of depth. One would expect this process to be most viable in evaporitic sequences.

Geopressures are known to occur in the foredeeps of young orogenic belts. In these areas a number of authors feel that lateral tectonic compression (not direct loading by thrusting) has increased those fluid pressures and a direct relationship between pore pressure and porosity cannot be expected (see e. g. SAHAY, 1972, p. 154; HOTTMAN et al., 1979, p. 1478). It is known that these lateral stresses do affect the seismic velocities (LOHR, 1969) and therefore it is reasonable to assume that these rocks are more highly compacted than in areas of pure gravitational loading. The process seems to have merit. It is naturally associated with a definite geological province and in that sense is predictable.

One must also consider that there are many reports in the literature of what we call «migrated geopressures», i. e. geopressures that through permeable conduits have spread from their place of origin both laterally and vertically. In order to preserve them as overpressures the migration is clearly into a «cul-de-sac», i. e. it is a pressure – rather than a fluid – migration. The simple message is: geopressures must not always originate in the place where they are found.

In areas where the geological history is complex and burial may be interrupted by uplift one must also consider the case of transplanted (uplifted) geopressures. If a system becomes almost perfectly isolated «on the way down», it will retain the pressure during uplift and a geopressure will develop. BARKER (1979) discusses the role of free gas in over- and under-pressuring during burial and uplift. Certainly the rules of the U.S. Gulf Coast cannot be applied uncritically in such areas.

In the early days of geopressure research, and to some extent even to this day, much attention was focussed on rapid loading. Lately, the other processes mentioned have been considered by a number of authors. As the above mentioned controversies demonstrate, no agreement exists at this time on the relative merits of the various proposed mechanisms. One of the most convincing papers has been published by PLUMLEY (1980). PLUMLEY points out, as others did, that one can prove beyond a shadow of a doubt that rapid loading cannot be the sole mechanism leading to excess fluid pressures. Geopressures caused solely by rapid loading demand undercompaction, i. e. low density and high porosity within the overpressured zone. In fact, the high porosity and the excess fluid pressure both have to be compatible with what CHAPMAN (1983, p. 312 – 313) has called the «equivalent depth». The case can be illustrated with the following simple example. Assume a sediment becomes perfectly isolated (possibly under a layer of salt) the moment it has been deposited. No fluid will ever escape and compaction is prevented from the very beginning. The surface porosity (ϕ_o) is retained and the fluid must carry the total overburden load (S_z) at all times. Under these conditions we have:

$$p = S_z \tag{16}$$

$$\phi = \phi_o \tag{17}$$

Equations (16) and (17) simply state that for a case of continuous burial (no uplift) both porosity and fluid pressure must be compatible with the equivalent depth. PLUMLEY (1980) points out that even in the U.S. Gulf Coast, where undercompaction is certainly common, porosity is never high enough, for the measured pressures, to indicate that rapid loading is the sole cause of geopressuring. Thus even in the classic area of undercompaction (classic in the sense of best studied) one must accept PLUMLEY'S argument and postulate processes of geopressuring other than just rapid loading.

This is not without consequences in regards to the timing of overpressuring. In areas of very high overpressures (often referred to as «hard geopressures») we must assume that the sediments were isolated throughout their geological history if we are intent to acknowledge rapid loading as the only viable pressuring mechanism. If we accept as reasonable the interaction of several, and possibly all, of the processes mentioned we can envisage a very normal compaction history for such sediments followed by a late pressuring event (e. g. increase in the geothermal gradient). Clearly this affects profoundly our views on the fluid flow history of such sediments which in turn colours our ideas on the HC migration process. This view is further supported by the fact that not all high pressure sediments are undercompacted. CARSTENS and DYPVIK (1981, p. 348, Fig. 4) report a case from the North Sea where no density reversal at all is associated with the onset of strong geopressures. GRETENER (1982) reports on a case in Central Iran where there is good evidence that rapid loading combined with kerogen transformation to produce pressures which are at, or very near, the theoretical limit. PARKER (1974) in discussing the Mississippi interior salt basin points out that the conventional «Gulf Coast View» of undercompaction is not valid for this area.

PLUMLEY (1980) has described the situation in the clearest possible manner. In the case of continuous burial with rapid loading as the sole cause of geopressure generation we have:

$$\sigma_p = \sigma_m \tag{18}$$

where: σ_p is the present effective overburden stress, and
σ_m is the maximum effective overburden stress

When other mechanisms are permitted to produce late overpressuring we have:

$$\sigma_p < \sigma_m \tag{19}$$

One must only remember that during compaction, porosity ($\emptyset$) is closely related to the maximum effective overburden stress (σ_m), or:

$$\phi = f(\sigma_m) \tag{20}$$

Thus for the case described in equation (19) there will be no definite relationship between depth and porosity. More on this in section 5.

There is no escaping the conclusion that we must consider all the pore pressure generating mechanisms as potentially viable, given the proper circumstances. However, no geopressures can be generated unless the appropriate restrictions to fluid flow have developed.

Before closing this section it is necessary to return once more to the concepts of «geopressure event» and «geopressure condition». Certain pressure generating processes can be enormously effective. Rapid loading becomes impact loading under a landslide and instantaneous loading under a thick turbidity flow deposit. Aquathermal pressuring in the vicinity of an intrusion is both vigorous and fast. Thus it is possible to create the temporary – seconds to tens of years – «geopressure event» in sediments of high permeability in the absence of any substantial fluid flow restrictions. Sandstone dikes, flame structures and other types of sedimentary deformations are the permanent evidence of such momentary pore pressure aberrations. The long lasting – millions of years – and often directly observable «geopressure condition» does, however, require the presence of severe fluid flow restrictions.

4. 2 Nature and Development of Fluid Flow Restrictions

There are potentially three types of sedimentary fluid flow inhibitors: salt, shale, and tight sands and carbonates. For the case of salt a seal is formed as soon as the salt layer has a substantial thickness. Isolation is, therefore, instantaneous, complete and permanent. Not so in the case of shales where isolation is gradual and never perfect. The case of tight sands and carbonates defies prediction depending on many poorly controlled variables.

Salt [1] is the most effective fluid flow barrier known to us. Besides permafrost, which is a somewhat temporary condition on the geological time scale, salt is the only material that qualifies as a seal. It does not change its properties markedly with depth and is, therefore, effective at any depth. It thus permits the occurrence of high fluid pressures at very shallow depths and early restriction of fluid movement in beds overlain by salt must be anticipated.

Shales will change their permeability in a regular manner with depth of burial. According to WELLER (1959, p. 276, Fig. 1) the porosity of a normally compacted shale is about 2 % at 3,000 m (10,000 ft). Below that depth shales quickly become very effective barriers to fluid flow. The restrictive quality of these rocks is enhanced by the fact that permeability is highly anisotropic, vertical permeability being one to three orders of magnitude smaller than the horizontal permeability. Thus long lasting geopressures may be contained by shales that are, or have been, at substantial depth of burial. The poorly compacted shales of the shallow subsurface do not form very effective fluid barriers. One must, however, never forget that a number of factors contributing to the lithification of mud rocks are not strictly dependent on depth. For any porosity versus depth plot a high noise level must be anticipated.

The formation of tight sands and carbonates depends on many random factors and is thus not predictable. Where present, these rocks will also control the distribution of geopressures (PARKER, 1974).

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[1] Anhydrite is widely mentioned as a cap rock in the Middle East and the Continental U.S. From a rock mechanics point of view this is puzzling. Anhydrite is known as a brittle rock (HANDIN, pers. com.) and brittle rocks do not make seals.

The occurrence and distribution of geopressures is controlled by the location of the permeability barriers in the sedimentary sequence. Therefore it might be useful to introduce the terminology of the groundwater hydrologists into the vocabulary of the deep subsurface hydrology. De Wiest (1965, p. 133) defines an aquifer as follows: «Aquifer: a geologic formation or stratum containing water in its voids or pores that may be removed economically and used as a source of water supply.» Obviously, in order to use these terms in a rational manner for the deep subsurface, slightly modified definitions are called for (see also glossary):

Aquifer, unconfined: a rock unit of sufficient permeability to allow pressure equilibrium to be maintained throughout its geological history with the pore space of the unit being in communication with the surface.

Aquifer, confined: a rock unit with the permeability of an aquifer but separated from the surface by an aquitard or aquiclude.

Aquitard: a rock unit of such low permeability that fluid equilibrium is temporarily or permanently retarded in terms of geological time spans.

Aquiclude: synonymous to seal, a rock unit that permits no fluid movement.

Figure 2 shows how these units will manifest themselves on a pressure-depth plot. Geopressures are restricted to confined aquifers and aquitards. Salt qualifies as an aquiclude and in arctic areas permafrost may play this role, even though in geological terms the latter represents merely a curiosity. Table 4 lists the pressures, pressure-depth ratios (PDR), and the fluid pressure gradients (FPG) that are associated with the various hydrological units.

In subsection 3.9 we have presented evidence that geopressures are not properly described by plots such as shown in Figure 1. Their occurrence as lenses or wedges is strongly supported

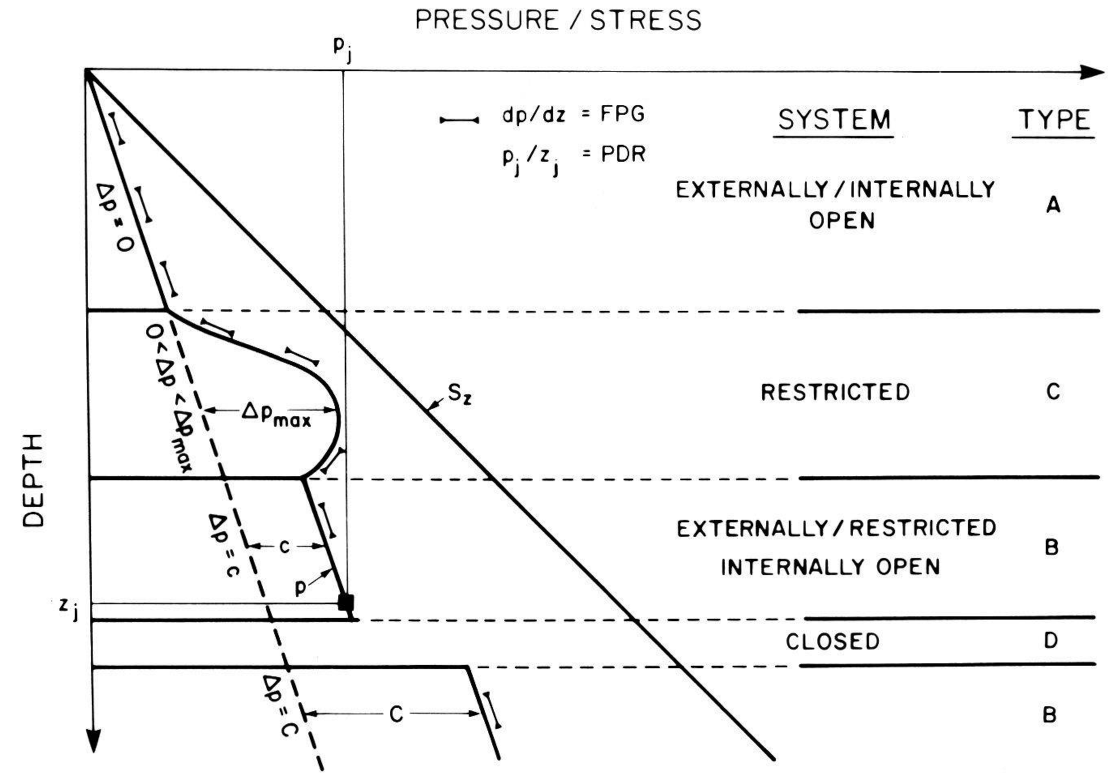

Figure 2 The pressure regimes of the subsurface.

by evidence given in the literature (see subsection 3.9). In our view the most realistic pressure-depth curve ever published is the one by SCHMIDT (1973, p. 124, Fig. 1). This opinion seems to be widely held since SCHMIDT's curve must be just about the most republished figure that ever appeared in the AAPG Bulletin. Our Figure 3 demonstrates that all the pressure regimes postulated in Table 4 can be recognized on the SCHMIDT curve with the exception of the aquiclude which one does not except to exist in a clastic sequence.

An important point has been made by BRADLEY (pers. com.) in regards to this classification. Measured pressures can only be obtained in aquifers. Pressures given for aquitards are always of the indicated pressure type.

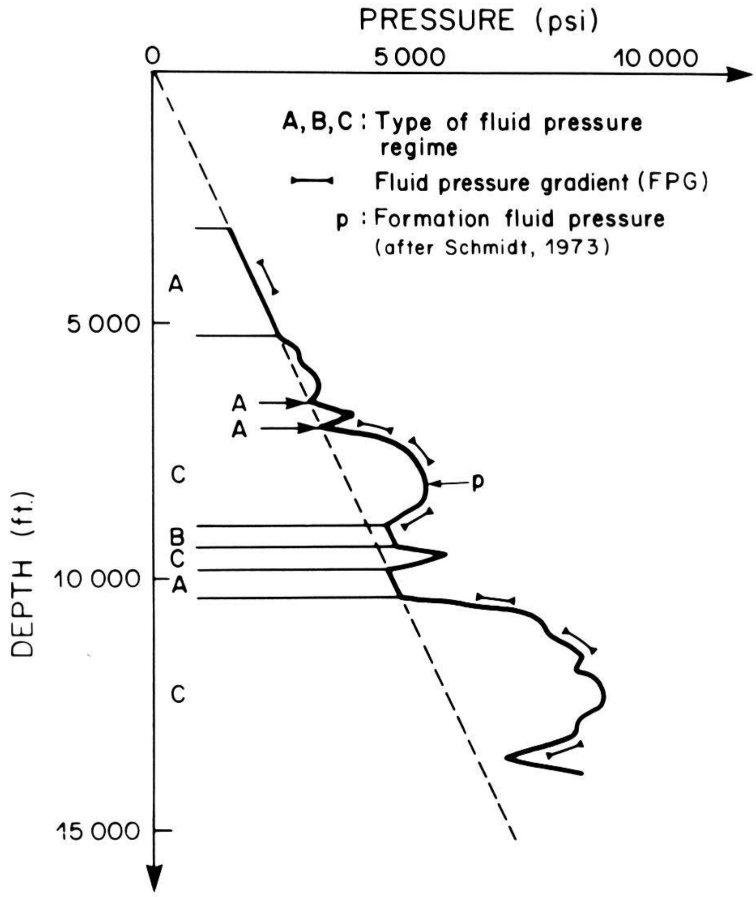

Figure 3 Geopressures occur as wedges or lenses. Note the occurrence of the different pressure regimes shown schematically in Figure 2 with the exception of the seal (no salt present in this sequence).

4. 3 An Attempt to Qualitatively Reconcile Ideas and Observations

For all the generating mechanisms considered in this paper we can say the following:

a) Rapid loading (RL) will have an effectiveness that diminishes rapidly with depth. Its effectiveness will follow a curve similar to the published compaction curves.
b) Clay transformation (CT) will be effective only over a limited depth range. Following BURST (1969, p. 79, Fig. 5) we place that range at 8,000 to 13,000 ft (2,500 to 4,000 m). However, according to the latest information by BRUCE (1984) this range may be both wider and highly variable for different geological provinces.
c) Kerogen transformation (KT) will act over a depth range from about 3,000 to 8,000 m (10,000 to 25,000 ft) when lumping the oil and gas windows together.

Table 4

The fluid pressure regimes of the subsurface

Type	Name	Condition	Pressure	Fluid pressure gradient (FPG) pressure-depth ratio (PDR)	Rock types
A	aquifer unconfined	externally open/ internally/ open	$p = \bar{\rho}_w \cdot g \cdot z$	$dp/dz = p_j/z_j = \bar{\rho}_w \cdot g = C$ $\Delta p = 0$	med. to high permeability clastics and carbonates
B	aquifer confined	externally restricted/ internally open	$p = \bar{\rho}_w \cdot g \cdot z + C$	$dp/dz = \bar{\rho}_w \cdot g \neq p_j/z_j$ $\Delta p = C$	same
C	aquitard	internally restricted	$p = f(z)$	$dp/dz \neq \bar{\rho}_w \cdot g \neq p_j/z_j$ $0 < \Delta p < S_z - p_n$*	shales, tight sands and carbonates
D	aquiclude	internally closed no connected pore system	p: non-existent	dp/dz: non-existent	salt, (permafrost)

* for regional conditions: $p_a = p_n + \Delta_p \leq S_z$

d) Aquathermal pressuring (AP) is a function of the geothermal gradient and in our model will be constant over the full depth range.
e) Osmotic and tectonic pressuring are not definite functions of depth and thus cannot be included in our considerations.

It is essentially impossible at this time to judge the relative effectiveness of the various processes at any given depth, i. e. is CT > RL at 3,000 m? One can say that at maximum generation clay transformation should be more effective than kerogen transformation simply because of the greather abundance of mud rocks in the section. Our attempt to show generation effectiveness as a function of depth is given in Figure 4a. The sum of the individual curves gives the expected total generative power at any depth level.

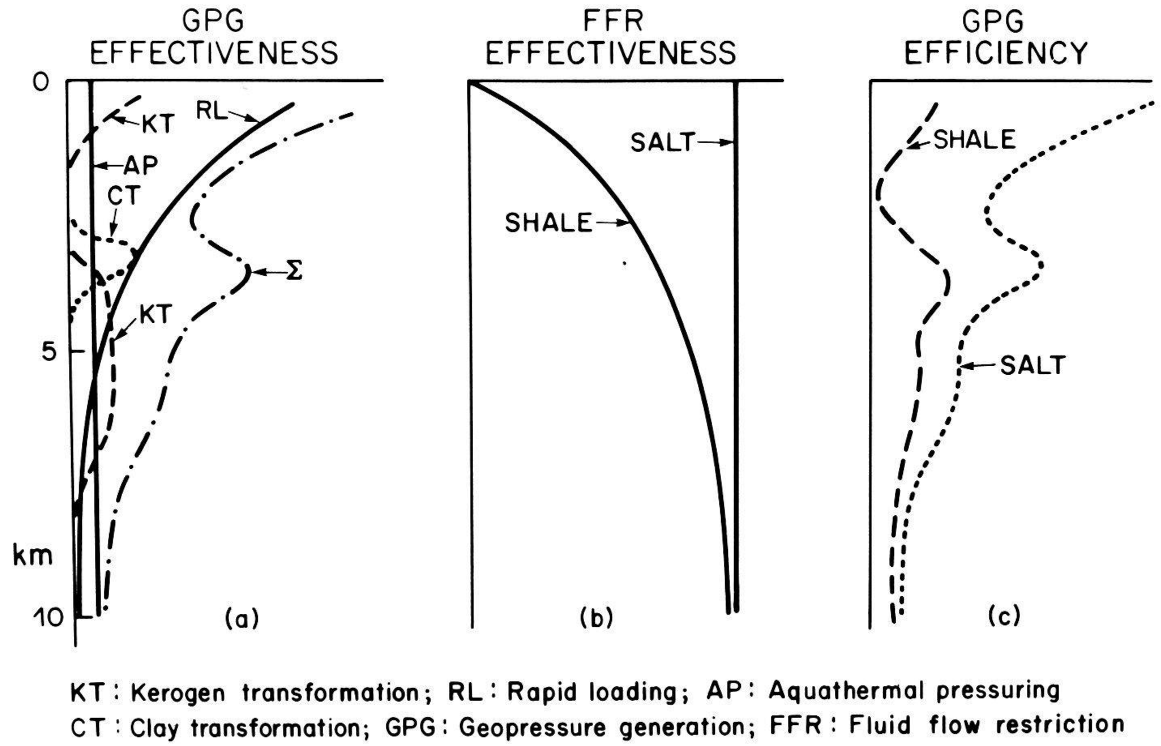

Figure 4 An attempt to assess qualitatively the geopressure generation within a sedimentary sequence. Geopressure generation efficiency is a function of both the generation effectiveness AND the fluid restriction effectiveness. Note that particularly the shale curve in 4b is highly schematic and subject to considerable fluctuations.

Geopressures can neither be generated nor maintained unless a fluid flow restriction is present. In Figure 4b we assess the effectiveness of fluid flow restrictions with depth. We consider salt and shales. Salt is a seal at any depth, whereas the restrictive power of the shales increases with depth in a manner analogous to the compaction curve. We do not consider the formation of tight sands and/or carbonates since their occurrence is unpredictable. For the same reason we also do not consider the development of secondary porosity in sands and carbonates as described by SHANMUGAM (1984).

We now must make the distinction between geopressure generation (GPG) effectiveness and geopressure generation efficiency, the latter being also a function of the fluid flow restriction (FFR) effectiveness. Symbolically we can write this as follows:

GPG EFFICIENCY = GPG EFFECTIVENESS x FFR EFFECTIVNESS

The result is shown in Figure 4c. For the case of an evaporite section with salt present the GPG efficiency curve is equivalent to the sum-curve of Figure 4a. Salt is a seal at all depths. For a clastic sequence, with shales as the fluid flow barriers, the sum-curve of Figure 4a gets depressed at shallow depth such that the GPG efficiency curve shows little variation with depth (Figure 4c). We conclude that in evaporite environments high geopressures may be formed early (at shallow depths) whereas in clastic environments, geopressures have an almost equal chance to form at any depth. The fact that high fluid pressures are often encountered in salt mining (BAAR, 1977) seems to support our first conclusion. The second conclusion may appear to be contradicted by the observation of shallow mud flowage in coastal areas (MORGAN et al., 1968). However, these are, geologically speaking, short lived phenomena (geopressure events), not affected to the same extent by the lack of strong fluid flow restrictions as the more permanent geopressures that are of interest here.

One must realize that Figure 4c is both qualitative and tentative. The shape is strongly affected by the inclusion of clay transformation which, as we have seen, is not a settled issue. On the whole, however, these considerations confirm the complexities of geopressure formation and are in agreement with the meager data shown in Tables 1, 2, and 3, which do not restrict either geopressures or normal pressures to any particular part of a sedimentary section.

4. 4 Comments on Pressure-Depth and Pressure-Time Curves

Much of the current disagreement about geopressures seems to arise from the confuison about pressure-depth and pressure-time curves. The former give the current condition of pore pressure as a function of depth. The latter provide the pressure history of a rock element. We have:

$$(dp/dz) \times (dz/dt) = (dp/dt) \tag{21}$$

where: dp/dz is the fluid pressure gradient

dz/dt is the burial rate

dp/dt is the pressuring rate

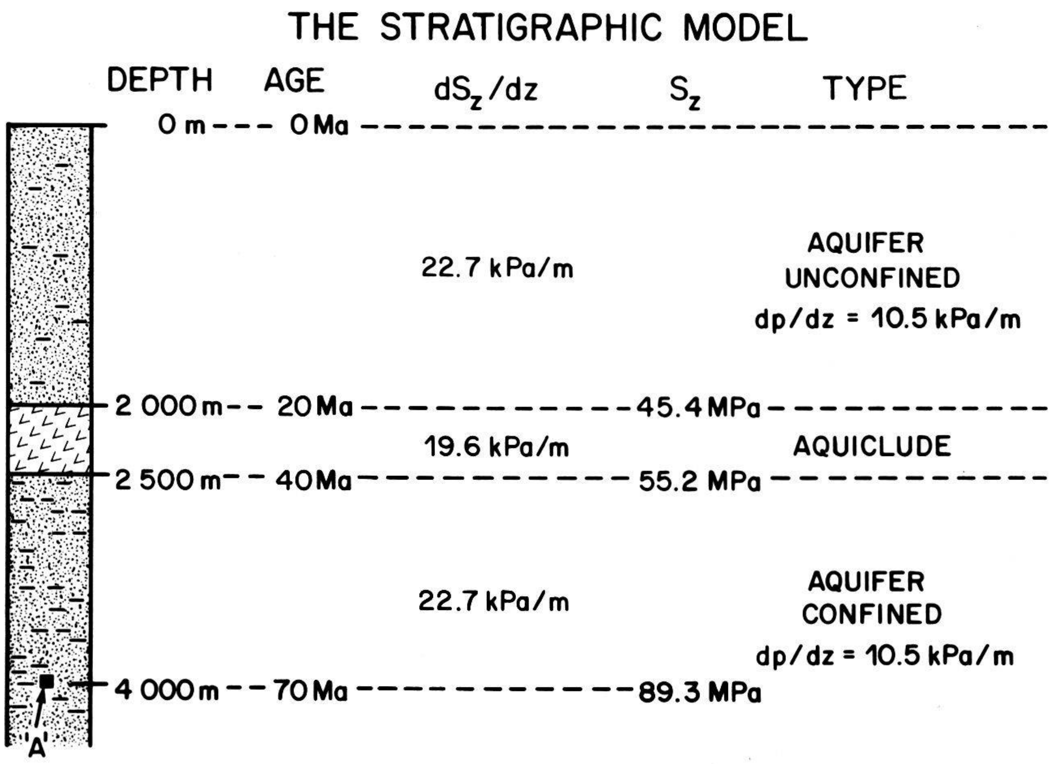

Figure 5 The stratigraphic model.

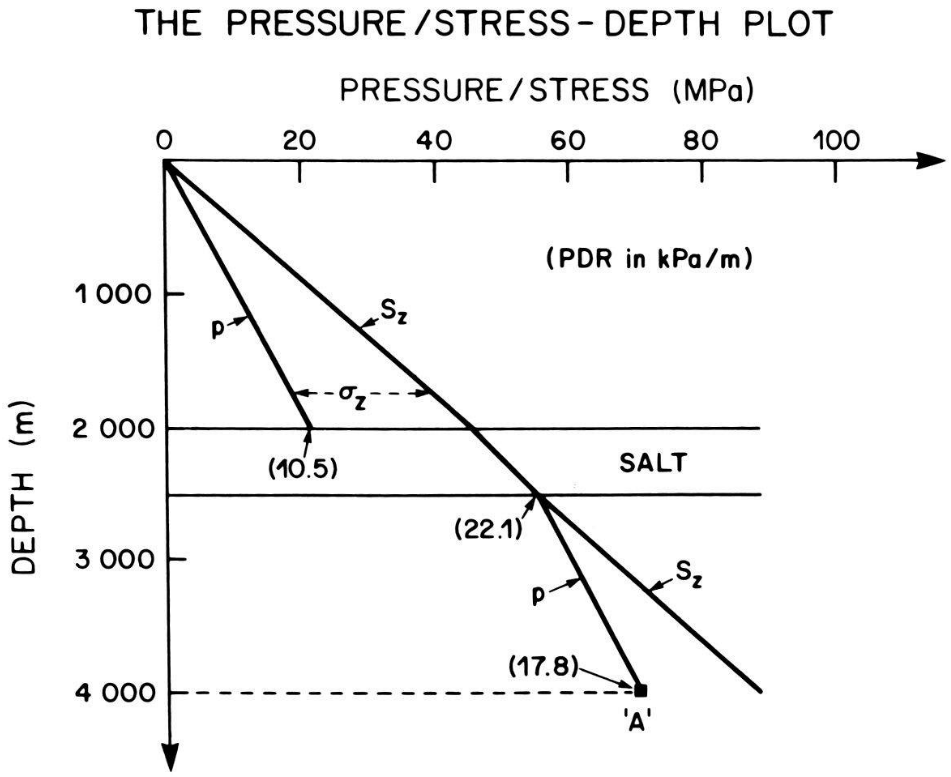

Figure 6 The present pressure and stress versus depth relationship.

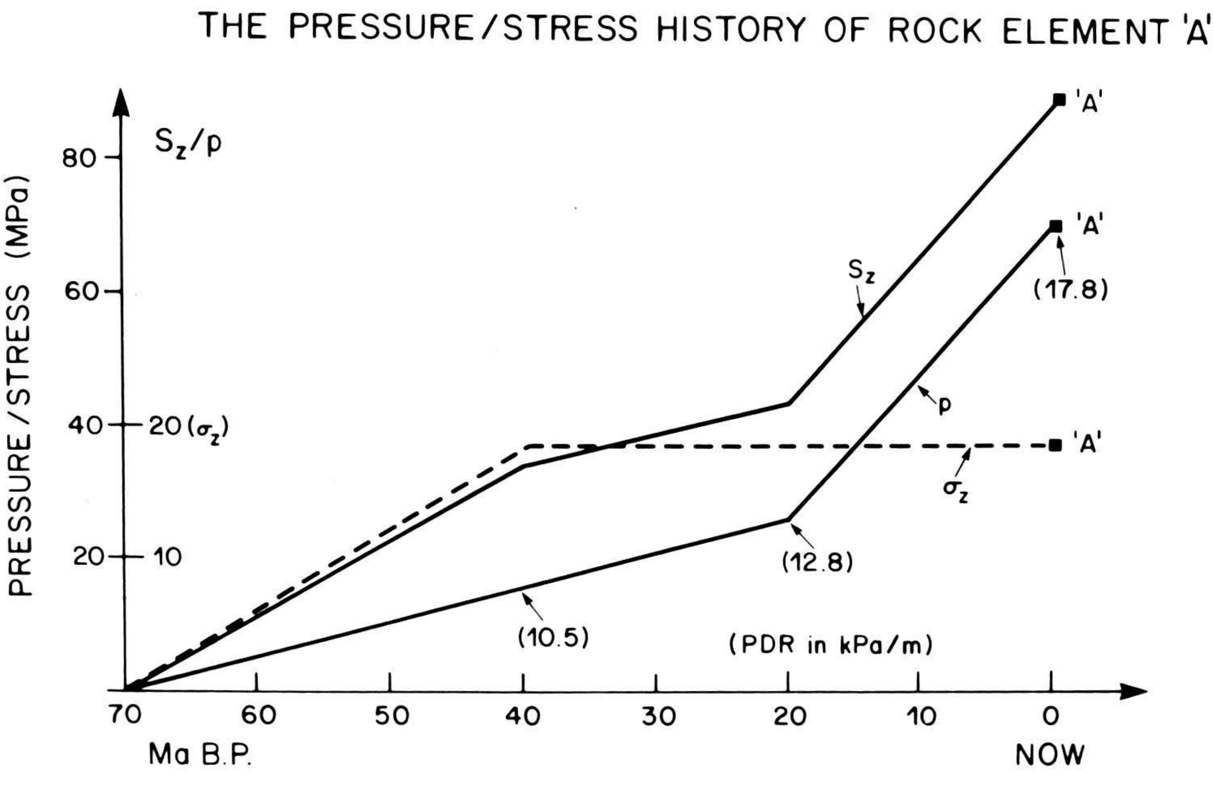

Figure 7 The pressure and stress history of rock element 'A'.

Plumley (1980) has basically made this point but never seems to have received proper attention. We repeat it here and hope the simple example will clarify matters. The section of Figure 5 contains an aquiclude (salt) separating an unconfined aquifer above from a confined aquifer below. As the sole mechanism of overpressuring we recognize the process of rapid loading. Figure 6 gives the present pressure-depth configuration and Figure 7 traces the pressure-stress history of the rock element 'A' located in the confined aquifer. It seems that these figures are self-explanatory and plainly show the difference between the two concepts.

5. Manifestations of Geopressures

5.1 *Types of Manifestations*

In 1965 in a classic paper entitled «Estimation of Formation Pressures from Log-Derived Shale Properties», Hottman and Johnson pointed the way to the recognition of geopressures via a change in physical properties. They showed that shale velocities and resistivities when plotted versus depth showed a regular trend of increasing velocity and resistivity. At the top of the geopressures these trends exhibit a reversal and once calibrated it is actually possible to translate the amount of deviation into excess pressure. Hottman and Johnson's (1965) findings were based on data gathered in the U.S. Gulf Coast. Soon it was discovered that while the method can be used in many parts of the world, recalibration is necessary and equal deviations correspond to very different pressure differentials in various geological provinces (Fertl, 1976, p. 108, Fig. 3.5; p. 311, Fig. 8.20; Nyein et al., 1977, p. 70, Figs. 10 & 11).

It was also found that in some areas these methods fail altogether. The following quotes may suffice to make the point that this approach is not universally applicable.

For the interior salt basin of Mississippi, Klementich (1972, p. 2) had the following to say: «At this point it was apparent that the on-site geopressure detection techniques developed in the Gulf Coast formation do not provide even a qualitative indication of incipient abnormal pressures.»

Referring to electrical resistivity anomalies in the foothills belt of the Himalayas, Sahay (1972, p. 154) made this statement: «However, no such anomaly has been observed in the Suruinsar well. Therefore, the generation of high pressures in this well appears to be of tectonic origin rather than compaction of shales.»

In the Gulf of Alaska Hottman et al. (1979), p. 1483) found: «A relationship exists between the appearance of thrust faulting and its implied high lateral stresses exceeding the overburden and the onset of abnormal pore pressure in the Gulf of Alaska. For this reason, it is not surprising that the traditional methods for abnormal pressure prediction developed in basins such as the Gulf of Mexico are not successful in the Gulf of Alaska.»

Other methods of recognizing geopressures have been suggested. One of the most popular is the d-exponent (Jorden and Shirley, 1966) or the modified d-exponent («d_{CS}») of Rehm and McClendon (1971). This exponent is basically a normalized penetration rate. The normal trend for bit penetration rate is to decrease with depth and a reversal of that trend is picked as the top of the geopressures. After calibration the amount of deviation can be translated into excess pressure. It is interesting to note that Hottman et al. (1979, p. 1478) found the d-exponent a useful indicator of geopressure in the Gulf of Alaska where electrical resistivity and sonic velocity failed to provide such information.

The densitiy log, too, has been used to forecast geopressures. Shale density with depth and reversals from that trend are indicative of the onset of geopressures.

Flow line temperatures have also been used to determine the presence of geopressures. Generally it is found that the flow line temperature increases rapidly at the top of geopressures (Lewis and Rose, 1970; Wilson and Bush, 1973).

5. 2 Discussion of these Manifestations

In 1980 Carstens coined the very useful term «porosity tools». Carstens calls attention to the fact that many of the manifestations listed above occur in response to abnormally high porosities rather than abnormally high fluid pressures as such. It seems useful to review these tools in the light of Carstens' (1980) suggestion.

Sonic velocity ist strongly affected by porosity as shown by the well known «time average equation». Yet seismic velocity also varies with effective stress (see e. g. Gardner et al., 1974, p. 776, Fig. 5). Their stress versus velocity plot shows that the stress effect is most pronounced below 30 MPa (4,500 psi). In that range velocity changes by about 15 to 20 %. We conclude that the stress effect is most pronounced under extreme geopressures where the effective overburden stress approaches zero. The time average equation lets us expect a velocity decrease of about 20 % for a change from 10 to 20 % porosity. Thus, under most conditions normally encountered the sonic velocity must be considered a pure porosity tool.

It is customary for geophysicists today to predict the occurrence of geopressures on the basis of velocity determinations from surface seismic data (Reynolds, 1970). Clearly such forecasts require the association of geopressures with strong undercompaction as observed in the U.S. Gulf Coast.

Electrical resistivity of rocks is primarily a function of the amount, geometry, and nature of the pore filler. Provided the brine is of fixed concentration this is a porosity tool.

The same can be said of the density log, which is unquestionably a porosity tool. As such this tool can only be used where undercompaction prevails. Carstens and Dypvik (1981) show that it does not work in the North Sea.

The penetration rate («d_{cs}») is affected by both effective stress (confining pressure) and porosity. Higher penetration in geopressure zones can be attributed to both higher porosity and lower effective stress. This suggests that the d-exponent is a hybrid tool.

The fact that in many places the onset of geopressures is accompanied by an increase in the geothermal gradient – resulting in an increase in the flow line temperature – can hardly be denied. Lewis and Rose (1970) ascribe this to the fact that all pore fillers are notoriously poor thermal conductors and high porosity shales, therefore, constitute a heat barrier. Gretener (1981, p. 43) has pointed out that the difference in the thermal conductivity between clay and water/gas/oil is minimal. In areas such as the U.S. Gulf Coast the onset of the major geopressures invariably coincides with the loss of the carrier beds, the sands. It is thus the higher shale/sand ratio that is responsible for the higher geothermal gradient (Gretener, 1981, p. 44 – 45, Figs. 4.6 – 1/2). It is to be expected that this method will not work in evaporite provinces where salt – both a seal and an excellent thermal conductor – takes the place of the shale. The flow line method may be called a «shale tool».

In summary a careful assessment of a geological province must be made before any of these methods can be applied. Geopressure recognition is evidently more complicated than originally envisaged. This again points to the fact that geopressures can arise in many different ways and it will be futile to look for THE generating process. Translation of any physical measurement into geopressures requires that at least one point of calibration be available. One must be prepared to drill this first well under extremely tenuous circumstances and one must pay the high economic price in order to gain the necessary experience (Nyein, pers. com.).

The intense discussions that ensued at the National Conference on Earth Science in Banff in November 1984 compel us to take another look at the concept of «porosity tools».

We shall concentrate on the seismic velocity of shales and its change with depth. There are three factors that effect shale velocities in the top 5,000 m:

1. The effective overburden stress as pointed out by GASSMANN (1951) leads to:

$$V \propto z^{1/6} \tag{21}$$

often referred to as the «one-sixth power law».
2. The decrease of porosity results in an increase of velocity according to the time average equation by WYLLIE et al. (1956):

$$1/V = (1 - \phi)/V_{matrix} + \phi/V_{fluid} \tag{22}$$

3. Since the smectite-illite transformation falls somewhere into this depth range (BURST, 1969; BRUCE, 1984) the matrix velocity itself is subject to a change, which at this time must be considered an unknown.

In summary we can say:

$$V_{shale} = f\ (V_{matrix}, \phi, \sigma_z) \tag{23}$$

Obviously this is a complex problem requiring a major research effort exceeding the scope of this review paper. It is not surprising that equal deviations of transit time ($\Delta\Delta t$) correspond to strongly different stress relief factors in various geological provinces, a fact already well documented by FERTL (1976, p. 311, Fig. 8.20).

6. Effects of Geopressures on:

6. 1 *The State of Stress*

According to the concept of effective stress (equation 8) geopressures will result in abnormally low matrix stresses. When geopressures reach the limiting value and fully support the overburden, the rock matrix is completely destressed. In terms of stress the rock matrix is in a surface, or onburied, condition. Under these circumstances, randomly oriented, open fractures are to be expected with the concomitant excellent permeability. Such a condition seems to exist in the Alborz structure in Central Iran (GRETENER, 1982).

A reduction of the matrix stress (confining pressure) results in a weakening of the rock. Prime examples are the overpressured shales found on all continental margins. Because of undercompaction and overpressuring these shales are both mobile and buoyant. In terms of strength and buoyancy they behave much like salt and form another major source material for diapirism. These shales differ from salt in as much as their seismic velocity and thermal conductivity are both low (GRETENER, 1979, p. 73), but neither of those properties affect their structural behaviour.

Figure 8 shows a concept of SECOR (1965, p. 643, Fig. 8). SECOR claims that an increase in fluid pressure can lead to shear faulting when the initial stress difference is large (large Mohr circle in Fig. 8). This is generally accepted and we have no argument with this interpretation. However, when the stress difference is small (small Mohr circle in Fig. 8), an increase in pore pressure may «sneak the Mohr circle into the realm of tension». This, in our view, is an untenable concept. It essentially implies that a rock may be «exploded» by internal fluid pressure and the term hydraulic fracturing is used in this context. This is erroneous. The concept of effective stress is a static or steady state concept. It does not allow for fluid pressure gradients which form the very essence of hydraulic fracturing. If SECOR's idea is used in order to explain primary oil expulsion (DU ROUCHET, 1981) then the statement of MOMPER (1978):

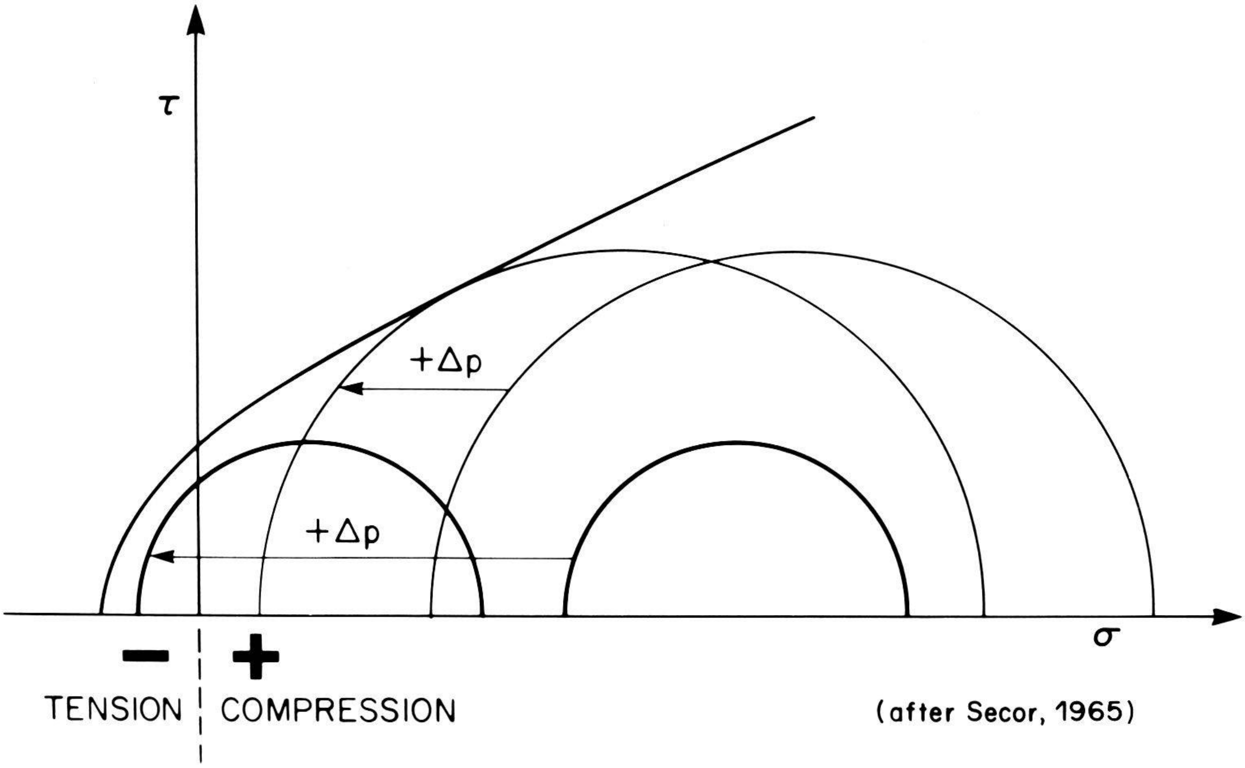

Figure 8 Secor's way to generate tensile stresses in rocks through an increase in pore pressure. This is possible when the virgin stress differential is small (small Mohr circle). We do not think that this is physically possible (for details see text).

«Two properties of argillaceous rocks that permit overpressuring are heterogeneity and anisotropy» illuminates a crucial point. During oil formation in a source rock, fluid pressure at the microscopic level is highly irregular, thus indeed permitting microfracturing. The situation is similar to that of grain contact stresses which also have little to do with the overall effective stress. Geopressures can relieve matrix stresses completely and under those conditions open fractures (oriented perpendicular to the direction of zero matrix stress) are possible. When the geopressures reach the limiting value of $\lambda = 1$, vertical dilation will occur and no preferred stress orientations exist. Open fractures will be randomly oriented with a corresponding superpermeability (Gretener, 1982). Be it as it may the concepts of hydraulic fracturing and effective stress cannot be related in this manner and negative rock stresses, as shown by Secor (1965) cannot be produced in this manner, despite many followers (see e. g. Graves and Zentilli, 1982).

6. 2 *Permeability and Porosity*

It seems logical to assume that both these properties will be affected by the level of the fluid pressure in a rock, or rather by the maximum effective stress the rock is subjected to (eq. 20). Zoback and Byerlee (1975) and Walls and Nur (1980) have shown that permeability can be quite sensitive to pore pressure under certain conditions. It seems that particularly dirty sandstones react strongly to pore pressure with the permeability being considerably better at high fluid pressures. The explanation given assumes that the clay particles coat the sand grains. Under high fluid pressures, the coatings are compressed resulting in larger diameter pore throats.

The question of pore volume reduction by pressure solution seems clear cut: higher pore pressures with resulting reduced effective stresses must favour the preservation of pore space through the retardation of the pressure solution process. Sprunt and Nur (1977) have shown that reality may not be quite so simple. According to their experiments, pressure solution occurs primarily in response to high differential stress – a quantity not affected by higher than normal pore pressures. In addition they found that the solubility of quartz in water increases with increasing fluid pressure. The end result may well be enhancement rather than retardation of the pressure solution process by high fluid pressures. In this context it is interesting to note that Atwater and Miller (1965) find that sandstone porosity decreases by 1.265 per cent of total volume per 1,000 feet of burial (300 m) and in regards to the geopressures they state: «The porosities of the abnormally pressured reservoirs, averaged by 1,000 foot depth increments, fit a straight line of plot of porosities from all reservoirs.»

6. 3 *Brittle and Ductile Deformation*

High fluid pressures result in low confining pressures that enhance brittle deformation. This type of deformation can thus extend to much deeper levels than under ordinary circumstances. This is important since many reservoirs only become commercial because of fracture permeability. Others, not recognized as fractured, may nonetheless owe their productivity to fractures. We maintain that geological field observations suggest that fractured reservoirs containing open joints are the rule and not the exception as conventional wisdom would have it. Unfortunately vertical fractures easily escape detection by logging methods, VSP surveys, and conventional seismic surface surveys. This may be the reason for the prevailing biased view against their presence. The existence of fractures is, however, extremely important during the exploitation of a reservoir and becomes dominant during the stages of secondary and tertiary recovery. Geopressures favour the formation of fractures.

6. 4 *Drilling*

When drilling into geopressured zones, one by necessity develops a high overbalance in the section of the well that is situated in zone 'A' of Figure 1. Protecting the well over this interval is critical and setting casing at appropriate depth is a crucial operation. This fact was already acknowledged by Dickinson (1953, p. 430 – 431) discussing the situation in Louisiana who wrote: «Pressures approaching this gradient have been drilled through without excessive trouble by using muds weighing 18 to 18.5 pounds per gallon. The main difficulty with such heavy mud is loss of circulation. Where abnormal pressures have been penetrated successfully, for example, in Iowa, St. Gabriel and Chalkley, casing was cemented in the top of the shale series before drilling into the high-pressure zones, thus precluding the loss of circulation into the main sand series.»

Once the pore pressure approaches the value of the total overburden stress, mudweight > 18 ppg ($> 2.1 \times 10$ kg/m^3), the well is in a very delicate state of balance in the overpressured series itself. The rock is completely destressed, no protective stress barrier exists in the borehole wall, and the driller is merely balancing the mud column against the formation fluid pressure at that depth. A very fragile situation in a porous formation where a slight increase in mudweight results in lost circulation and a slight reduction brings on a kick.

The case gets even further complicated when the geopressures occur as lenses or wedges as described by Jaafari and Ghadimi (1971, p. 1164).

When drilling through a substantial salt section, a seismic prediction of subsalt pressure conditions is mandatory. When drilling out of the salt, the pressure conditions will be encountered instantaneously (Mostofi and Gansser, 1957) and unless casing has been set at the appropriate depth, such a well will be beyond salvation (Gretener, 1982).

7. Geopressures and Commercial Hydrocarbon Occurences

For the U.S. Gulf Coast, FERTL (1976, p. 319 – 321; TIMKO and FERTL, 1971) arrives at the conclusion that superpressures and commercial HC reservoirs are not compatible. Limited pool size and the lack of a viable drive lead to rapid pressure depletion without prolonged commercial production. This view is supported by others as evidenced in this quotation from FOWLER (1970, p. 421): «The deep lower Frio pays in East Chocolate Bayou that do not contain commercial hydrocarbons are those with pressure gradients in excess of 0.85 psi/ft.»

The fact that many superpressures ($\lambda > 0.8$) contain only small volumes of hydrocarbons is further supported by the observations that many troublesome pressures of this type subside to manageable proportions after short bleeding. The following two quotes may prove the point:

LEPINE and WHITE (1973, p. 160) referring to the Tovala 1 well in Papua, New Guinea state: «Testing proved that the gas and salt water reservoirs were of limited extent and it appears that partial pressure depletion enabled drilling to continue».

JAAFARI and GHADIMI (1971, p. 1164) in their report on the Qezel Tappeh well in the Gorgan plain of North Iran have included the following remark: «En forant les formations calcaires on rencontra plusieurs lentilles de gas de faible volume et sous haute pression,...»

However, these findings cannot be generalized in view of the fact that one can also muster evidence to the contrary. The Ventura field (certainly a commercial success) had initial reservoir pressures with a stress relief factor of about 0.9 (WATTS, 1948, p. 191). The Alborz structure in Central Iran certainly has the promise of a commercial accumulation after a giant blow-out lasting 82 days and «producing» about 5 million barrels of oil (MOSTOFI and GANSSER, 1957). The stress relief factor for this reservoir must be near 1.0. The situation of the Tuscaloosa in the U.S. Gulf Coast trend in the U.S. Gulf Coast is still unclear and DORFMAN (1982, p. 1918) sums it up this way: «Conclusions: (1) The too optimistic and sometimes simplistic view of strong advocates of geopressured resources does not hold. Recoverable high-volume flow rates of low-salinity fluids saturated with methane are not omnipresent in U.S. Gulf Coast geopressured sandstones. (2) The too pessimistic view of some industry specialists does not hold either. Large reservoirs capable of high flow rates over sustained periods have been located, and permeabilities of 3 to 6 Darcies have been found at depths below 15,000 ft (4,572 m) in geopressured standstones.» DOHERTY et al. (1982, p. 1597) phrase it this way: «Projectons of methane production still contain enormous uncertainties because of the lack of quantitative definition of drive mechanisms, pressure and temperature dependence of permeability, relative permeability to gas and to water, saturation of pores, methane content of brine, and drainage area limitations.»

An important factor for commercial HC occurrence under high geopressured conditions seems to be the size of the reservoir. Note that DORFMAN mentions «large reservoirs». The Alborz structure measures 12 by 50 km (7 by 30 mi). High geopressures are indicative of near perfect isolation or, no fluid loss but also no influx. Thus the only viable driving mechanism seems to be a solution gas drive which in turn demands a large trap. Small traps are non-economical, but it would be wrong at this time to condemn the hard geopressure environment in its entirety.

Another factor that will affect the relationship between hydrocarbons and high geopressures is the timing of the pressuring. We have shown previously that number of processes allow for late pressuring, preceded by a normal fluid flow history. WATTS (1948, p. 196) states the following in regards to the D-7 zone of the Ventura field: «Abnormal pressures are inherited or 'fossil' pressures, remaining from an age when the reservoir was sealed at greater depth. Presumably the pressure was normal for the original depth of the accumulation; the reservoir was then sealed, after which it was elevated to the present depth.» Thus trapping took place under normal hydrodynamic conditions and the reservoir isolation is seen as a later feature.

8. Concluding Remarks

1. Evidence is overwhelming that high fluid pressures can be created in different ways. An open mind is the first requirement for further study.
2. Fluid restriction takes precedence over pressure generation. It is the aquitards that control the distribution of geopressures within the sedimentary cover. In the absence of powerful fluid flow restrictions even the most effective generation process can only lead to temporary geopressures.
3. Pressure generation is possible throughout the sedimentary section. The generation efficiency depends on both the generative power and the quality of the flow restriction (Fig. 4).
4. The upper limit for regional geopressures is usually set by the total overburden stress (S_Z). This does not prove that the overburden load is the generating factor but rather that it constitutes the maximum restraining element, since any further increase in fluid pressure «simple lifts the lid».
5. Maximum geopressures ($\lambda \sim 1$) have been recorded as deep as 7,000 m (23,000 ft). This proves that geopressures can be generated at the deepest levels of a sedimentary section, regardless of what theoretical considerations, model studies, or laboratory experiments imply.
6. Geopressures occur as lenses or wedges throughout the sedimentary sequence. The geometry of these bodies is determined by the permeability distribution in the sedimentary cover.
7. There seems to be no exclusive level for geopressures. Both normal and geopressures can be found at any depth (Tables 1 and 2). There is only a weak tendency for geopressures to prevail at depths greater than 3,000 m (10,000 ft).
8. Geopressures are found in many geological provinces. Continental margins are the preferred, but not sole, habitat. Rapid burial (or heating) favours most forms of geopressure generation.
9, Geopressures occur preferentially in young sediments. This indicates that pressure maintenance is usually not permanent. This is not surprising since aquitards are common whereas aquicludes are rare. Also, long time spans favour damage to, and destruction of, aquitards and aquicludes.
10. The question of commercial HC occurrences in high geopressure environments remains unsettled. Reservoir size is obviously of prime importance, small reservoirs being subject to rapid pressure depletion. There are, however, indications that large reservoirs may not only be commercial but in fact may by very prolific.
11. Further insight into the distribution, formation, and maintenance of geopressures is not likely to be obtained by laboratory measurements, as they can never properly assess the bulk properties of large rock masses. Solutions will also not be found through the fabrication of elaborate computer models with results that are determined by – due to lack of information – arbitrary boundary conditions. Rather, progress will be made by carefully cataloguing the occurrence and environment of geopressures, an aspect where much remains to be done. Such an inventory should provide reliable pressure and temperature measurements, detailed lithological descriptions of the whole section, the ages of the rocks involved, the general geological setting, and reference to any published source material.

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10. List of Symbols and Abbreviations

$\bar{\rho}_b$: average bulk density of water saturated overburden (sediments)

$\bar{\rho}_f$: average fluid (brine) density

$p_n = \bar{\rho}_f \cdot g \cdot z$

$p_a > p_n$ strictly speaking also: $p_a < p_n$ or $p_a \neq p_n$

$S_z = \bar{\rho}_b \cdot g \cdot z$

p_j / z_j = PDR (pressure-depth ratio) an «average gradient»: $\overline{\Delta p / \Delta z}$

dp/dz = PGR (pressure gradient) $dp_n/dz = \overline{\Delta p / \Delta z} = \bar{\rho}_f \cdot g = C$

$dp/dz = \bar{\rho}_f \cdot g$: aquifer; confined if $\text{if } p_j/z_j \neq \bar{\rho}_f \cdot g$;

unconfined if $\text{if } p_j/z_j = \bar{\rho}_f \cdot g$

$dp/dz \neq \bar{\rho}_f \cdot g$: aquitard

$dp/dz = \infty$: aquiclude (seal)

$PR = p_a/p_n$

$\lambda = p/S_z$; $\lambda_n \sim 0.45$; $\lambda_{max} = 1$; a dimensionless parameter, here called the stress relief factor

σ_m : maximum effective overburden stress } after PLUMLEY (1980)

σ_p : present effective overburden stress

$$\sigma_z = S_z - p = S_z \cdot (1 - \lambda)$$

FFR: fluid flow restriction

FPG: fluid pressure gradient

GPG: geopressure generation

HC: hydrocarbons (oil and/or gas)

PDR: pressure depth ratio

11. Glossary

Abnormal pore pressure: (p_a) equivalent to *geopressure;* an abnormally high pore pressure ($p_a > p_n$) for most authors. Strictly speaking subnormal pressures ($p_a < p_n$) are also abnormal. Beware of confusion.

Aquiclude: synonymous to *Seal,* permitting no fluid movement, about the only rock that qualifies is salt (and/or permafrost as a material of limited geological life).

Aquifer confined: a sediment (sequence) with the permeability of an aquifer but separated from the surface by an aquitard.

Aquifer unconfined: a sediment (sequence) of sufficient permeability to allow pressure equilibrium to be maintained over geological time spans which is connected to the surface.

Aquitard: a sediment (sequence) of such low permeability that fluid pressure equilibrium is retarded to the point where it does not take place over geological time spans.

Effective overburden stress: (σ_z) the fraction of the total overburden stress carried by the rock matrix.

Fluid flow restriction effectiveness: the degree to which fluid dissipation is precluded. A seal has a FFR effectiveness of 100%.

Geopressure: abnormally high pore fluid pressure. *Hard geopressure,* term used for very high geopressures, such as $\lambda > 0.8$.

Geopressure condition: a long lasting abnormal pore pressure situation that is maintained over geological time periods (million(s) of years) and may be directly observed.

Geopressure event: a short (even by human standards) pulse of abnormal pore pressure. Such events can only be deduced indirectly by observations of manifestations left in the geological record.

Geopressure generation effectiveness: the rate at which a certain process produces an excess pressure.

Geopressure generation efficiency: combining the rate of pressure generation with the severity of the flow restriction, the true measure for geopressure occurrence.

Hard geopressures: (see superpressures)

Indicated pressures: pressures deduced from log deviations or mud weights.

Isolation: refers to the time and/or depth at which an aquifer converts into an aquitard, i. e. retardation of fluid dissipation becomes effective. Isolation is always gradual and never perfect, except where salt is present.

Lithostatic pressure: used by some authors for total overburden stress.

Measured pressures: pressures determined during drill stem tests or reservoir shut-in observations.

Migrated geopressures: allochthonous geopressures that have propagated through permeability channels (faults, aquifers) from their place of origin into higher levels.

Normal pore pressure: (p_n) a subsurface fluid pressure equivalent to that found in an unconfined aquifer. A standard of reference rather than a common condition.

Petrostatic pressure: used by some authors for total overburden stress.

Pore pressure: synonymous with formation fluid pressure and fluid pressure.

Pressure-depth ratio (PDR): (p_j/z_j), a sort of an average pressure gradient ($\overline{\Delta p/\Delta z}$).

Pressure gradient: (dp/dz) the first derivative of the pressure-depth curve.

Pressure Ratio: (p_a/p_n) ratio of actual pressure to normal pressure.

Stress relief factor: the ratio of pore pressure to total overburden stress. The 'λ' of HUBBERT and RUBEY (1959, p. 142). A dimensionless parameter. Maximum value is unity in which case the rock is completely destressed and the overburden is in a state of floatation (TERZAGHI, 1950, p. 92). Minumum value for dry materials is zero. The pressure-depth ratio in psi/ft is numerically equivalent (or very close to) 'λ'.

Superpressures: very high geopressures, $\lambda > 0.8$

Total overburden stress (S_z): the sum of the effective overburden stress (σ_z) and the pore pressure (p). Since this term contains a stress component it should not be referred to as a pressure.

Total overburden load: used by some authors for total overburden stress.

Transplanted geopressures: geopressures moved to a different depth level by uplift and erosion.

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