

# Abnormal fluid pressures caused by deposition and erosion of sedimentary basins

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## Abstract

Gravitational loading or unloading due to deposition or erosion in sedimentary basins is one of the most common mechanisms responsible for abnormal fluid pressures in geologic formations. This paper examines the integrated response of fluid pressures to both deposition and erosion using vertical one-dimensional numerical models. The modeling results show that vertical loading and unloading of sedimentary basins containing thick interbeds of low permeability can give rise to abnormal fluid pressure-depth trends that closely resemble those observed in the field. On a geological time scale, an under-pressured formation may become normally pressured or over-pressured and vice versa because of transient flow induced by vertical geologic movements. A case study in the Guymon area of Texas County, Oklahoma, shows that there are two underpressured reservoirs in this area. The burial curve constructed from geologic information indicates that this area has undergone multiple subsidence and uplift events. Based on stratigraphic information, a vertical geologic section of this area is represented by a numerical model consisting of two reservoir formations and two shale (confining) units. The numerical model is able to reproduce the observed pressure abnormalities based on the drill-stem test (DST) data. The hydraulic conductivities of the two shale formations are estimated to be  $4.2 \times 10^{-14}$  and  $5.1 \times 10^{-14}$  m s<sup>-1</sup> from model calibration. © 1998 Elsevier Science B.V.

*Keywords:* Basin hydrogeology; Fluid compartment; Abnormal pressure; Overpressured; Underpressured

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## 1. Introduction and previous work

A formation is abnormally pressured when the pore fluid pressure is significantly below or above the normal hydrostatic pressure for the depth considered. Discussions of various factors which may generate abnormal pressures can be found in Neuzil (1995); Ortoleva (1995); Ortoleva et al. (1995). This article focuses on the abnormal fluid pressures caused by gravitational loading or unloading, one of the most common mechanisms responsible for generating

abnormal pressures in geologic formations (Domenico and Palciauskas, 1979).

Neuzil (1995) summarized two distinct conceptual approaches to abnormal pressures as: (1) static phenomena, such as the seal and compartment concepts developed by Bradley (1975) and Powley (1990), who described abnormal pressure regimes as static and occurring where the subsurface is compartmentalized by impermeable barriers to fluid flow, and (2) hydrodynamic phenomena, such as those invoked by hydrogeologists (Bredehoeft and Hanshaw, 1968; Toth and Millar, 1983; Belitz and Bredehoeft, 1986, 1988; Bethke and Corbet, 1988), who characterized abnormal pressures as generally dynamic, in most

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cases representing a balance between ongoing geologic processes that perturb the pressure and fluid fluxes that tend to dissipate the perturbations.

Analytical and numerical approaches were used to study the abnormally high pressures caused by sedimentation (Bredehoeft and Hanshaw, 1968; Keith and Rimstidt, 1985; Bethke and Corbet, 1988). However, there was much less research on abnormally low pressures caused by erosion. Calculations suggest that subnormal pressures can persist for geologically significant periods of time after the generating processes stop (Bredehoeft and Hanshaw, 1968; Toth and Millar, 1983). Abnormal pressures may reflect processes acting in the present or the past, or both. For example, a previously subsided basin may be uplifted and eroded before the transient fluid movement caused by subsidence ceases. This results in pressure changes from all current and past processes being superimposed (Neuzil, 1986). However, previous studies have treated erosion and deposition as separate geologic events and the integrated response of the fluid pressure to sequential depositional and erosional events is yet to be examined. This response will be investigated in this article. Because the main concern of this study is the basin fluid flow caused by vertical geologic movements which involve an area much larger than a single basin, vertical one dimensional models will be used.

This study also attempts to explain various patterns of vertical pressure distribution shown by drill-stem test (DST) data. Pore-fluid pressure measurements from DST data are the most direct indication of abnormal pressures (Bradley and Powley, 1995). Powley (Powley, D.E., 1993, Using commercial pressure data sources (unpublished)) presents a large number of pressure–depth plots based on DST data, showing that fluid pressures may abruptly increase or decrease at a certain depth. It was the discovery and interpretation of these abnormal pressure–depth graphs during the late 1970s and early 1980s that led directly to the use of the term ‘fluid pressure compartments’ (Powley, D.E., 1993, Using commercial pressure data sources (unpublished)). Detailed investigations of the geologic settings and fluid pressure gradients in some deep sedimentary basins revealed the presence of multiple, abnormally pressured domains. Combinations involving normally and abnormally pressured domains have also been reported. These include a

normally pressured domain underneath several overpressured domains (Al-Shaieb et al., 1995), and underpressured, normally pressured, and overpressured domains co-existing in a single basin (Serebryakov and Chilingar, 1995) and in a geologic section (Bradley and Powley, 1995 Figure 29).

Little research has been done on the mechanisms responsible for the multiple pressured domains indicated by DST data. An attempt is made in this study to offer an explanation for multiple pressure domains in deep sedimentary basins using both hypothetical examples and actual field data. The integrated response of fluid pressures in layered geologic formations to consecutive subsidence and erosion events will be examined in this article, using vertical one-dimensional numerical models. It will be demonstrated that a combination of various multiple pressure configurations may be reproduced by considering the responses of stratified formations to past and current geologic events. The Guymon area in Oklahoma is used as a field study. Pressure–depth plots based on DST data show that there are two underpressured formations in this area. Geologic information indicates that this area has undergone multiple events of subsidence and uplift. The vertical geologic section is simplified by a one-dimensional numerical model, which is calibrated against the observed DST data to estimate the model parameters.

## 2. General features of excess head in response to erosion and deposition

### 2.1. One-dimensional numerical model

The equation which describes the excess head within sediments caused by erosion or deposition is (Bredehoeft and Hanshaw, 1968):

$$\frac{1}{S_s} \frac{\partial}{\partial z} \left( K \frac{\partial h_e}{\partial z} \right) = \frac{\partial h_e}{\partial t} - \frac{\rho'}{\rho} \omega \quad (1)$$

where  $h_e$  is the excess head defined as the amount of the head in excess of the hydrostatic value;  $\rho$  is the density of water;  $\rho'$  is the submerged density of the sediments (i.e. the difference between the density of water and bulk density of the sediments);  $K$  is the vertical hydraulic conductivity (referred to as hydraulic conductivity hereafter);  $S_s$  is the coefficient of

specific storage;  $\omega = (\partial l / \partial t)$  is the rate of deposition ( $\partial l / \partial t > 0$ ) or erosion ( $\partial l / \partial t < 0$ ); and  $l$  is the total thickness of the sediments at time  $t$ . The sediment density is assumed not to change with depth. For most geologic problems this is held to be a reasonable simplification (Neuzil, 1986). Other important assumptions behind the equation are that the solid and fluid phases are individually incompressible. The derivation of this equation can be found in Domenico and Palciauskas (1979); Neuzil and Pollock (1983).

Assume that the initial thickness of the column before erosion or deposition is  $L$  and that the excess head is zero at the upper boundary ( $Z = L$ ) and that the basement rock ( $Z = 0$ ) is impermeable. Thus at the lower boundary, the gradient of the excess head is zero. The initial excess head is zero in the entire column. The boundary and initial conditions can be described mathematically as

Boundary conditions:

$$\left. \frac{\partial h_e}{\partial z} \right|_{z=0} = 0 \quad t \geq 0 \quad (2)$$

$$h_e(l, t) = 0 \quad t \geq 0$$

and initial conditions:

$$l = L \quad h_e(z, 0) = 0 \quad (3)$$

where  $l$  is the thickness of the column at any time. Eqs. (1)–(3) describe the excess head in response to the change of stress resulting from loading or unloading of saturated elastic rock caused by increasing or decreasing thickness. The thermal effects are neglected.

Eq. (1) can be discretized by a fully implicit finite-difference approximation with a moving boundary. The moving boundary at the sedimentation surface is accommodated by adding or removing a certain number of cells at the top of the column (Neuzil and Pollock, 1983). The number of cells added or removed at a time step depends on the rate of deposition or erosion. It is assumed that the top of the column always coincides with the water table. After calculations for each time step the condition of zero excess head is assigned to the uppermost cell.

The original thickness of the column is assumed to be 10 or 15 km, depending upon whether deposition or erosion is occurring. The rate of deposition or erosion is 100 m per one million years ( $\text{m ma}^{-1}$ ). The spatial increment used in the numerical model

is 100 m. The time step is one million years so that a full cell is added or removed after each time step. A constant value of  $0.001 \text{ m}^{-1}$  is assumed for  $S_s$ . The value of  $K$  will depend on the problem under discussion. For formations of very low permeability, it is fixed at  $1 \times 10^{-12}$  or  $1 \times 10^{-13} \text{ m s}^{-1}$ . For reservoir formations between the formations of very low permeability, it is taken to be  $1 \times 10^{-9}$  or  $1 \times 10^{-10} \text{ m s}^{-1}$ . The densities of fluid and sediment are assumed to be 1.0 and  $2.3 \text{ g cm}^{-3}$ , respectively. These parameter values and column thicknesses are physically realistic and are based on, or are comparable to, those used by Bredehoeft and Hanshaw (1968); Bethke and Corbet (1988). The solution agrees well with that presented by Bethke and Corbet (1988) when the same parameters are used. For the hypothetical study in this section, the response of excess head in homogeneous and heterogeneous formations to deposition, erosion, and a combination of the two will be examined.

## 2.2. Change of excess head in response to deposition

The initial thickness of the entire column is 10 km and is increased to 15 km as a result of deposition. Curves 1–4 in Fig. 1 show the excess head after 50 ma. In curve 1, the formation has a uniform hydraulic conductivity,  $K$ , equal to  $1 \times 10^{-12} \text{ m s}^{-1}$ . In curves 2–4, the hydraulic conductivity remains the same except in the high  $K$  zones ( $K = 1 \times 10^{-10} \text{ m s}^{-1}$ ) introduced at the bottom, middle and top of the column, respectively. Generally the excess head increases from zero at the top to a maximum at the base of the column. From curves 1–4, the excess head progressively decreases. Curves 2–4 show that the more permeable zone plays an important role in reducing the excess head. The location of the zone determines the size of the reduction. When the high  $K$  zone is at the bottom, the decrease in excess head is not very significant. When the high  $K$  zone is near the top and the same permeable sediments are added to the column, the excess head in the system is significantly reduced. The excess head in the shallow zone is virtually zero and this zone is almost hydrostatic. Abnormally high pressure exists only below this zone (see curve 4 in Fig. 1).

Curve 5 in Fig. 1 shows the change of excess head in response to deposition in a multi-layered system. At the beginning, the column has three high hydraulic

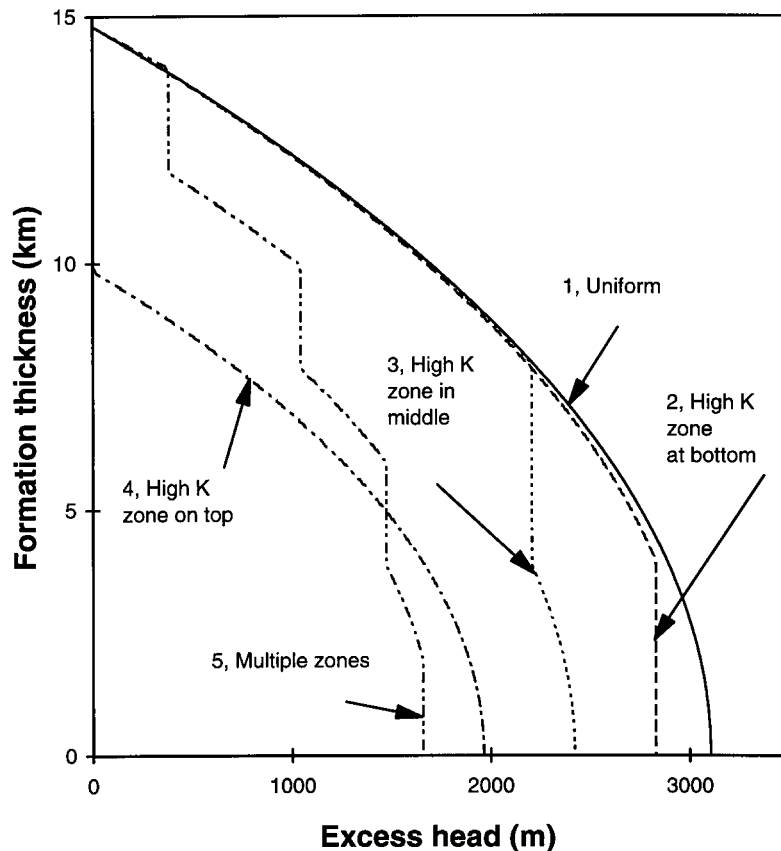


Fig. 1. Excess head at 50 ma in uniform and layered geologic columns caused by deposition at the rate of  $100 \text{ m ma}^{-1}$ . The column is initially 10 km and increased to 15 km at the end of deposition (Curve 1, uniform case with  $K = 1 \times 10^{-12} \text{ m s}^{-1}$ ; Curves 2–4, a more permeable or high  $K$  zone with  $K = 1 \times 10^{-10} \text{ m s}^{-1}$  at the bottom, the middle, and the top; Curve 5, multiple layers with  $K = 1 \times 10^{-12}$  and  $1 \times 10^{-10} \text{ m s}^{-1}$ ).

conductivity zones ( $K = 1 \times 10^{-9} \text{ m s}^{-1}$ ) and three low hydraulic conductivity zones ( $K = 1 \times 10^{-12} \text{ m s}^{-1}$ ) (The top zone is one of the low hydraulic conductivity zones.) The excess head shows a stepwise increase with depth. In a low hydraulic conductivity zone, the excess head increases almost linearly with depth and in the high hydraulic conductivity zone, the excess head is almost constant. The different responses of various hydraulic conductivity zones generate a pattern which is similar to that of observed multiple fluid compartments (Powley, D.E., 1993, Using commercial pressure data sources (unpublished)). This shows that a vertical array of overpressured formations can be created by deposition over layered geologic formations with considerable depth-wise contrast in hydraulic conductivities. The head difference indicates a flow from the bottom to the

top, implying that these abnormally overpressured formations are not isolated hydraulically from each other.

### 2.3. Change of excess head in response to erosion

In contrast to deposition, erosion and unloading can generate abnormally low pressures. Most of the previous conclusions on the influence of the geologic setting and hydraulic conductivity on the pressure distribution are equally applicable, except that the excess head is negative, instead of positive.

Fig. 2a shows the change of excess head with time during an erosional period. The initial thickness of the column is 15 km. At the beginning, the absolute value of excess head increases as erosion proceeds. However, it decreases slightly during the time interval

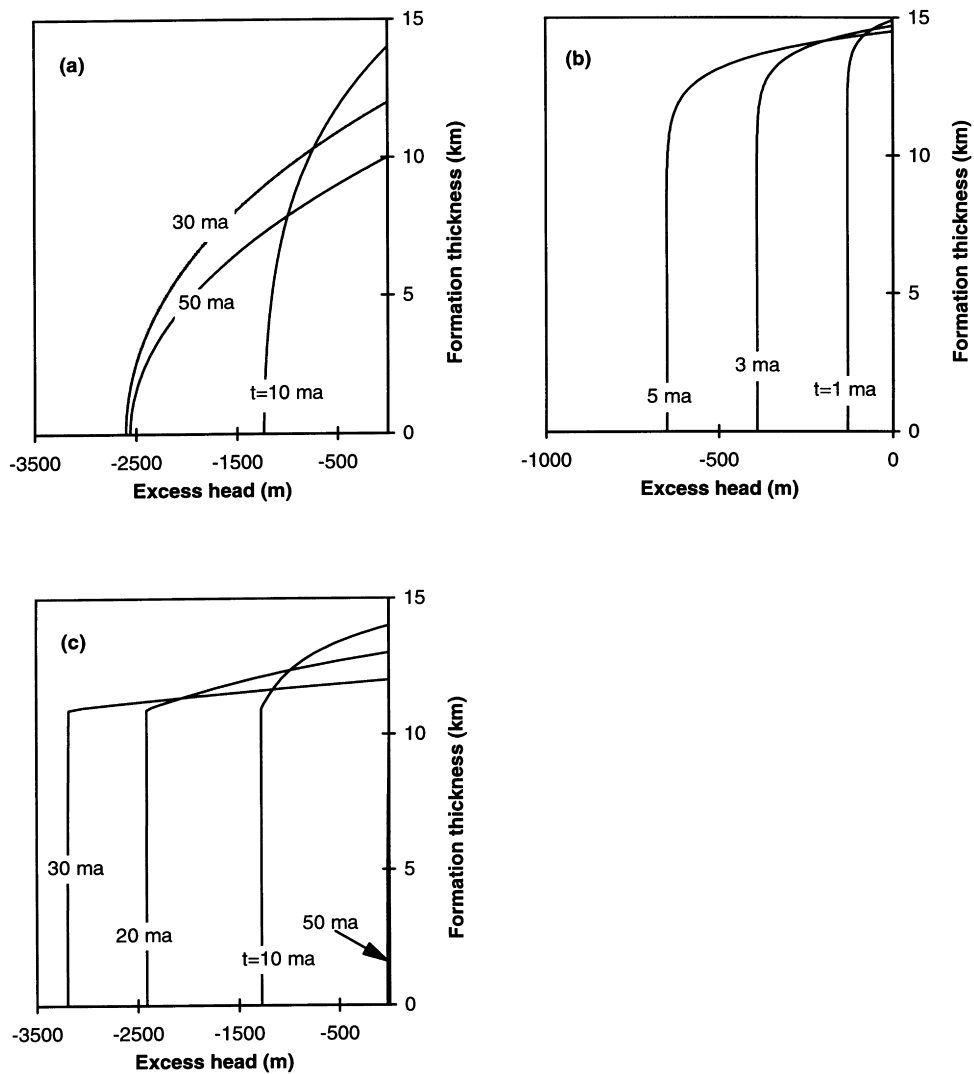


Fig. 2. Response of excess head to erosion at the rate of  $100 \text{ m ma}^{-1}$  in uniform and layered geologic columns. The column is initially 15 km and decreased to 10 km at the end of erosion. (a) Uniform ( $K = 1 \times 10^{-12}$ ), long time; (b) Uniform ( $K = 1 \times 10^{-12}$ ), short time; (c) Two zones ( $K = 1 \times 10^{-13}$  and  $1 \times 10^{-10}$ ).

from 30 to 50 ma. This is different from the deposition case where the excess head always increases with time. As the erosion ensues, the length of the column becomes smaller and the zero-head boundary condition at the top significantly influences the head distribution in the system. The whole system may be hydrostatic with an excess head of zero when the vertical column is sufficiently short.

If the hydraulic conductivity of a column is uniformly low and only the pressure distribution in the

initial stage of erosion is examined, it can be seen from Fig. 2b that the excess head increases with depth significantly only in the shallow part and then remains almost constant. This is because the time is not long enough for the deep part of the column to respond to the pressure change caused by erosion at the top. Thus, if pressure data are used as the only evidence, a formation of uniform hydraulic conductivity may be misinterpreted as an abnormally pressured formation beneath a confining unit.

The hydraulic conductivity of the shallow portion of the system plays a very important role in determining the overall pressure distribution, as in the case of deposition. Suppose that there is a two-zone system. The top 5 km has a low hydraulic conductivity of  $1 \times 10^{-13} \text{ m s}^{-1}$  and the remaining 10 km has a higher hydraulic conductivity of  $1 \times 10^{-10} \text{ m s}^{-1}$ . In response to erosion, the formation will have a typical under-pressured profile as shown in Fig. 2c. The absolute value of excess head progressively increases with time from 10 to 30 ma. However, after 50 ma, the top low hydraulic conductivity zone is eroded away, and the entire system is now very permeable. The excess head drops to almost zero and the whole system becomes hydrostatic. This may happen in a real aquifer system. If the top confining layer of an abnormally pressured aquifer is breached due to erosion, the groundwater head in this aquifer system may unexpectedly show a significant change over a very short period.

If the change of excess head in a multi-layered system in response to erosion is examined, multiple, underpressured formations similar to curve 5 in Fig. 1 may be observed. A detailed discussion of this case is omitted.

#### 2.4. Change of excess head in basins undergoing subsidence and then uplift

In a deep sedimentary basin having very low hydraulic conductivity formations, excess head resulting from a single geologic event may be so significant

that the pressure may survive much longer than the geologic event itself (Neuzil, 1986). Assume that a basin undergoes subsidence during the first 50 ma. Then subsidence ceases and there is no further deposition. Fig. 3 shows how the excess head changes with time at the bottom of the column during both subsidence and static periods. For the case where  $K = 1 \times 10^{-12} \text{ m s}^{-1}$ , the excess head decreases with time significantly in the static period. However, at even 50 ma after subsidence ceases, there is still significant residual excess head (over 200 m). If the hydraulic conductivity is lower, the residual excess head is even more considerable, as shown by the case where  $K = 1 \times 10^{-13} \text{ m s}^{-1}$ . Therefore, if the hydraulic conductivity is low enough to prevent the timely release of excess pressure, it is very possible that another geologic event such as erosion or more subsidence could occur before the excess head caused by the first event bleeds off to zero. The behavior of fluid pressure in a basin undergoing different geologic events is examined in the following discussions.

The basin is assumed to subside and receive sediments during the first 50 ma, and then is uplifted and unloaded at the same rate for another 50 ma. Fig. 4a shows the excess head at the early period of erosion when the excess head begins to change gradually from positive to negative. As shown in Fig. 4a, at 60 ma, about 10 ma after erosion begins, the excess head is still positive and the system is overpressured. At 64 ma, the top part of the column is underpressured, but the bottom part is still overpressured. At 66 ma,

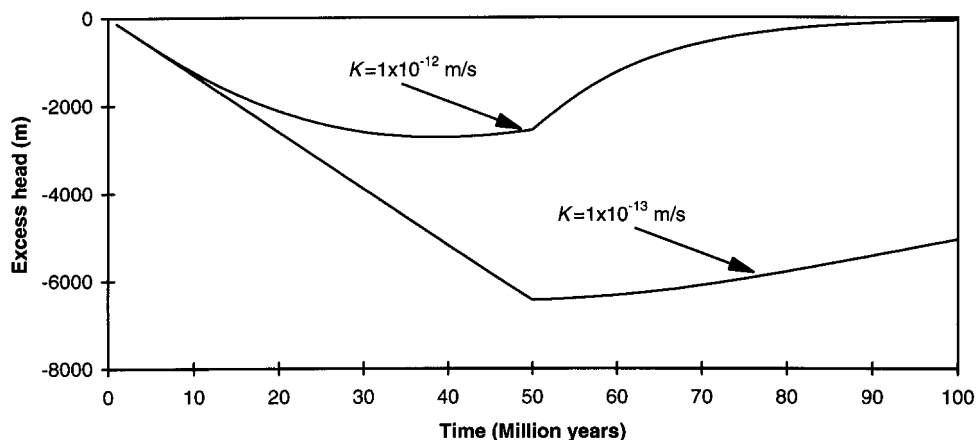


Fig. 3. Longevity of excess head at the bottom of an uniform column. The system is first subsided for 50 ma at the rate of  $100 \text{ m ma}^{-1}$  and then becomes static for another 50 ma.

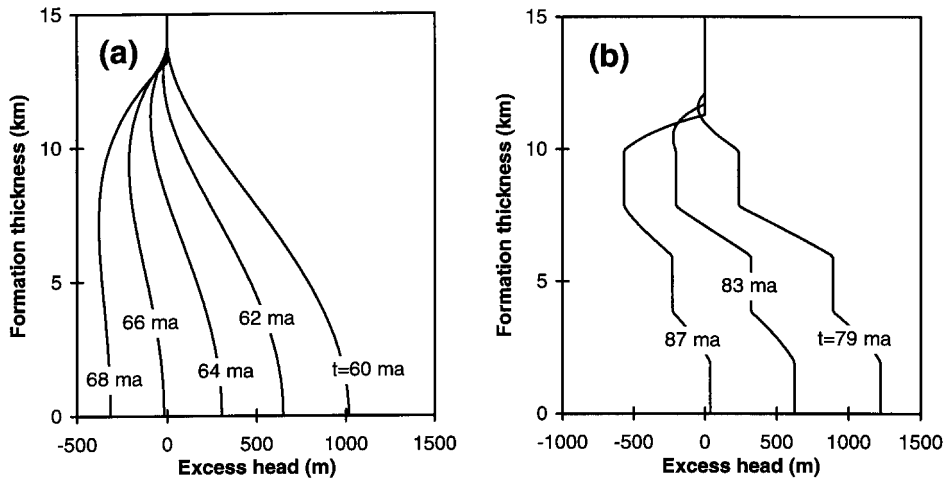


Fig. 4. Response of excess head to deposition and subsequent erosion at the same rate of  $100 \text{ m ma}^{-1}$  in uniform and layered geologic columns with initial thickness of 10 km. (a) Uniform column ( $K = 1 \times 10^{-12}$ ), (b) Layered column ( $K = 1 \times 10^{-9}$  and  $1 \times 10^{-13}$ ).

the whole system becomes underpressured. The column appears to be hydrostatic at the very bottom because the excess head is almost zero.

Fig. 4b shows the distribution of the excess head during a transition period in a layered system. There are four high hydraulic conductivity zones where  $K = 1 \times 10^{-9} \text{ m s}^{-1}$ . The deposited sediment also has a hydraulic conductivity of  $1 \times 10^{-9} \text{ m s}^{-1}$ . The other three intermediate zones have low hydraulic conductivity of  $1 \times 10^{-13} \text{ m s}^{-1}$ . Again this multi-layered system generates multiple pressure domains. At 79 ma, the formations are overpressured. After 87 ma, the formations are underpressured. During the period from 79 to 87 ma, the formations in this column can be overpressured, underpressured, or even hydrostatic.

The simulation results discussed before show that an overpressured formation may become underpressured because of slow transient flow induced by subsidence and then uplift on a geologic time scale. However, the change is so slow that it may be undetectable on a human time scale. In an old basin, the formation may have undergone several cycles of vertical movements. The pressure distribution is a superposition of pressure changes over different geologic periods. Therefore, in a vertical geologic section, any combination of underpressured, overpressured, or normally pressured formations is potentially possible.

Because the pressurization of a system may change

over time, it is important to examine the history of a basin before an underpressured formation may be used as a potentially safe waste disposal site. If pressure increases naturally with time because of loading, the injection of waste liquids would only speed up the natural trend. However, a currently underpressured formation in a geologically active basin may be poorly suited for waste disposal.

### 3. Simulation of subnormal pressures in the Guymon area, Oklahoma

#### 3.1. Site geology and subnormal pressures

Guymon, Oklahoma, USA is located in the transition area between the Anadarko Basin and the Hugoton Embayment (Fig. 5), which are bounded on the west by Cimarron Arch and Las Animas Uplifts, on the north by the Central Kansas Uplift, on the south by Amarillo Uplift, and on the east by Nemaha Ridge (Breeze, 1971). The Guymon area is on a monoclinical structure which dips gently toward the east-southeast.

The stratigraphy of the basin shows extreme heterogeneity caused by long-term cycles of sedimentation in different environments. The sedimentary rocks are chiefly marine Paleozoic formations with Mississippian and Pennsylvanian sediments attaining the greatest thickness (Breeze, 1971). The stratigraphic information is summarized in Table 1. The

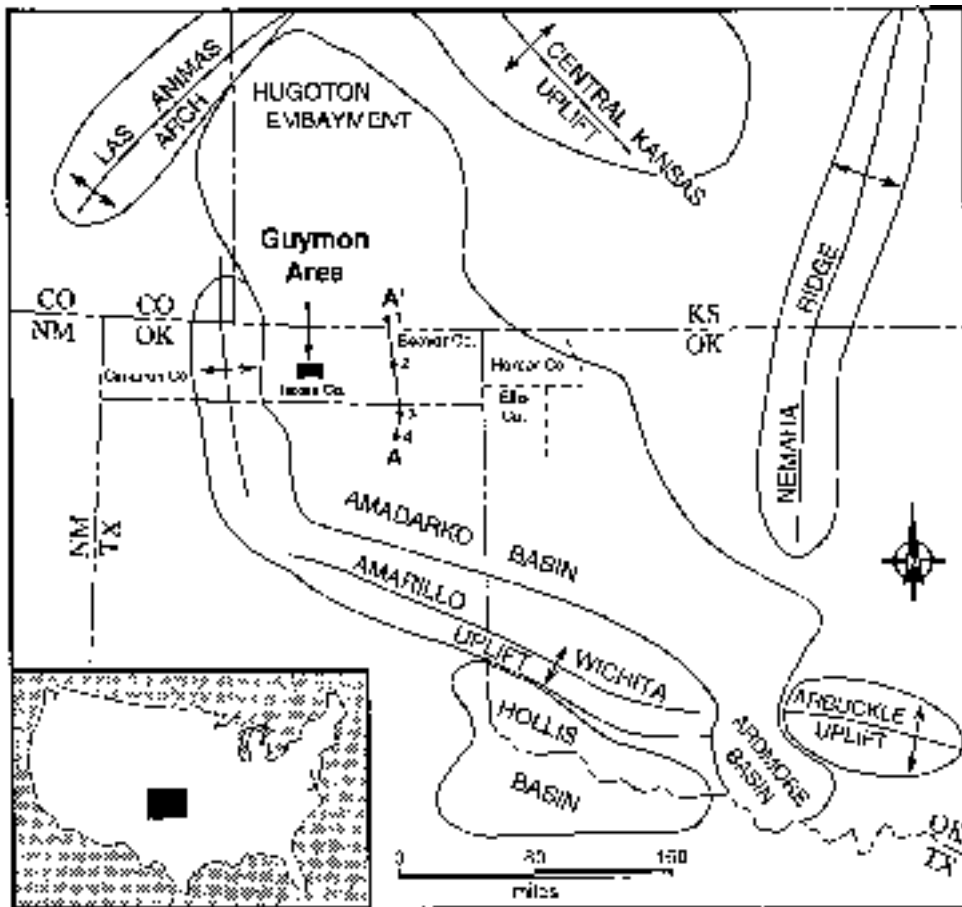


Fig. 5. Study area in relation to major tectonic features (modified from Breeze, 1971).

geologic section A–A' across Beaver County (Fig. 6) shows that the section is dominated by carbonate formations.

This area has two important gas reservoirs: the Chase and Morrow reservoirs. A large part of both reservoirs is filled with brine. Thick anhydrites and dolostones of Leonardian age cap the Wolfcampian section and provide a seal above the Chase Group reservoir (Siemers and Ahr, 1990). The Upper Morrow has over 50 m of shale and numerous thin coal beds (Arro, 1965) which become the confining unit above the Morrow reservoir consisting of sandstone and limestones. Generally the low permeability layers in this area are laterally extensive and reservoir formations terminate before reaching the margins of the basin.

Decompacted time–depth burial histories (Fig. 7)

for neighboring Ellis and Harper Counties, Oklahoma were constructed by Schmoker (1989). These histories can be used as proxies for the Guymon area because of the relatively short distance.

The curves can be subdivided into three segments by discontinuities in slope that correspond to major shifts in basin-subsidence patterns. The curves show a rapid subsidence 260 ma ago, slow sediment accumulation between 260 and 60 ma ago, and uplift and erosion beginning 60 ma ago and continuing to the present (Schmoker, 1989). For simplicity, the influence of excess head caused by subsidence 260 ma ago has been neglected in the numerical model. Only the late two periods, referred to as subsiding and uplifting periods, are considered in the numerical model. The subsiding period lasts about 200 ma, and is accompanied by 1400 m of sedimentary deposit.

Table 1  
 Guymon stratigraphic column<sup>a</sup>

Series	Stage	Formations	Description	Depth (m)
Quaternary		Alluvium		0–30
Tertiary		Ogallala	With aquifer	30–150
Cretaceous		Dakota	With aquifer	150–270
Jurassic		Mornson		
Triassic		Dockum	With aquifer	
Permian	Guadalupe	Cimarron		
	Leonard	Sumner	With Wellington shale	720–820
	Wolfcamp	Chase Council Grove Admire	Reservoir (limestone)	820–970 970–1100
Pennsylvanian	Virgil			1100–
	Missouri			
	Cherokee			
	Atoka	DesMoines		
	Morrow	U. Morrow L. Morrow Keyes	With shale Reservoir (sandstone)	1920–2070
Mississippian	Chester			
	Meramec			
	Osage			
	Kinderhook			
Devonian	Woodford			
Silurian	Hunton			
Ordovician				
Cambrian				
Precambrian				2656

<sup>a</sup> Based on Bradley (1985); Johnson (1989); Curtis and Ostergard (1980).

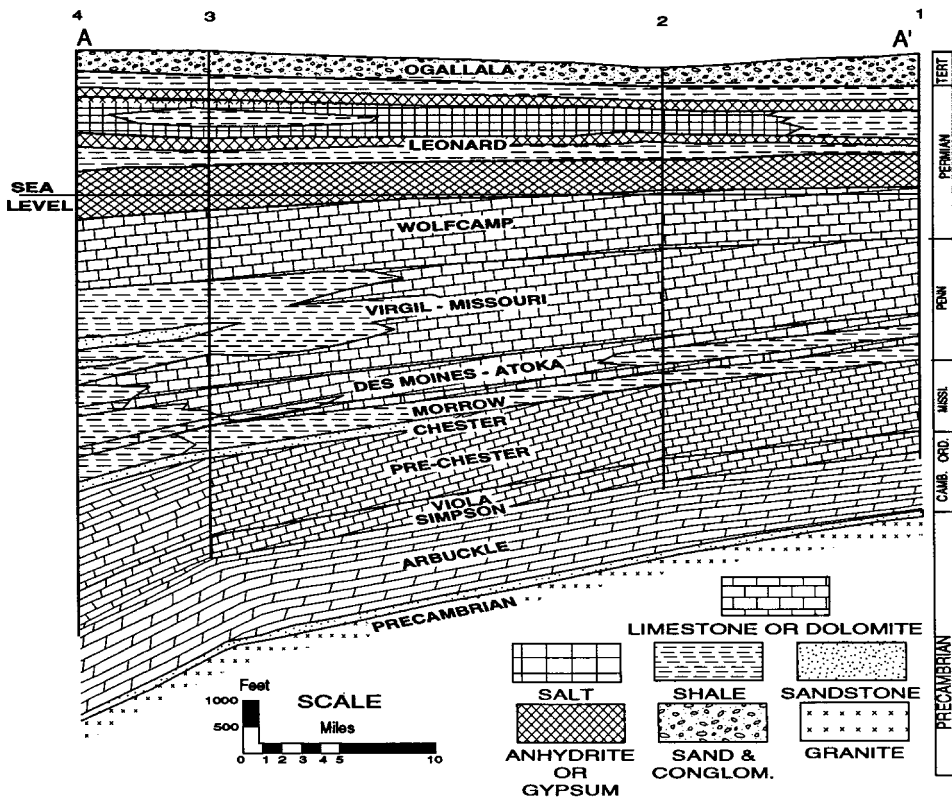


Fig. 6. Cross section A–A', south–north across Beaver County showing structural configuration and stratigraphy (modified from Adler, 1971).

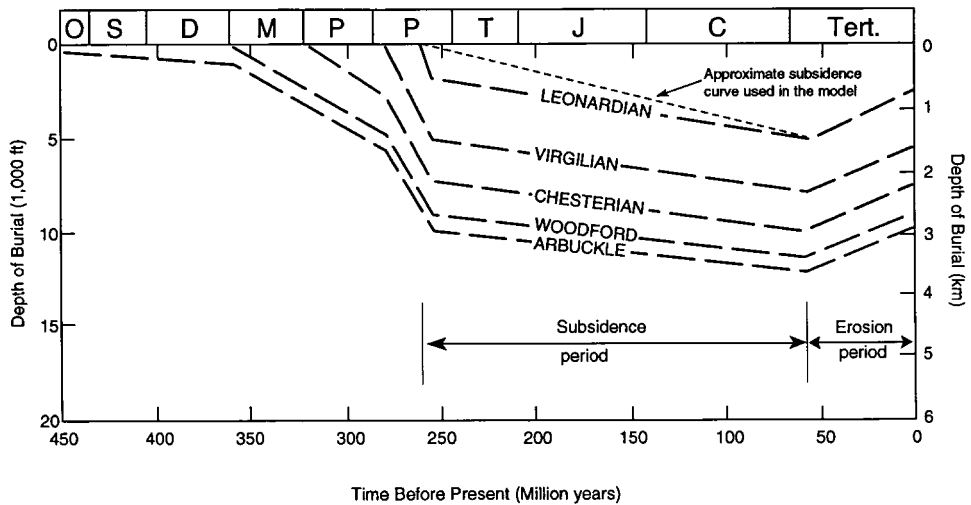


Fig. 7. Burial curves for Ellis and Happer Counties, Oklahoma (letters on the top are short for the geologic times) (modified from Schmoker, 1989; Al-Shaieb et al., 1995).

The subsidence rate is about  $7 \text{ m ma}^{-1}$ . In the last 60 ma, the formations are uplifted by approximately 830 m. The rate of uplift is about  $14 \text{ m ma}^{-1}$ , which is twice the rate of subsidence.

Fig. 8 shows a pressure–depth plot based on the observed DST data in an area of four townships near Guymon City, Texas County, Oklahoma. The pressure distribution is very similar to that based on the data from the whole Texas County (Powley, D.E., 1993, Using commercial pressure data sources (unpublished)). This indicates that there is little horizontal flow in the Guymon area and a vertical flow model may be adequate to simulate the pressure distribution. The formations were observed to be

underpressured soon after the first well was drilled in 1918 (Mason, 1968). Fig. 8 shows that the formations are underpressured below a depth of about 800 m. The head difference between the hydrostatic and the subnormal pressures is over 400 m. Below a depth of about 1750 m, the pressure begins to drop again. The head difference between the normal and subnormal pressures is over 600 m. Based on the theory of Bradley and Powley (1995), there are two distinct pressure compartments in the Guymon area and the Wellington and Morrow shales act as the seals for these two compartments.

### 3.2. Simulation of subnormal pressures

Assume that 260 million years ago, the system was hydrostatic, with excess head  $h_e$  being zero. The vertical column from the Wellington shale of Leonardian age to the Precambrian basement is chosen for discussion. Assume that the Wellington formation was on the top of the column 260 ma ago. Further assume that all formations in the column subsided uniformly at the rate of  $7 \text{ m ma}^{-1}$  from 260 to 60 ma, and then uplifted uniformly to the present time at the rate of  $14 \text{ m ma}^{-1}$ . The spatial increment used in the numerical model is 14 m and the time step is 1 ma. In the subsidence period, one model cell is added every two time steps. In the erosion period, one cell is removed every time step. There are a large number of low-permeability layers. Based on the pressure–depth plot, it is assumed that only the Wellington and Morrow shales have sufficiently low permeability and are areally continuous enough to behave as confining units. The vertical column is therefore represented by four zones, two reservoirs and two low permeability formations. The total thickness of the column from the Wellington formation to the basement can be obtained from Table 1. However, the information in this table is compiled from data collected over a region much larger than the Guymon area, thus the thickness is only an approximation. In this study, the initial thickness prior to subsidence is assumed to be 1932 m so that 138 cells are used in the numerical model. The thickness of each zone is shown in Table 2.

As a large portion of the sedimentary rocks above the Wellington formation is of aquifer material (Table 1), a relatively high hydraulic conductivity

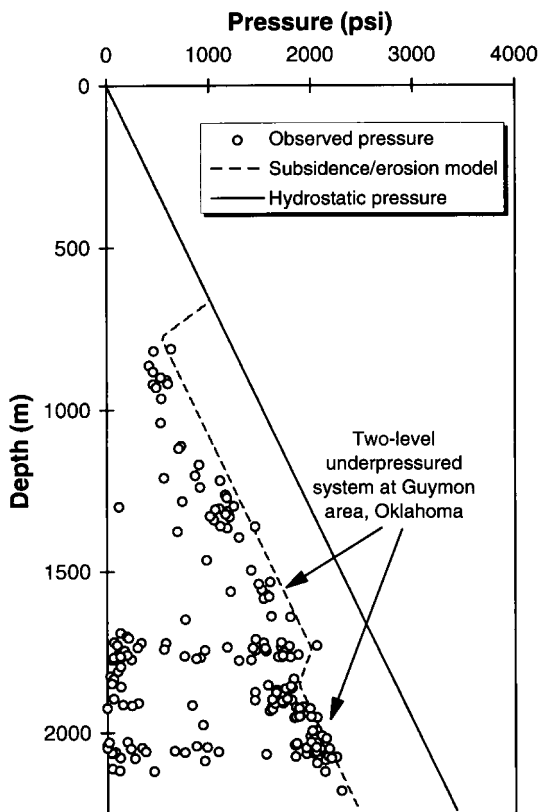


Fig. 8. Observed and calculated pressure–depth plots in an area near Guymon, Oklahoma, USA. Pressure values from DST are typically lower than the true formation water pressure because adequate time may not have elapsed for recovery of pressure after flow tests (Orr and Kreitler, 1985). Thus emphasis should be placed on the highest pressures at a specific depth (Powley, D.E., 1993, Using commercial pressure data sources (unpublished)).

Table 2

Formations, thicknesses and properties in the idealized model for the Guymon area

Formation Name	Thickness (m)	Vertical hydraulic conductivity ( $\text{m s}^{-1}$ )	Specific Storage ( $\text{m}^{-1}$ )
Wellington formation	84	$4.8 \times 10^{-14}$	$1.0 \times 10^{-4}$
Reservoir 1	980	$9.6 \times 10^{-11}$	$2.0 \times 10^{-4}$
Morrow formation	98	$4.2 \times 10^{-14}$	$1.0 \times 10^{-4}$
Reservoir 2	770	$9.6 \times 10^{-12}$	$1.5 \times 10^{-4}$

( $K = 1.0 \times 10^{-10} \text{ m s}^{-1}$ ) is assigned to the sediments deposited on the Wellington formation during the subsidence period. This value is not calibrated because it is so large compared to the hydraulic conductivity of the Wellington formation that its influence upon the pressure distribution is negligible. The trial-and-error method is used to calibrate other parameters against the observed pressure–depth distribution. The final parameters are listed in Table 2. The hydraulic conductivity of the Morrow shale formation is slightly smaller than that of the Wellington shale formation. The fit between the calculated and observed pressure distributions is shown in Fig. 8. It can be seen that the deposition and erosion model can satisfactorily reproduce the subnormal pressure distribution in this area.

#### 4. Discussion and conclusions

The pressure perturbations caused by a single geologic event may last longer than the event itself. The current pressure distribution in deep sedimentary basins can be a superposition of the pressure caused by several erosional and depositional events. This study is believed to be the first to examine abnormal pressures caused by multiple geologic events.

This article shows on the basis of numerical calculations that the different responses of formations with varying hydraulic properties to deposition and erosion can naturally generate multiple, overpressured or underpressured configurations, as observed in some sedimentary basins. This is further confirmed by the reproduction of the two underpressured formations in the Guymon area, Oklahoma. Although other geologic and physico-chemical processes such as osmosis, non-darcian flow, and diagenesis may also generate multiple pressure abnormalities (Qin and Ortoleva, 1995), this paper shows that the vertical

geologic movement alone may be sufficient to create multi-level abnormally pressured formations.

The estimation of hydraulic parameters of deep shale formations is one of the important topics in modern hydrogeology. The hydraulic conductivity of the shale formations in the Guymon area can be estimated using a vertical one-dimensional model incorporating erosion and subsidence. This approach is of general use in estimating shale permeabilities in other abnormally pressured basins caused primarily by vertical geologic movement. The hydraulic conductivities of the Wellington and Morrow formations are estimated in this study to be between  $4.2 \times 10^{-14}$  and  $5.1 \times 10^{-14} \text{ m s}^{-1}$ . These values are comparable to those estimated by previous researchers. For instance, Neuzil (1993) estimated the hydraulic conductivity of the Pierre Shale to be  $10^{-14}$  to  $10^{-13} \text{ m s}^{-1}$ ; Corbet and Bethke (1992) estimated the permeability of the Cretaceous shales to be less than  $3 \times 10^{-20} \text{ m}^2$  (or equivalent to a hydraulic conductivity of  $2.9 \times 10^{-15} \text{ m s}^{-1}$ ).

The transient feature of pressure distribution in a geologic formation should be examined when considering an underpressured formation for possible waste disposal. It has been mentioned elsewhere that an underpressured formation is advantageous for waste disposal because it behaves as a sink and has a tendency to keep waste for long times (Bradley, 1985). An underpressured formation may become a normally pressured and then overpressured formation and vice versa because of the slow, natural flow among these formations. Before a currently underpressured formation is considered for possible waste disposal, it is necessary to examine the geologic history and the possibility for vertical movement in the future which may lead to a gradual increase in the pressure caused by the natural transient flow.

One limitation of the study is the assumption that the hydraulic parameters are constant over time. The

formation permeability can decrease because of increasing stress in the deposition period or slightly increase because of rebound in the erosion period. As pointed out by Bethke and Corbet (1988), the excess head will be over-predicted if the changes in the hydraulic parameters with effective stress are ignored in compacting basins. It is believed, however, that the general conclusions that vertical geologic movement can lead to multi-level abnormally pressured formations will remain unchanged. For the observed DST data in the Guymon area, the pressures were not corrected for salinity and temperature effects due to lack of information. The resulting errors are believed to be insignificant because the depth of the modeled layers is small. The influence of temperature on abnormal pressure in the shallow part of a basin is generally considered negligible. As pointed out by Neuzil (1993) in a study dealing with transient pressure in response to erosion in a basin in South Dakota, thermal effects, even though enhanced by a large thermal gradient, apparently had little effect. The detailed influence of temperature, salinity, and inelastic deformation on abnormal pressure distribution in the Guymon area requires a further study.

Another limitation is the assumption of vertical one-dimensional flow. To better represent the abnormal pressure distribution in a system, two or three dimensional models are required. The formations in a sedimentary basin may change horizontally from underpressured to overpressured (Breeze, 1971). Based on the discussions in this paper, it can be expected that such a pressure distribution can be generated if the nonuniformities in lithology and deposition or erosion rates are simulated.

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