EXAMINATION OF OVERPRESSURE RESERVOIRS IN THE SOUTHERN GREAT HUNGARIAN PLAIN: A CLASSIFICATION OF THE CAUSES OF OVERPRESSURE

A. SOMFAI

INTRODUCTION

The experience of drilling oil- and gas-wells, the spectacular oil- and gas-blowouts of recent years as well as the pressures measured during formation-testing have proved convincingly that the pressure of reservoir fluids is higher than the hydrostatic pressure. The knowledge of *„reservoir pressure"* is important for designing optimum drilling mud technology, casing program and well completion, for calculating the oil-and-gas reserves as well as for the design of optimum exploitation, etc. If reservoir pressure can be characterized by overpressure, which is though not the general rule, but which occurs more and more frequently with the spread of deep and super-deep drilling, then its recognition and eventual forecasting are of very great significance (beside the above considerations) for preventing any upset of borehole equilibrium. This will certainly have substantial economic effect, being necessary for safe well-drilling.

During wildcatting in unknown structures one has to know the causes responsible for the development of overpressures and the results of preliminary geophysical and geological exploration of the area.

In the present paper the author seeks to make use of his experiences, both direct and indirect, in connection with the overpressure reservoirs of the southern Great Hungarian Plain and the laboratory analyses of rock and fluid samples from the territory, in order to summarize the theories which are to be taken into account under the conditions existing in Hungary.

The tests and conclusions as well as the basic information utilized refer primarily to the Algyő deposit. However, they can be extended to a number of Hungarian compaction structures as well.

GEOLOGICAL SETTING

The *"core"* of the compaction structures under consideration is formed by a relative elevation of the pre-Tertiary basement. This is made up of Paleozoic (metamorphic schists, granites, quartz porphyry, etc.) or Mezozoic rocks (marl-shale, limestone, dolomite, etc.), as a rule, heavily affected by tectonic deformation or of intensively folded Upper Cretaceous to Paleogene flyschoidal sediments (marls, clay-marls, sandstones, conglomerates, etc.). In many places — usually at the limbs of the structure — the basement is unconformably overlain by a Miocene sequence of varied lithology (sandstones, conglomerates, marls, tuffs, limestones, etc.) which fills up the deeper basin portions in a spotted or zonal pattern.

The Lower Pannonian sequence locally begins with a so-called *"basal conglomerate"* consisting of basement rocks and this is covered by calcareous marls usually a few metres, eventually several tens of metres thick. The sandstones of the next sequence consisting of clay-marls and sandstones are quantitatively subordinate (accounting for about 20% of the sequence). In fact, they are totally absent in some places (Szank, Ásotthalom). They are characterized by the lack of sorting, high clay content, usually low porosity and permeability, relative changes of facies grading into marls and by the lenticular occurrence of the sandstones. In the clay-marls illite predominates over montmorillonite. Since the finer-grained sediments are more liable to compaction than the coarser ones, the Lower Pannonian sediments show a more advanced stage of compaction and their adjusting to the morphology of the structure-forming basement "core" is — because of the predominant clay content and the higher pressure of the overburden — substantially more pronounced than it is the case with the Upper Pannonian sediments. Consequently, the dip of the strata of this structure shows a gradual upward decrease.

The Upper Pannonian sequence is constituted predominantly by a frequent alteration of sandstones, clay-marls and siltstones. In the Upper Pannonian the sand content is substantially higher and the so-called *"pure sandstones"*, more sorted, poor in clay, rather porous and permeable, occur more frequently. The succession and connection of the sequence consisting of sandstones and clay-marls and their transitions are such as they do not form any hydrocarbon trap or reservoir structure of regional extension, as they pinch out within rather small distances and show an intricate pattern of intertonguing. Thus in respect of the comparatively large lenses, it cannot be found out whether it is the sandstones that form intercalations in clay-marls or vice versa? This conclusion is crucial for oil geology, as it means that — even though in the Upper Pannonian several reservoirs, separated from one another by impervious layers, can form a vertical succession within one structure and though the reservoirs may include such oil- and gas-pools which may be considered independent hydrodynamic units — these latter are nevertheless hydraulically interconnected in some intricate way and this hydraulical connection is traceable up to the surface. The Upper Pannonian beds too are adjusted to some extent to the morphology of the basement, though their curvature is smaller than that of the Lower Pannonian sediments. Their position is closer to the horizontal, for their compaction is also lower. The Quaternary sediments form a sequence of sandstones, clays and siltstones. These being of little significance from the point of view of oil- and gas accumulations, there is no use discussing them here in detail.

RESERVOIR PRESSURE

The fluids (water, oil, gas) are situated in the pores (possibly fissures or caverns) of the reservoir rock. To denote its pressure the term *"reservoir pressure"* has been proposed.

As regards such terms as "*bed pressure*" (referring just to the pressure of the hydrocarbon-bearing body) or "*formation pressure*" or "*strata pressure*" or even "*overburden pressure*", etc., none of them does cover the notion more satisfactorily, for the notion of reservoir pressure can be extended to include the pressure value of any bed or formation occurring within the reservoir structure.

In the compaction structures of the southern Great Hungarian Plain the reservoir pressure is hydrostatic in the Upper Pannonian and Quaternary sediments which are in the state of "*pressure equilibrium*".

Hydrostatic pressure means that the pressure of the reservoir being considered is equal to the pressure of water column corresponding to the vertical distance between the piezometric surface and the depth of the reservoir in pressure equilibrium. Consequently, the value of formation pressure results from the potential energy of the water-bearing sequence. The specific weight of the water column is defined by the average specific weight of the aquifers as calculated with regard to the temperature of the sedimentary sequence. In the Great Hungarian Plain the piezometric surface corresponds approximately to the surface of sediment.

Pressure gradient:

$$\frac{P\ (\mathrm{at})}{H\ (\mathrm{m})},$$

is the ratio of reservoir pressure to the depth of the reservoir (vertical distance between the rock surface or piezometric surface and the virtual (observed) position of the reservoir, i. e. the rise in pressure corresponding to 1 m depth increment.

In case of hydrostatic pressure the pressure gradient will vary between 0.1 and 0.108 atm/m in dependence on the density and temperature of water contained in the sedimentary sequence.

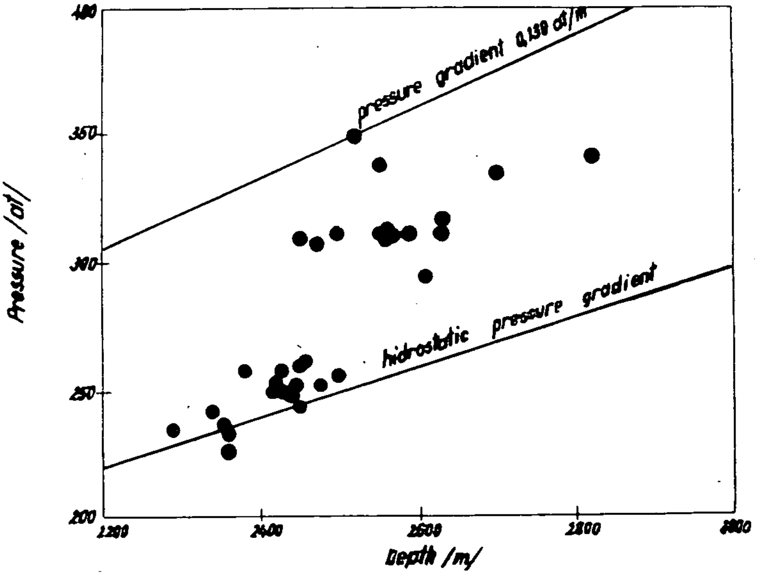

Fig. 1. Pressures measured in the Lower Pannonian sandstone reservoirs of Algyő, varying between the hydrostatic pressure and the pressure gradient 0.130 atm/m.

In some of the structures explored in the southern Great Hungarian Plain, in pre-Upper Pannonian Neogene sediments, pressure values differing from the hydrostatic pressure, i. e. a rise in the pressure gradient, can be measured. For instance, for the oil-water interface of the basal conglomerates at Algyő, a pressure gradient of 0.124 atm/m was calculated, while the maximum obtained for the gas cap of the same bed was 0.130 atm/m. The Lower Pannonian sandstone reservoirs show a pressure gradient attaining a maximum of 0.110 to 0.115 atm/m. The measured pressures are shown in *Fig. 1.*

At Szank, the pressure gradient within a Miocene bed varies between 0.130 and 0.140 atm/m, whereas in the gas reservoir of the Tortonian conglome-

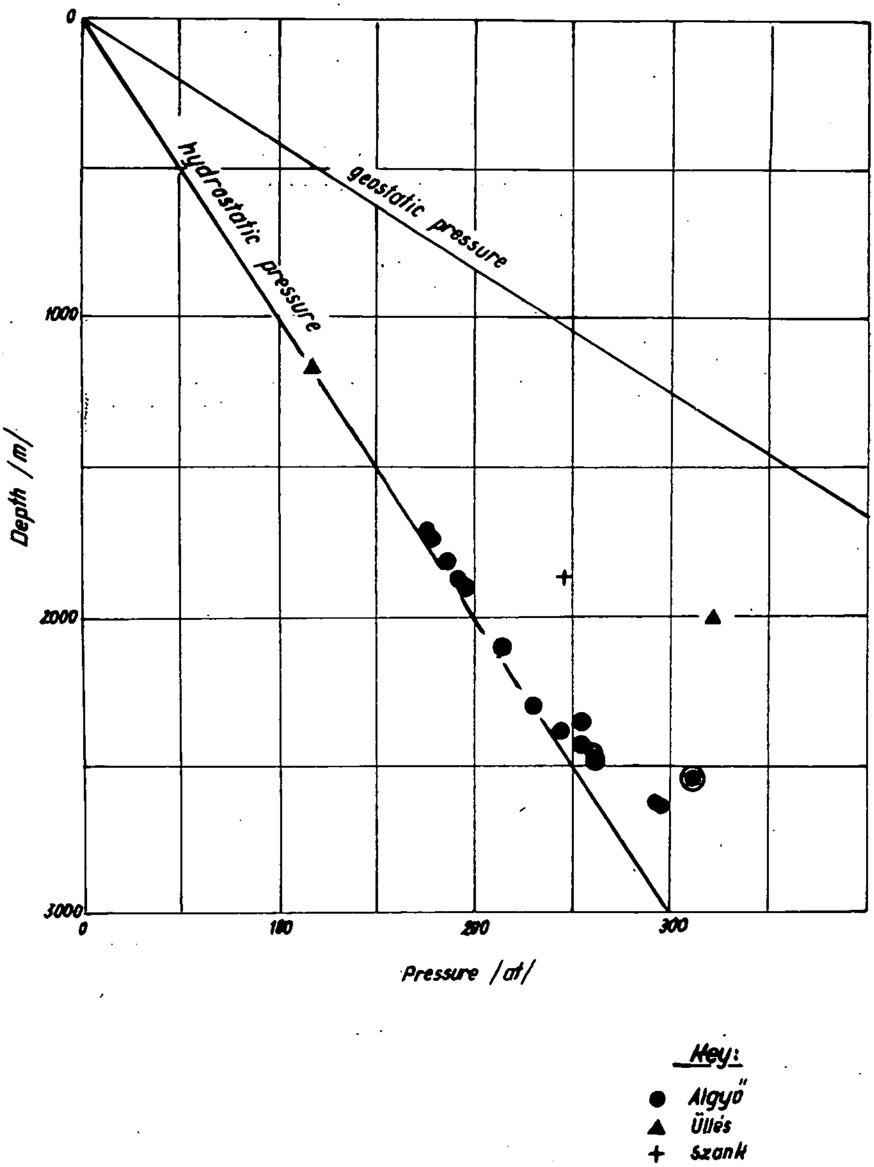

Fig. 2. Pressure versus depth of the overpressure reservoirs of Algyő, Üllés and Szank, southern Great Hungarian Plain, as compared with the hydrostatic and geostatic pressure gradients.

rates at Üllés, at 2,002 m depth, a formation pressure of 322 atm was measured, a value indicating the presence of a pressure gradient of 0.161 atm/m. In *Fig. 2* a few characteristic pressure values of the afore-mentioned areas are shown.

The figure shows a straight line corresponding to the hydrostatic pressure values and the line of the geostatic pressure gradient, indicating the overburden pressure values at particular depths.

(Geostatic pressure is also called overburden pressure or formation pressure. Its gradient equals about 0.23 atm/m.)

When the pressure of a reservoir exceeds the hydrostatic value, the reservoir is considered to have *overpressure*. Consequently, overpressure means that the pressure of the reservoir is higher than the pressure of the water column corresponding to the vertical distance between the land surface and the depth of the reservoir.

Overpressure is often given in terms of percentages, this being a value equalling thousandfold pressure gradient minus 100. For instance, at Üllés: (0.161×1000) — 100=61%.

None of the reservoir beds of the Algyő structure does show a fluid pressure lower than the hydrostatic value. Prospectors of hydrocarbons in Hungary encountered in a number of cases the so-called *"iszapveszteséges réteg"* (a bed characterized by significant losses of drilling mud) which can be easily confused with reservoirs referred to as *"of low pressure"* or *"of unsatisfactory pressure"*, *"of subnormal pressure"*, etc. In this connection the following observations should be made. On one hand, because of the fracturing, natural or artifical, of the reservoir, its caverned structure, low degree of consolidation or *"rough permeability"*, the rock may be liable to lose drilling mud even in case of hydrostatic reservoir pressure or possibly even at overpressure. On the other hand, not even the strata *"of unsatisfactory pressure"* must show mud losses.

Unsatisfactory pressure means that the pressure of the reservoir is lower than the pressure of the water column corresponding to the vertical distance between land surface and reservoir depth.

THE ORIGIN OF OVERPRESSURES AND DESCRIPTION OF THE RESERVOIRS

Of the overpressure reservoirs, first of all, the Lower Pannonian conglomerates are to be considered; it is they that show the highest pressure gradient and that contain a gas reservoir of great industrial value, bordered by a thin oil-bearing layer. The basal conglomerates consist of white-grey, unconsolidated quartz and metamorphite debris cemented by calcium carbonate, silt or sandstone particles. They rest immediately on a Paleozoic basement, fractured, heavily affected by tectonic strains. In *Fig. 3* the countour-map of the Paleozoic surface, in *Fig. 4* the map of the upper surface of the conglomerates are shown. Seemingly of transgressive origin, the conglomerates surround the basement high in a collarlike pattern, as illustrated by *Fig. 5* plotted axonometrically. As evident from the picture drawn with a vertical scale of fivefold exaggeration, the conglomerates vary in thickness and extend little, if any, below the 2,900 m depth limit. In the deeper horizons they thin and then pinch out. However, they do not extend above the 2,400 m subsurface level, either, being absent there too. Consequently, the Lower Pannonian basal conglomerates, lying between the impermeable basement and the hanging calcareous marls or clay-marls, represent a closed lens or, rather, ring which is isolated from the overlying Lower Pannonian sandstones. According to present-day evidence, they are not interconnected with the Miocene rocks uncovered in the deeper limb portions, either. By the way, a connection of this kind would — as evidenced clearly by later parts of this paper — just widen the scope of the isolated system, and even though it would imply a common pressure system for the two formations, it would not modify the results presented here.

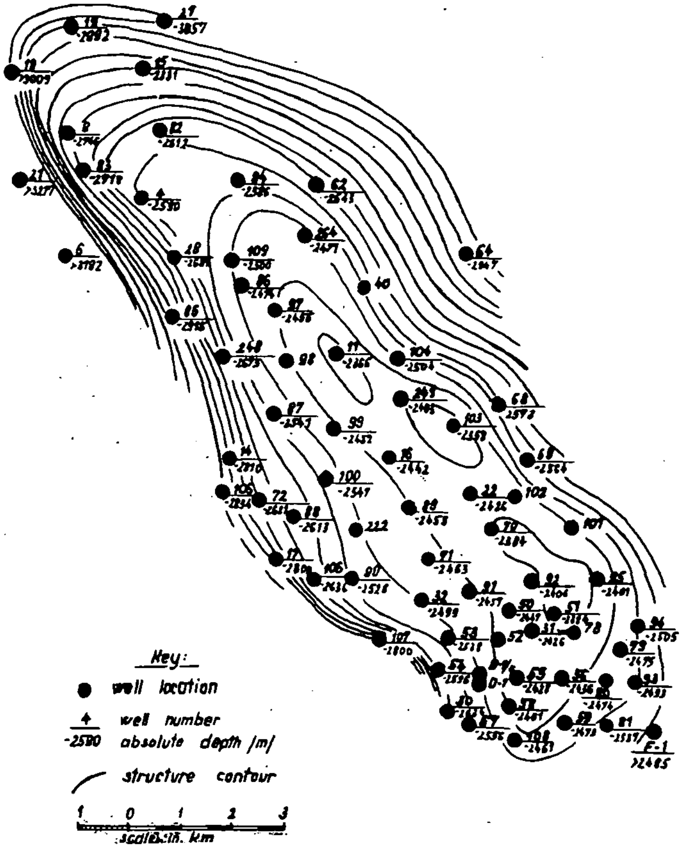

Fig. 3. Contour map of the surface of the Paleozoic basement of Algyő with indication of borehole locations.

Like the basal conglomerates, the Lower Pannonian sandstones of higher structural position can also be interpreted as such closed reservoirs which either grade into marls or pinch out within smaller or greater distances. In the Lower Pannonian some of the sandstone reservoirs can be shown convincingly (by data of drilling) to pinch out in certain direction still within the wild-cat area, while in the near-by Ásotthalom or Szank areas the Lower Pannonian does not include a single sandstone layer.

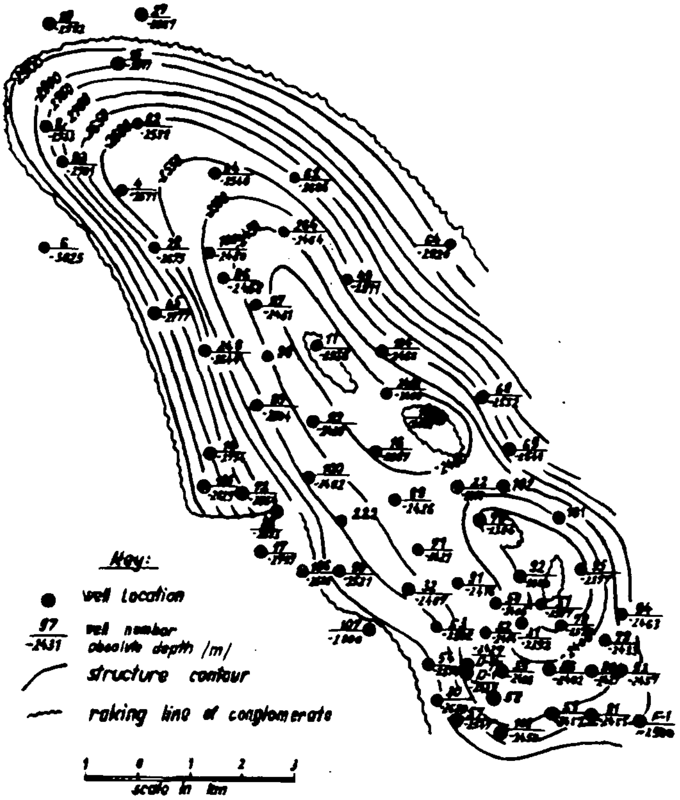

Fig. 4. Map of the upper surface of the Lower Pannonian basal conglomerates at Algyő. Wavy line indicates the limit of pinching out.

It can be stated unequivocally here that, unlike in the case of the Upper Pannonian, it is the sandstone layers that are interbedded within the clay-marl sequence rather than clay-marls within sandstones. (Of course, this regional interpretation does not preclude the possibility that sandstones may also include clay-marl intercalations.)

DIAGENESIS OF CLAYEY SEDIMENTS

Since overpressure reservoirs are always connected with sedimentary sequences of extremely high clay content, it seems to be logical that the examination of the characteristics of clays or clay minerals and their diagenetical changes is most important for the tracing of the origin of the pressure in overpressure reservoirs.

Diagenesis is controlled by four factors:

- the depth of burial (overburden pressure),
- the activity of the essential ions,
- the geothermal gradient and,
- the time factor.

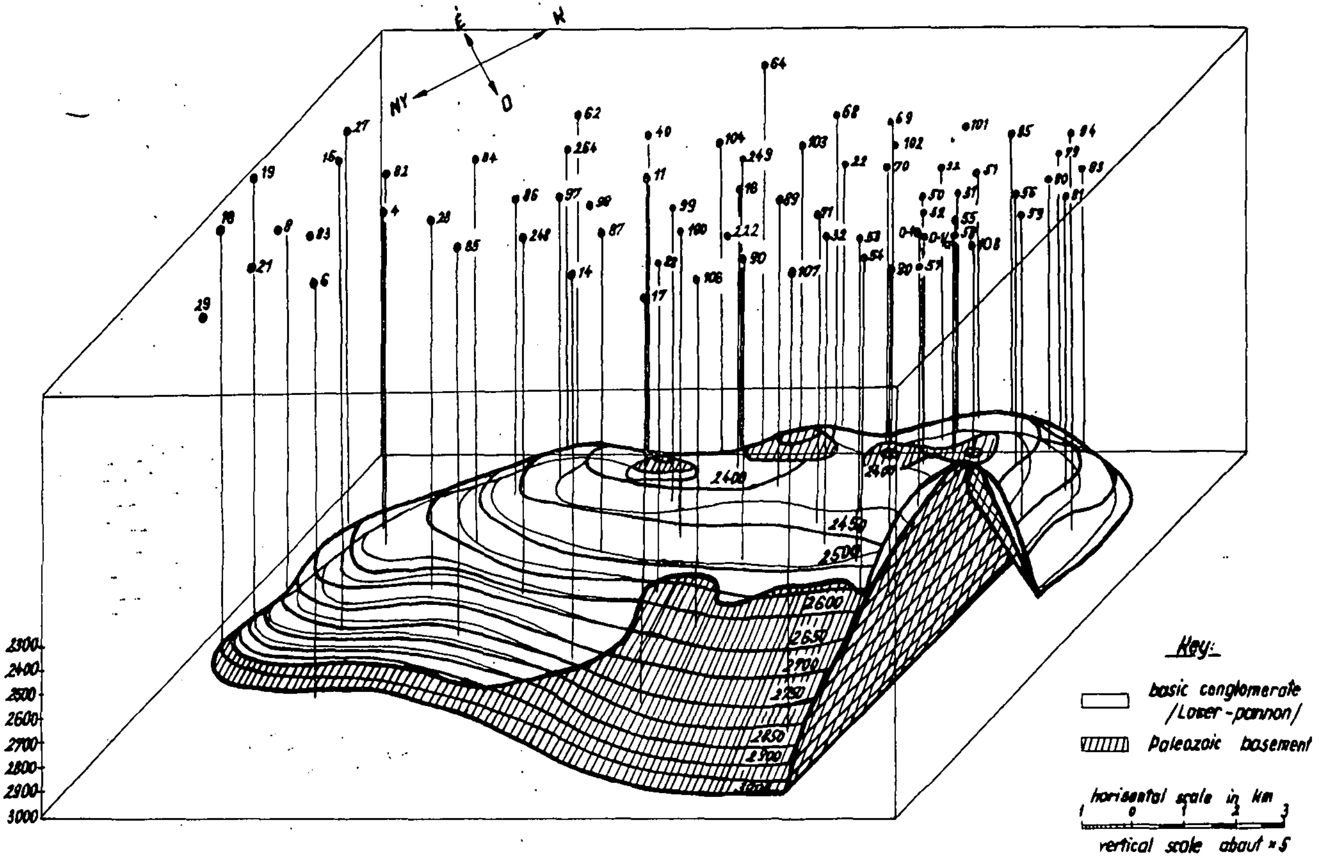

Fig. 5. The extension, line of pinching out and thickness of the conglomerates, resting on the pre-Tertiary basement, are illustrated by an axonometric diagram (in places of intersection the locations of boreholes are also shown).

The clay flakes deposited in the Pannonian inland sea or lake were initially converted into a gel extremely abundant in water. Their original water content equalled 50%. With increasing depth of burial the materials began to release water. Under the effect of compaction, down to 600 — 800 m depth, the material lost most of its water content. Thus water content decreased to about 20 to 30% *(first dehydration phase).* The water content of clays is dependent upon the properties of the clay minerals present. Expanding clay minerals can adsorb much more water than it is the case with non-expanding ones. Despite the rise in pressure with increasing depth of burial, the water film of 4-molecule thickness, adsorbed to the surface of expanding montmorillonite particles, will not be removed. Nearly 50% of the volume of montmorillonite are bonded water [STEINFINK—GEBHARDT—OLPHEN]. There are two ways for removing hydration water: by electrostatic force or by heating.

Under the effect of *electrostatic attraction,* the capturing of calcium leads to desorption, so that montmorillanite develops into illite. In doing so, it releases again much of its water. According to BURST, POWERS and WEAVER, this process sets in usually at 1500 to 1800 m depth and after a gradual increase, it ceases at 2700 to 3000 or a maximum of 3600 m depth. Consequently, below this depth limit there is no montmorillonite anymore. This is the upper limit of the so-called *"montmorillonite-free horizon".*

When montmorillonite alters into illite, the water on the crystal faces is desorbed and introduced into the interstices of the grains. The faces get closer to one another. Thus the volume of the individual particles will be reduced, whereas effective porosity and permeability will increase. Because of the rise in pressure provoked by the weight of the overburden, interstitial water will be displaced from the material. The quantity of released water will be approximately equal to the half of the volume of altered montmorillonite.

Consequently, the alteration of montmorillonite into illite will provoke changes in the porosity, permeability and interstitial water content of the sediments. Water content is increased by the fact that, at the innermost water molecule layer, the density of the water hydrated on the montmorillanite faces is higher than normally. (As shown by recent results in crystal chemistry, it may attain even the value of 1.7 g per cm^3.) The average density of the last four water films is 1.4 g per cm^3. In the case of interstitial water, this value is 1.0 g per cm^3 which corresponds to a 40% increase in water volume.

The virtual increase of water, i. e. the history of compaction of clay sediments, is of course dependent on the quantitative ratio of expanding clays to the rest of the clay minerals.

On the basis of the qualitative testing of the pelitic fraction of the Algyő structure the role montmorillonite may have played in the compaction of clay sediments cannot be assessed in quantitative terms.

At closer scrutiny, the problem proves to be even more complicated. In fact, since in Late Pannonian time the conditions for the formation of montmorillonite were substantially more favourable than they were in Early Pannonian time, the quantity of still unaltered montmorillonite available in the Upper Pannonian sediments cannot be used for any conclusion as to the original montmorillonite content of Lower Pannonian clays. However, the present-day montmorillonite content of the Lower Pannonian sediments can be regarded only as a "residue" which escaped illitization — again a result which does not provide any indication of the original quantitative proportions. However, in

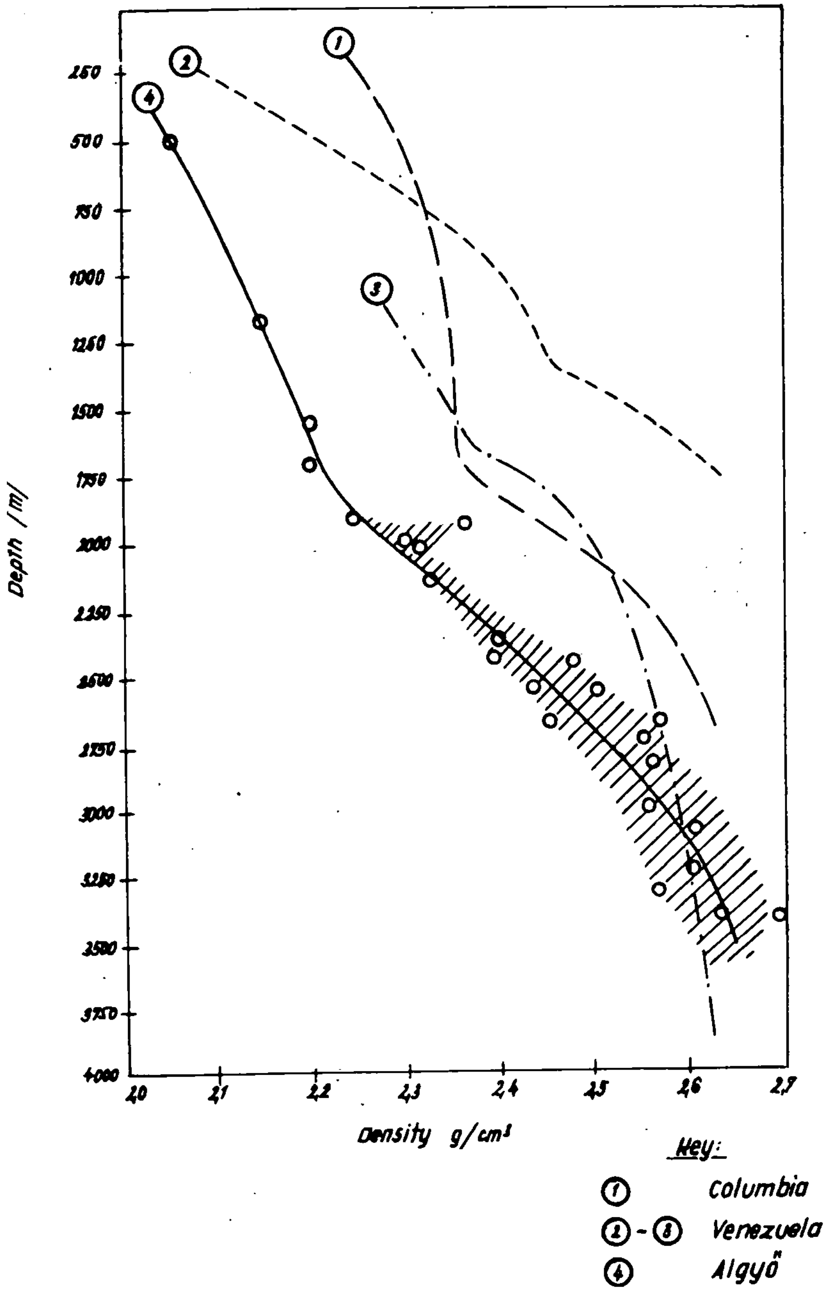

Fig. 6. Clay density versus depth in the Algyő structure as compared with data from other areas.

Early Pannonian time the conditions were favourable for montmorillonitization, so the montmorillonite content can be supposed to have been considerable initially. Summarizing the above, let us conclude that during burial montmorillonite develops into illite according to the above process and this causes an increase in water amount. This can be considered a fact also in examining the Algyő structure, and what still remains a question is to know the size of this water increase — a question to be answered by further testing of clay minerals. Increasing porosity due to alteration will lead to a decrease of clay density. *Fig. 6* illustrates the density of Algyő clays as a function of depth. Just like in the case of the comparative curves, it is at about 1750 m that a characteristic change in density can be observed.

Dehydration may also occur when the uptake of heat due to burial becomes so high that it mobilizes the water molecules according to the following formula:

$$M(H_2O)x + \Delta H \rightarrow M + xH_2O$$

where

$M(H_2O)x$ = the hydrated clay mineral,
ΔH = the absorbed heat (dehydration energy),
M = the dehydrated clay mineral.

Temperature of the sediments

The few temperature values measured in the wells of the Algyő structure are given in Table 1.

TABLE 1

Well number	Depth (m)	Temperature (°C)	Well number	Depth (m)	Temperature (°C)
3	1800	98	47	1713	91
4	2422	142	50	2325	118
4	2012	97	53	2122	112
8	2919	140	56	2300	123
14	2352	120	57	2601	135
16	2513	133	69	2625	140
16	1765	95	81	2550	137
21	3206	156	82	2406	124
21	2118	105	247	1940	97
28	2435	121	264	1838	95
31	2539	134	268	2025	96,5

As evident from *Fig. 7* plotted from the data of the tabulation, the geothermal gradient of the area is < 20 m/°C almost everywhere. Surprizingly enough, the characteristic GGA curve shows a break at point P. A general phenomenon in the Great Hungarian Plain, this change in gradient takes place on the boundary between the Lower and Upper Pannonian. With a view to earlier statements concerning the geology of the area and to the following considerations, the causes of phenomenon can be accounted for as follows. Heat transfer through water-saturated sediments is possible in 3 different ways:

- by the flow of interstitial fluids,
- through the mineral grains of the rock skeleton,
- by heat emission.

On account of the closing effect of the thick clay marls of the Lower Pannonian sequence, the possibility of any upward vertical heat transfer by flow of fluids is precluded, the possible agents of this kind being thermal conductivity and heat emission by the mineral grains of the rock skeleton. Therefore the hanging wall and the foot-wall of the reservoirs become *"overheated"*. Overheating promotes dehydration of montmorillonite which leads to an increase of porosity and, at the same time, to the reduction of thermal conductivity, so that overheating will increase. Since in the Upper Pannonian the continuous hydraulic interconnection of the reservoirs extends up to the surface, it is not only the thermal conductivity of the rock and heat emmission but also the flow of the fluids that are involved in heat transfer. For the setting-in of flow with heat transfer, a difference in temperature is necessary. Movements will increase if a heat-induced change in fluid density brings about a buoyant force. Thus the heat reaching up to the Upper Pannonian formation is unable to accumulate at the same rate as it is in the Lower Pannonian. In other words, a considerable part of heat will *"be wasted"*, so that a remarkable decrease of temperature occurs within the Upper Pannonian, a decrease beginning with the Lower/Upper Pannonian boundary. The loss of the hydration water of montmorillonite owing to the illitization of montmorillonite and/or to heating is characteristic of the so-called *second dehydration phase.* The last stage of dehydration, when residual water is released

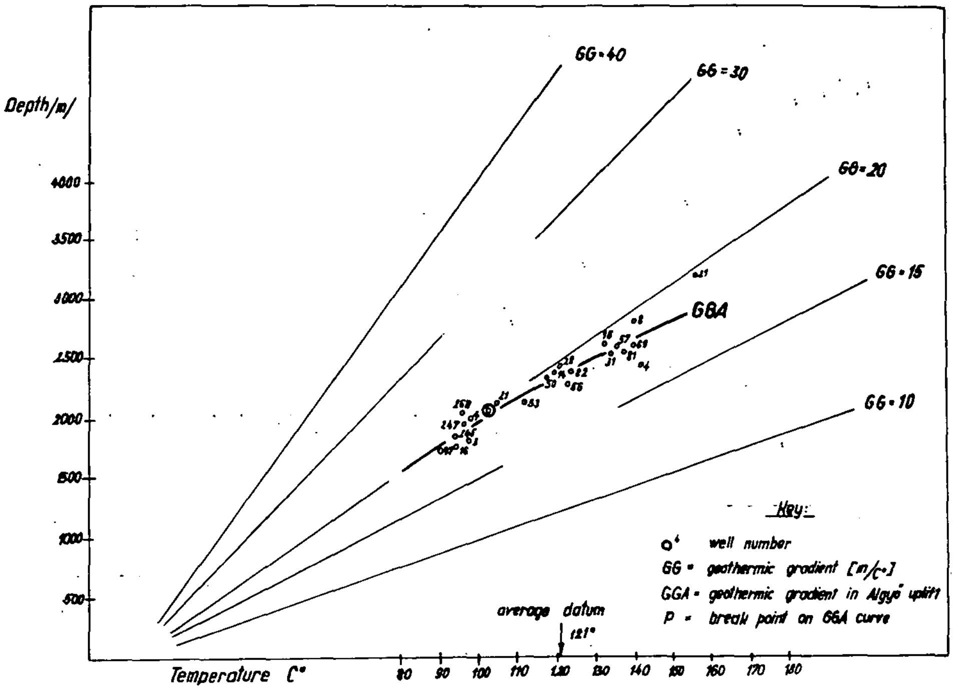

Fig. 7. Geothermal gradient characteristic of the Algyő structure. Break in the gradient is indicated by "P".

from clay lattice, appears to develop very slowly, during 10, or possibly 100, million years in dependence on the conditions of burial and the temperature regime. This is the *third dehydration phase.*

Osmosis

It is the third dehydration phase that is most responsible for development of overpressure. Nota bene, though considered to be impervious layers, clays have still some permeability in respect of water. If this were not the case, no compaction could take place. There is no reliable evidence of clay permeability, which can be explained by the possibly non-Newtonian behaviour of water in the pores of clays. As shown by recent observations, the clay and clay-marl layers separating the reservoirs act as semi-permeable films, inducing osmotic pressure between reservoirs containing solutions of different salt concentration.

Well-known is the case when in a natural environment the pressure difference on the two sides of a clay layer was higher than 250 atm [P. M. Jones]. It is plausible that fluid pressure of osmotic origin may exceed the weight of overburden and provoke fracturing or folding of the reservoir. This holds true especially of those places where the load-carrying capacity of clays is reduced by the increase of interstitial water content as a result of the removal of hydration water.

Osmotic pressure across a semi-permeable clay layer is defined by the contrast of salinity in the waters separated. In Table 2 the pressures of a few Neogene hydrocarbon reservoirs and the salt contents of their marginal waters are shown.

Table 2

	Name and age of reservoir	Place (m)	Value (atm)	Over-pressure (%)	Total salinity of marginal waters (ppm)
		of measured pressure			
UP	Szőreg—1	1847	183.56	0	4072.89
	Szeged—1	1933	187.5	0	5093.63
	Algyő—2	1934	193.9	0	4966.16
	Algyő—1	1943	193.94	0	4250.00
LP	Algyő—III.	2351	236.72	0	5544.00
	Algyő—IV.	2442	259.6	7	6713.80
	Algyő Basal conglomerate	2506	310.3	24	11519.04
UP	Üllés sandstone	1126	111.5	0	2805.81
Miocene	Üllés conglomerate	2002	322.0	61	30980.00
Miocene	Szank conglomerate	1880	247.0	31	17348.06

Accordingly, at Algyő the salinity of the Upper Pannonian reservoirs of hydrostatic pressure varies between 4000 and 5000 ppm. In the Lower Pannonian, Reservoir III, where the salinity of marginal waters is about 5500 ppm, there is no overpressure yet. The salinity of the reservoir containing Bed IV is considerably higher, about 6700 ppm, whereas the overpressure of the bed amounts to 7%. The contrast in salinity and overpressure between the Lower

Pannonian sandstones and basal conglomerates is yet sharper, as the total salinity of the water in the conglomerate is as high as 11 500 ppm, a property associated with an overpressure of about 24%. On the basis of the above, it seems to be quite natural that in the Miocene of Szank of 17 000 ppm salinity the value of overpressure is about 31% and that in the Miocene conglomerates of Üllés characterizable by even higher salinity this figure is as high as 61%.

Consequently, the origin of pressure can be readily traced back to osmosis due to contrast in salinity, provided that the other conditions discussed above are granted. (However, not all highly saline reservoirs must be pregnant with overpressure!)

Owing to the lack of fluid communication in the Lower Pannonian sandstones, the formation pressures of the deeper-seated beds should — unlike the case of hydrostatic reservoirs — not be necessarily higher than that of the beds of higher structural position. That the pressure in the higher horizons of the Lower Pannonian is yet lower can be readly explained, for because of the grading of saline water into freshwater in the higher horizons, both salinity and osmotic pressure are lower.

Statements

The Pannonian sediments were deposited and buried at a quick pace.

As a rule, pre-Upper Pannonian Neogene reservoirs are closed "lenses", lacking any continuous intercommunication with one another.

The sediments seem to have had a high montmorillonite content.

Below the 600—800 m depth limit, montmorillonite does preserve nothing but its hydration water.

The pressure of the overburden is not sufficient for dehydrating hydration water.

Within the depth range of about 1,800 to 3,600 m montmorillonite develops into illite and much of the strictly bonded water becomes interstitial water.

Dehydration of bonded water takes places at a temperature as low as 110 °C or so.

The temperature of the sediments increases with the depth of burial.

In the Lower Pannonian the geothermal gradient shows a considerable increase, so that dehydration increases.

Production of interstitial water by dehydration and diagenesis of montmorillonite is conducive to an increase of the porosity and permeability of the clay layer and, consequently, to a reduction of its density, load-carrying capacity and heat transfer. Dehydration is associated with the growth of water volume, for the density of water is reduced from the average, 1.4 g per cm^3, to 1.0 g per cm^3.

The salinity of waters in the Lower Pannonian conglomerates and the Miocene sequence increases with depth by leaps and bounds.

If the adjacent reservoirs separated by a clay layer contain waters of different salinity, a pressure difference can be induced by osmosis, a process during which the clay layer acts as a semi-permeable film.

The weight of the overburden brings about compression in the unconsolidated sediments. If the rock skeleton is not strong enough to take up the entire load, a part of geostatic pressure will be kept by the fluids.

Summary

The Miocene reservoirs resting on the basement, i. e. the presumably transgressive Pannonian basal conglomerates and the Lower Pannonian sandstones characterized by hiatuses due to rapid sedimentation and unsteady subsidence, are separated by thick clay sediments. So there is no continuous fluid communication between them. On account of the increasing weight of the overburden, the uncompacted clays released their water which passed over into the interbedded conglomerates and sands where water was flowing toward spaces of lower pressure. In the reservoirs pinching out, the pressure increased rapidly, to attain a value at which the waters of the reservoirs were squeezed across the overlying clays. This slow upward flow was gradually decreasing in rate, as the osmotic force resisted the process. The plastic clay layers behaved as semi-permeable films or *"ion sieves"*. Letting the water flow through, they blocked the movement of the ionized substances in solution. Thus in the deeper horizons an increase of salinity occurred, a phenomenon which was associated with the leaching of saline waters occurring in the so-called *"zone of volatilization"*. (Nota bene, these horizons were supplied with *"salt-free"* water from the formations underneath.) This phenomenon took place in hydrostatic reservoirs. Osmotic pressure, which was oriented toward the salt-water reservoir, could resist the attacking stresses and thus prevent water from being removed. After a gradual increase it finally reached the value of equilibrium with the outward-acting reservoir pressure, so that the water stopped flowing through the clay layer.

During burial, under the effect of the increasing weight of the overburden, the afore-mentioned pressure equilibrium may have been upset and again a flow may have set in until a new pressure equilibrium was reached. Since in the Lower Pannonian sediments the upward flow of water was hindered by an upward heat flow, it decreased greatly and the reservoirs became overheated. With increasing reservoir temperature, vapour pressure increased, while the density and viscosity of the water diminished. Osmotic pressure became stronger.

Thermal dehydration of montmorillonite, or its alteration into illite with the bonding of potassium, resulted in interstitial water which was equal in volume to the altered montmorillonite. Under the increasing weight of rock, the resulting water was again squeezed from the clay into the reservoirs. This resulted in a little decrease in salinity, but the surplus water volume, which was further increased by the volume increase due to the decrease of water density, went on growing and led to higher reservoirs pressure. Pressure equilibrium began to be re-established. The water squeezed through the clay layers could be accompanied only by dissolved solid substances and gases. As a result of the pressure decrease and chemical reaction, carbonates and silicates precipitated in the upper part of the hanging clay formation, thereby facilitating the closure of the overpressure reservoir. This fact accounts for the comparatively high density and poor drilling characteristics observed in the clays closing up the overpressure reservoirs.

Accordingly, the increased volume of the reservoirs and the osmotic pressure produced by molecular forces as well as mechanical compression brought about an overpressure; at the same time, because of the precipitation of solids the virtual permeability of the overburden decreased practically to zero and thus preserved overpressure for millions of years.

Should one extrapolate the genetic interpretation of overpressure in the reservoirs of the Algyő structure to the Szank and Üllés areas, this would not preclude the possibility that the origin of other overpressure reservoirs to be explored in Hungary may be traced back to different causes.

Overpressure reservoirs forming closed systems

Theoretically, the overpressure reservoirs are closed systems of definite, constant volume.

Three causes of the closure of reservoirs are known to exist:

- pinching out,
- changes in lithology (eventually, cementation),
- faulting (eventually, block-faulting).

Mechanical compression can also produce overpressure within a closed system, as observable during compaction in unconsolidated rocks. If the contacting mineral grains, making up the rock skeleton of the reservoirs and behaving like *"supporting pillars"* carrying the sedimentary overburden, are unable to bear the increasing load or if they are suddenly attacked by tectonic stresses, the void volume will diminish and/or a part of the formation pressure will be transmitted to the void-filling fluids, becoming fluid pressure. Accordingly, in the procces of consolidation:

overburden pressure + fluid pressure = geostatic pressure.

The less graded the material of the reservoir, i. e. the higher its clay content, the more it is liable to diminish its void volume. Squeezing of clays into the pores (voids) under the effect of the pressure of sand grains may diminish permeability or render the material impervious.

Deformation of quartz grains and their subsolution at the contacts in deep burial produces a marked decrease in porosity even in sorted sandstones. The number of contact points increases with depth, the sand grains tend to be evenly distributed under the load.

If lateral pressure is also involved in mechanical compression (e. g. due to orogenesis), then overpressure can substantially exceed the geostatic value and the upper pressure limit is defined by the resistance of the strata in absence of fractures, faults or slips.

Osmotic pressure develops between reservoirs of different salinity. The separating clay layer behaves as a semi-permeable film. The sharper the contrast in salinity between the waters of the two reservoirs, the higher the resulting pressure difference.

Joints action of both mechanical compression and osmotic pressure brings about such a fluid pressure in which the combined effect of the osmotic pressure and geostatic pressure is diminished solely by the load taken up by the rock skeleton:

Fluid pressure = osmotic pressure + geostatic pressure = overburden pressure
or, respectively,
geostatic pressure = fluid pressure + overburden pressure = osmotic pressure

Changes of temperature in fluids provoke essentially greater volume changes than it is the case with temperature rise in rocks.

Thus the pressure of the reservoirs will increase. (The thermal expansion of sandstones is $[30 \pm 6] \cdot 10^{-6}$ or so, that of oil, water and gas being well-known.)

Chemical, physico-chemical changes

In reservoirs the original minerals may be dissolved and recrystallized; non-ionized solid particles may get into the pores of sandstones in the course of vertical percolation during compaction. Thus the void volume may be decreased by the cementing material and salt precipitations, a phenomenon conducive to pressure increase. Polymerization of hydrocarbons consisting of comparatively larger molecules may result from bacterial or catalytic reactions, radioactive decay or changes in temperature, phenomena which can also increase the reservoir pressure.

Communication with a reservoir of higher pressure

Upon tectonic stresses or in other ways, a reservoir closed at its top may come into communication with a deeper-seated oil- or gas body of higher pressure. If the channelways between that body and the reservoir (channelways which may later be clogged) are filled up by gas or oil, the upper reservoir may develop into an overpressure pool which preserves its overpressure for a long time even in terms of the geological time scale. Fluid movement between the two beds will persist as long as $P_a > (P_f + h\varrho)$, where

P_a = the pressure of the lower reservoir,
P_f = the pressure of the upper reservoir,
h = the vertical distance between the two reservoirs,
ϱ = the density of the upward-flowing fluid.

The fluids will stop moving when

$$P_a - P_f = h\varrho$$

The variation of pressure depends on the relative volumes of the two reservoirs and on the volume of the communicating channelway.

Increase in water content in the reservoir is brought about by the illitization of montmorillonite and/or its thermal dehydration. The change of hydration water into interstitial water is accompanied by an increase in water volume due to the expansion of water from the average value, 1.4 g per cm^3, to 1.0 g per cm^3.

Changes in the depth of burial

If a closed reservoir (which may originally have had a hydrostatic pressure and in which the pressure conditions do not change anymore) gets closer to the surface (e. g. as a result of denudation or uplift), the pressure gradient will increase and an overpressure set in.

Dynamic effects

Seismic waves (which caused numerous expansions and compressions in geological history), sea currents (tidal waves or, eventually transgressionregression), varying atmospheric pressures and the so-called *"vibrators"* affect the reservoirs with some delay. Thus it is by compacting or even fracturing that they influence their pressure conditions. (Examples are known, where the yields of the oil-wells of certain areas showed sudden changes after earthquakes.)

Overpressure reservoirs of open system

In the overpressure systems discussed earlier, one of the basic conditions was to have *"closed"* reservoirs. However, such reservoirs are also known in which the pressure gradient is different from the normal despite the fact that fluid communication is continuous up to the land surface. It is advisable to call these: *"overpressure reservoirs of open system"*.

In case of great thickness the pressure gradient of the bed may be substantially higher than the hydrostatic value which can be measured in the marginal waters of the reservoir. In case of a gas-capped oil-bed the pressure P measured at depth H at the oil-water interface will produce a pressure gradient equalling P/H, which is of hydrostatic value if fluid communication with the surface is continuous. If the pressure is examined at the gas-oil interface, a lower value ($P - h_0\varrho_0$) will be obtained, in dependence on the thickness h_0 and density ϱ_0 of the oil body.

If the thickness of the gas cap is h_g and its average density ϱ_g, then at the top of the gas cap the following formula will be valid:

$$P - h_0 \cdot \varrho_0 - h_g \cdot \varrho_g$$

Thus, calculated for the gas-oil interface, the pressure gradient will be:

$$P - h_0 / h_g - \varrho_g$$

while at the top of the gas cap

$$P - h_0 \cdot \varrho_0 - h_g \cdot \varrho_g / H - h_0 - h_g$$

It is especially in mass reservoirs that such an increase in pressure gradient and the resulting overpressure may be significant. Therefore in the gas cap an overpressure (the value of which may be high) can be observed and it is only with a more detailed knowledge of the reservoir that one can point ou that the causes responsible for the phenomenon are other than pressure anomaly. Consequently, the pressure gradient within one reservoir is a function of depth and fluid density.

The overpressure due to great thickness is illustrated by the following example:

Data of the reservoir:

depth of water-oil interface (H) = 2000 m
thickness of oil body (h_0) = 100 m (10^4 cm)
thickness of gas body (h_g) = 200 m (2.10^4 cm)
depth of the top of gas cap ($H - h_0 - h_g$) = 1700 m
density of oil in the reservoir (ϱ_0) = 0.72 kg/dm^3 = $7.2 \cdot 10^{-4}$ kg/cm^3
density of gas in the reservoir (ϱ_g) = 180 mg/cm^3 = $1.8 \cdot 10^{-7}$ kg/cm^3.

Pressure values:

at the water-oil interface $(P) \cong 200\ \text{kg/cm}^2$
at the oil-gas interface $(P - h_0\varrho_0) \cong 200 - 10^4 \cdot 7.2 \cdot 10^{-4}$
$= 200 - 7.2 = 192.8\ \text{kg/cm}^2$
at the top of gas cap $P - h_0\varrho_0 - \varrho_g h_g) \cong$
$\cong 200 - 7.2 - 2 \cdot 10^4 \cdot 1.8 \cdot 10^{-7} =$
$= 200 - 7.2 - 3.6 \cdot 10^{-3} =$
$= 200 - 7.2 - 0.0036 =$
$= 192.7964\ \text{kg/cm}^2$,

since at the top of the gas cap (at 1700 m) the pressure is 192.79 kg/cm^3 instead of the hydrostatic value, 170 kg/cm^3, thus an overpressure of $13^0/_0$ or so will result.

Pressure gradient values:

at the water-oil interface $P / H = 200 / 2000 = 0.1$ at/m
at the oil-gas interface $P - h_0\varrho_0 / H - h_0 \cong$
$\cong 192.8 / 2000 - 100 \cong$
$\cong 0.101$ at/m
at the top of gas cap $P - h_0\varrho_0 - h_g\varrho_g / H - h_0 - h_g \cong$
$\cong 192.79 / 2000 - 100 - 200 \cong$
$\cong 0.113$ at/m.

Morphology may also be responsible for overpressure. In case of a rough land a system can develop, in which a continuous fluid communication with the surface is granted, but because of the incision of a deep valley the piezometric level does not coincide with the surface of sediment. Since the hydraulic head of the water percolating in the reservoir corresponds to the value of the piezometric level, it is obvious that wherever the surface sinks below the piezometric level, an overpressure can be observed and the pressure gradient will increase.

Communication with a higher-pressure reservoir without establishment of a pressure equilibrium

If the fluids tend to migrate towards a hydrostatic oil- or gas body because of intercommunication (which was mentioned among the causes of overpressure), the pressure will increase in this latter. This is a common phenomenon in hydrocarbon-bearing structures, where owing to the poor completion of wells an intercommunication with higher horizons *("dismigration")* can be established in many cases. In a reservoir of increased pressure the equilibrium of pressures is not established for a long time, not even when the channelway of communication is clogged. Since fluid communication with the surface is continuous and though the pressure equilibrium ought to be re-established in principale, this re-establishment is delayed by the frictional resistance of the rocks, the water binding energy of mineral grains, the capillary forces, etc. (Because of the above causes, the individual member of a hydrostatic reservoir system in the Upper Pannonian can be considered to represent separate hydrodynamic units; the oil and gas bodies can be exploited to pressure values substantially lower than the hydrostatic pressure, or in lack of exploitation they will preserve their temporary overpressure for a long time. The rate of *"pressure regeneration"* depends on the physical properties of rocks and fluids, on the size of divergence from normal pressure, on temperature conditions and on the connections of single oil bodies and reservoirs. Therefore *"regeneration"* may take considerable time even in terms of the geological time scale.)

Genetic classification of overpressures

Overpressure reservoirs of a closed system

Physical causes:

- mechanical compression
- changes in temperature
- communication with a reservoir of higher pressure
- increase of water content in the reservoir
- changes in the depth of burial
- dynamic effects

Chemical and physico-chemical causes:

- chemical and physico-chemical changes
- osmotic pressure.

Combined effect of various physical and chemical agents and/or of several of the above-listed causes.

Overpressure reservoirs of open system

- great thickness of formation
- morphological causes
- communication with a reservoir of higher pressure without establishment of pressure equilibrium.

DISTRIBUTION AND FLUID CONTENT OF OVERPRESSURE RESERVOIRS

According to literature, in the uppermost 1500 to 1800 m or so, no overpressure reservoir of closed system has been usually encountered, and the greatest divergences from normal pressure were observed within the 1800 to 3600 m depth range. Any increase of pressure below this limit implies an overpressure with the hydrostatic pressure added to. In oil geology, compaction is important from two points of view:

- the development of the structure above a rough surface as a result of sedimentation and compaction;
- the waste, i. e. removal, of fluids indispensable for oil and gas migration.

Squeezed out of the clay rock as a result of compaction, the water will carry away the available organic particles, oil and gas, either in emulsion or in solution. Origin and primary migration of oil and gas are connected with the diagenesis of clays, taking place in the second dehydration phase dicussed earlier, at varying depths within the range of 1500—1800 m (minimum) and 3600 m (maximum), under the effect of temperature and other factors.

In absence of percolation, non-expanding illite and kaolinite are not suitable for serving as mother rock. Therefore the montmorillonite content is very important for oil geology.

The most favourable depth of oil and gas formation is defined a priori — a fact essentially determining the choice of most prospective areas. However, because of the great possibility of migration the zone of oil and gas accumulation will grow wider upwards, whereas with the deepening due to burial it will show a downward widening.

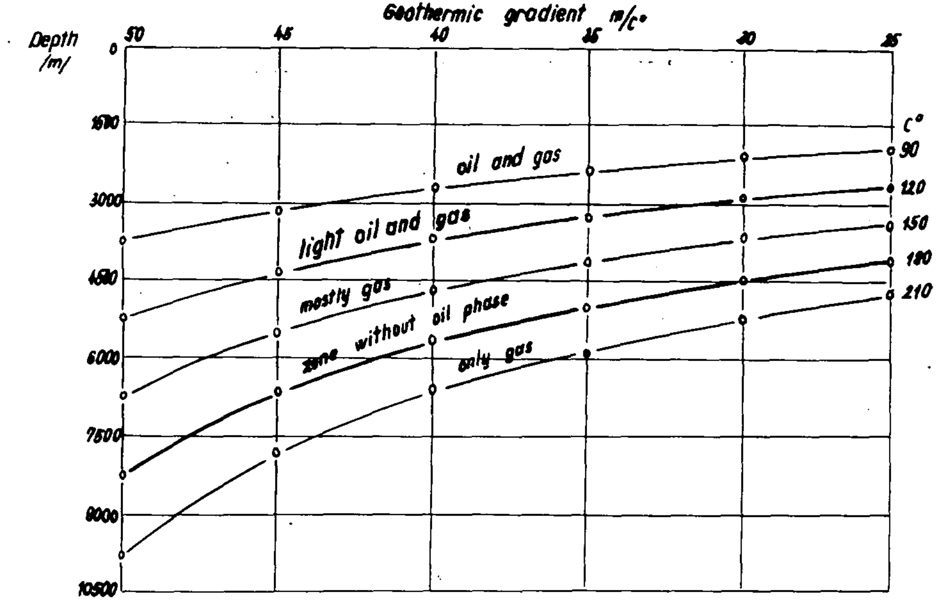

Fig. 8. The figure shows that at temperatures higher than 180 °C only gas accumulations are expected to occur.

In the deep-seated reservoirs the properties of oil and gas will change, as the oil in the reservoir rock is extremely sensitive to both pressure and temperature. Thermal decomposition (cracking) will lead to a decrease of density in the oils, since the small number of giant molecules are replaced by a great number of smaller ones, forming a more stable mixture under conditions like these. Because of condensation the aromatic compounds will develop into polycyclical molecules of higher molecular weight, losing their lateral chains. The final product of the process will be graphite. The paraffines will develop into light compounds, finally, into methane having a minimum of free enthalpy. In *Fig. 8,* borrowed from the literature, curves of oil and gas deposits, plotted against depth and temperature on the basis of theoretical considerations and the results of drilling a few hundred wells of great depth, have been presented. It is evident from these, that overpressure reservoirs may contain both oil and gas and that they are not connected preferentially with gas reservoirs at all. It is worth mentioning, however, that in overpressure reservoirs too it is the gas phase that predominates.

REFERENCES

Бкаиров, А.А, Васильев В. Г. [1967]: Вопросы роисков и разведки не нефтяних и газовых месторождений на VII. Всемирном Нефтаном Конгресс

Balogh, K., Kőrössy, L. [1968]: Tektonische Karte Ungarns im Masstabe: 1 : 1 000 000. Acta Geol. Acad. Sci.. Hung., *12,* 255—262.

Dank, V. [1964]: A dél-alföldi kőolaj- és földgázkutatások. Bányászati Lapok *97,* 775—788.

Dank, V. [1965]: A dél-alföldi neogén medencerészek mélyszerkezeti viszonyai és kapcsolatok a dél-baranyai és jugoszláviai területekkel. Földt. Közl., *95,* 123—129.

Dank, [1966]: Szeged környéki szénhidrogén kutatások. Bányászati Lapok, *99,* 122—136.

Dank, V., Bán, Á. [1966]: Az algyői kőolaj- és földgáz-előfordulás földtani viszonyai és termeltetésének elvei. Földtani Kutatás 1966. évi különszám.

Hobson, G. D.: Some Fundamentals of Petroleum Geology. Oxford University Press.

Hutchinson, C. A., Dodge, C. F., Polasek, T. L. [1961]: Indentification Classification and Prediction of Reservoir nonuniformities Affecting Production Operations. Journal Petrol. Techn., March.

Jones, P. H. [1969]: Hydrodynamics of Geopressure in the Northern Gulf of Mexico Basin. Journal Petrol. Techn., 1969, July, 803—810.

Kertai, Gy. [1962]: A magyarországi földgáztelepek kialakulásáról és továbbkutatásuk alapelvéről. Föld. Közl.,*92*, 274—279.

Kertai, Gy. [1960]: A magyarországi szénhidrogén-kutatás eredményei 1945—1960-ig. Föld. Közl., *90*, 406—418.

Körössy, L. [1963]: Magyarország medenceterületeinek összehasonlító földtani szerkezete. Föld. Közl., *93*, 153—172.

Landes, K. K. [1967]: Eometamorphism, and oil and gas in time and space. Bull. Amer. Assoc. Petrol. Geol., 828—841.

Levorsen, A. I., Freemen, W. H. *et. al.* [1958]: Geology of Petroleum. San Francisco.

Powers, M. C. [1967]: Fluid-release Mechanisms in Compacting Marine Mudrocks and their Importance in Oil Exploration. Bull. Amer. Assoc. Petrol. Geol., 1240—1254.

Соколов, В Л. Лоджевская М, И. [1967]. Зффективность разведочного бурения на больше глубины б США. Теология нефти и газа.

Dr. Attila Somfai
Great Plain Drilling and Prospecting Enterprise
Dorozsmai út 75, Szeged, Hungary