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Determination of hydraulic fracture gradients from Leak-off and well integrity tests

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Introduction

In today's life the energy demand keeps rising which compels the industry to increase the production of hydrocarbons. This can only be done either by drilling new exploration wells to find new enticing reservoirs or by using different stimulation methods on mature, normal or unconventional fields.

The goal of any well stimulation method is to increase the production by removing damage in the vicinity of the wellbore, or by creating new highly conductive pore channels. This way we increase the formation flow capacity and the wellbore radius, allowing more fluid to flow into the well. Commonly used stimulation techniques are matrix acidizing, hydraulic fracturing and acid fracturing.

A hydraulic fracturing operation consists of pumping a viscous fluid at a sufficiently high pressure into the completion interval, so that a two winged hydraulic fracture is formed. This fracture is then filled with a high conductivity proppant, which holds the fracture open after the treatment is finished. The propped fracture can have a width between 5mm and 35mm and a length of 100m or more, depending on the design technique employed and the size of the treatment. The candidate wells usually have low permeability 1-50 mD for oil, and 0.01-10 mD for gas reservoirs. After the treatment these poorly featured wells can produce 10 times more hydrocarbons.

Due to restriction of extent, in my work I put emphasis on the theoretical part of the operation. I gave a short description of the very basics of rock mechanics and fracture propagation, to have a better understanding on the topic. During my research, I examined more than 200 wells, drilled in Hungary, to gather data about the formations' strength. My research covers the whole country and involves pressures of different depths and formations.

From the data I collected, I managed to create a map of the formations' fracturing gradients, which clearly illustrates the pressure distribution in different depths. It is essential to know the conditions of a reservoir at any depth, since without exact data no safe design can be made.

Otherwise, any design could easily result in failure or in non-economic solutions, which should obviously be evaded.

As a conclusion, I would like to note, that this paper is unique; there is no similar database in Hungary. It was the first time, when Leak-off data were collected and summarized. This database and the gradients can make the future drilling, casing or fracturing designs easier and more precise. I hope this paper and my results will be great use in the future.

1 Theoretical basics of hydraulic fracturing

1.1 Formation stress

The in-situ stress, as it affects hydraulic fracturing, is the local stress in a given rock mass at depth. The three principal stress components are the result of the weight of the overburden rocks' properties, like porosity, pore pressure, tectonic features etc. In addition, drilling, production and fracturing can also alter some of these parameters, thereby changing the local stress field.

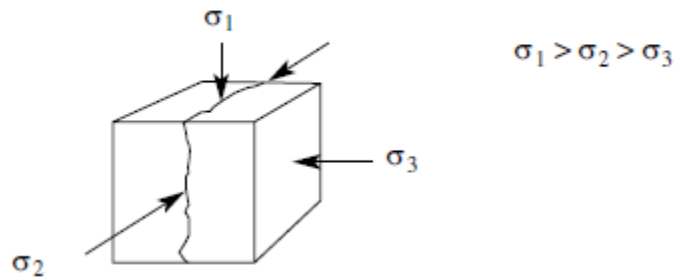


Figure 1: In-situ stress field

(Source: Economides: Modern fracturing)

Usually, these three principal stresses are different. The vertical stress (σ_1) equals the weight of the overburden, hence it is the largest. Its value can usually be obtained from density logs, or if that is not available, an average of 1.0 psi/ft stress gradient is a good approximation.

The other two unequal horizontal stresses (the so called minimum and intermediate stresses σ_2 , σ_3) are smaller and can be obtained by calculation with the help of the Poisson's ratio (ν), which is the ratio between lateral and longitudinal strains.

$$\nu = \frac{-\varepsilon_y}{\varepsilon_x}$$

Where: ε_y stands for the lateral strain

ε_x stands for the longitudinal strain

ν stands for the Poisson ratio

If we assume that the horizontal stress depends only on the elastic behavior of the rock, the overburden load can be related to the horizontal stresses via the above Poisson effect together with assumptions about the lateral boundary conditions. In a tectonically relaxed area, the two horizontal stress components will have the same value within a specific lithology: [1]

$$\sigma_H = \sigma_h = \left(\frac{\nu}{1 - \nu} \right) \times \sigma_v = \frac{1}{3} \sigma_v$$

If we assume $\nu = 0.25$ (usual value for rocks)

The equation indicates that the Poisson's ratio can have a significant influence on the horizontal stress and also shows, that its value (unless in extreme conditions) will always be less than the vertical stress.

The in-situ stress relations control the fracture orientation, propagation, containment etc. The split will propagate in the direction of the least resistance, hence perpendicularly to the minimum in-situ stress.

Figure 2 represents the fracture geometry for different wellbore situations. It perfectly illustrates how the fracture plane changes with different wellbore orientations. To optimize hydraulic fracturing, there are recommendations for the drilling phase. According to this, the wellbore should be oriented to the expected fracture plane to provide the best conditions for the treatment.

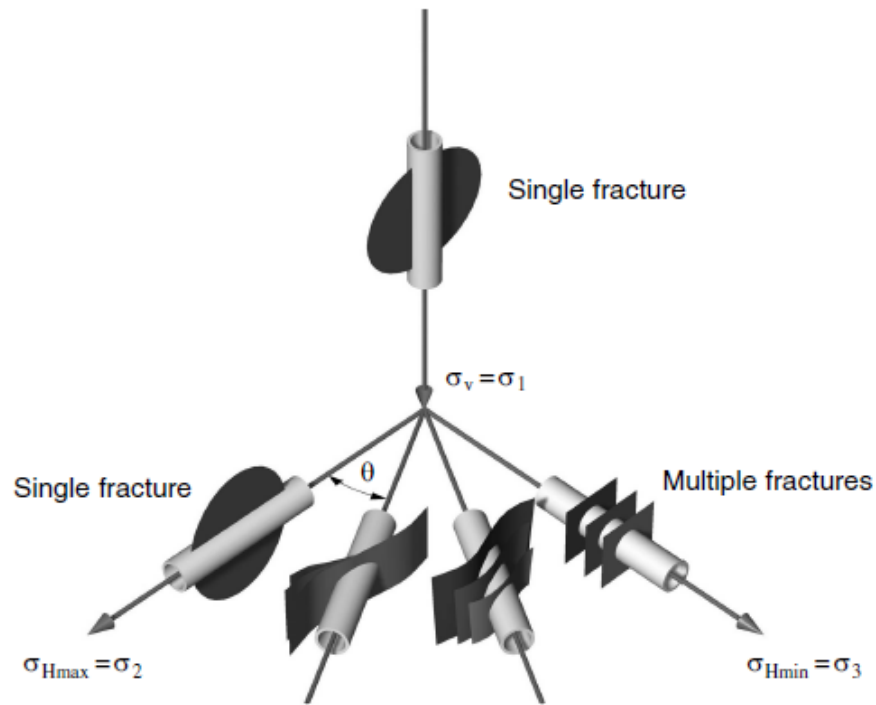


Figure 2: Fracture geometry

(Source: Heriot Watt University: Hydraulic fracturing)

1.2 Fracture propagation

As discussed before, the fracture propagates to the least resistant direction. To better understand its physics, let's see what this force is consist of.

Fracture propagation pressure (FPP) = minimum rock effective stress + pore pressure +
fracture toughness

The treatment's pressure must overcome these forces to penetrate the formation and create adequate fracture.

Another important factor is the Formation Initiation Pressure (FIP), which is needed to initiate the cracking of the rock. This is normally greater than the FPP, since extra force is needed to overcome the tensile stresses in the vicinity of the wellbore and the pressure drop through the perforation (especially if it is not oriented properly).

Perforation's orientation must be mentioned, since it plays an important role in the fracture propagation.

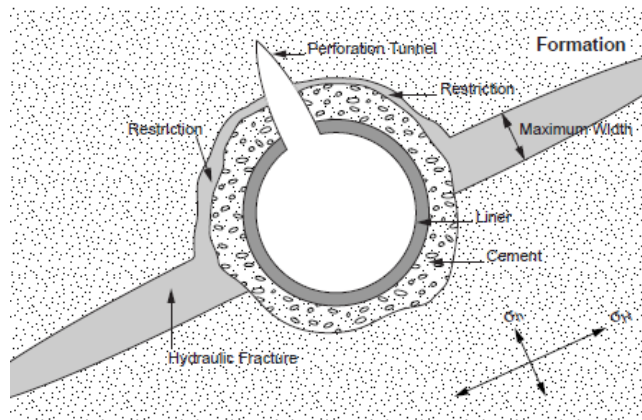


Figure 3: Perforation

(Source: Heriot Watt University: Hydraulic fracturing)

The picture shows a poorly oriented, 0° phasing, perforation. We can observe how the fracture initiates from the perforation, goes around the well towards the favorable direction to propagate away from the well. In this case, the difference between the fluid pressure and the in-situ stress field is low; hence the created flow path will be narrow. This restricted flow path can cause serious problems, like premature screen out.

Field experience shows, that 60° phasing perforations can solve this problem. It insures that some perforations will be within 15° of the maximum horizontal stress plane, but more shots are required and may not provide focused fracture initiation. [2]

In order to plan a hydraulic fracturing treatment it is necessary to gather data about the formation. Such tests are the so called minifrac and microfrac tests, which are hydraulic fracturing operations, but performed with much smaller fluid volumes. Although, these tests provide abundant and accurate information, the execution price is high. For this reason people rely on different, cheaper methods instead.

Leak-off tests are performed during almost every drilling operation, thus they are prevalent. Their main advantage is the low price, and they provide sufficient information on the formation.

However, their data is not as precise as a mini/microfrac, they can make a good use even so. The mechanics of Leak-off tests will be discussed later. [3]

Now, let us see how a data gathering test occurs. During these kind of operations fluid is pumped down at a constant rate, for a given time, and the bottom hole pressure is measured. The following figure illustrates the whole procedure.

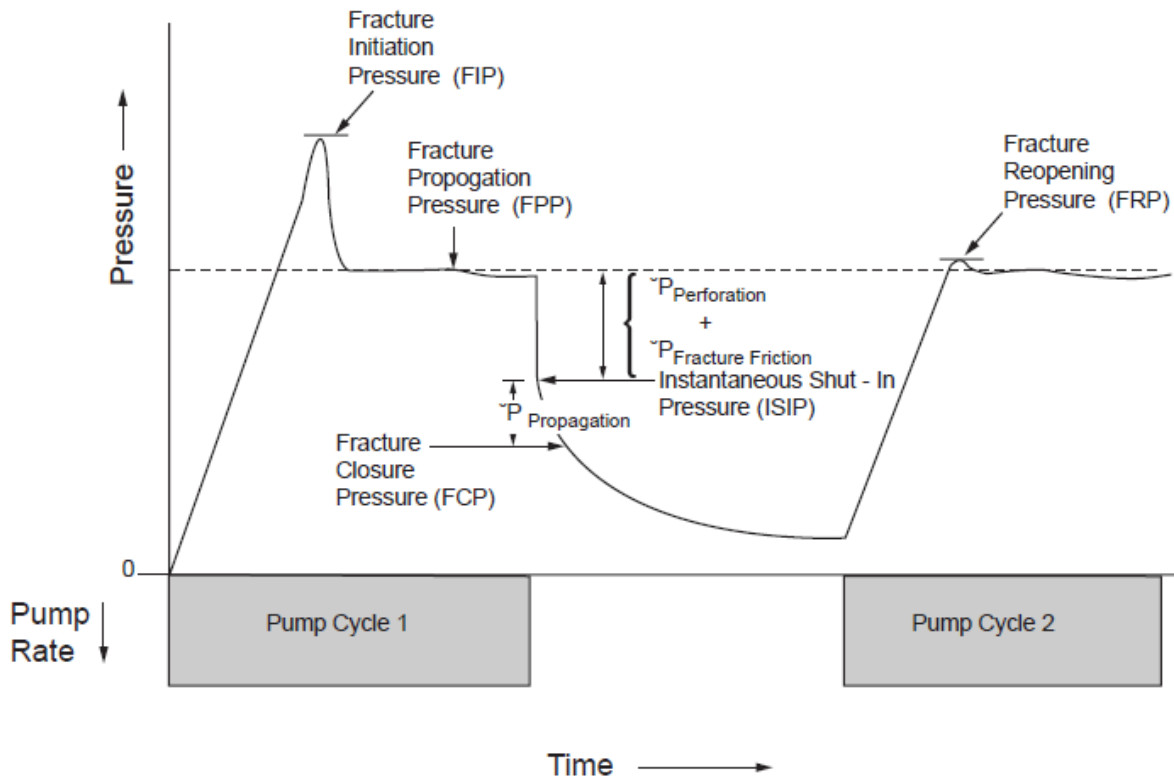


Figure 4: Bottom hole pressure measurement

(Source: Heriot Watt University: Hydraulic fracturing)

- The pumps start at a constant rate and the bottom hole pressure starts increasing as well. The pressure keeps rising until it reaches the so called Fracture Initiation Pressure (FIP), the point where the fluid's pressure overcomes the formation pressure and cracks it.
- After the FIP, the pressure rapidly drops to the Formation Propagation Pressure (FPP), meanwhile the fracture keeps growing, until the pumps are stopped.

- When the desired volume of fluid is pumped into the formation, the pumping stage gets suspended. This results in rapid pressure drop until it reaches the Instantaneous Shut-In Pressure (ISIP). In this time the fracture is still open, but starts closing.

$$ISIP = FCP - \Delta P_{\text{perforation}} - \Delta P_{\text{fracture friction}}$$

Where: $\Delta P_{\text{perforation}}$ is the pressure drop through the perforations

$\Delta P_{\text{fracture friction}}$ is the frictional pressure drop in the fracture

- The pressure keeps dropping until it reaches the Fracture Closure Pressure (FCP). It means that the pressure will be equal to the minimum in-situ stress, and the fracture closes.

$$ISIP = FCP + \Delta P_{\text{fracture propagation}}$$

Where: $+\Delta P_{\text{fracture propagation}}$ is the pressure needed to overcome the fracture toughness

- As we can read from the figure, while pumping the next stage of fluid, the fracture reopening pressure will be much lower, than it was originally. It is because the treatment does not have to overcome all the stresses again to reopen the fractured formation.

1.3 Fracture containment

A hydraulic fracture grows mainly in horizontal and vertical direction, having a much smaller width than height and length. The vertical lithological contrasts are the limiting factors for fracture height growth. Usually the growth in vertical direction decreases compared to the horizontal. This is called vertical containment. A fracture with much greater horizontal length than vertical height is called rectangular.

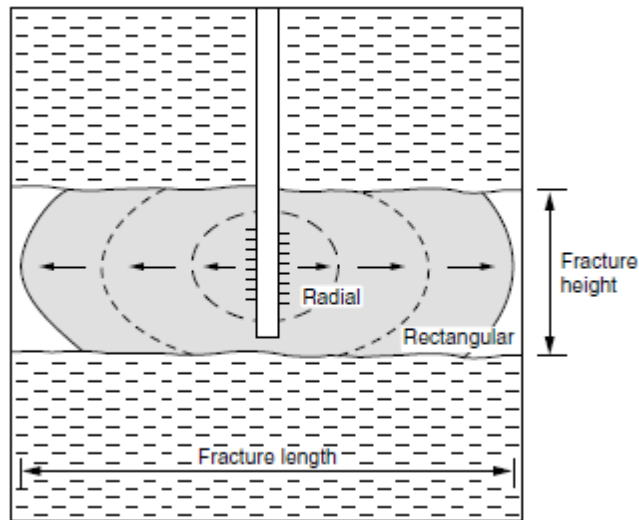


Figure 5: Fracture containment
(Source: Shell: Hydraulic fracturing manual)

There are several parameters that can lead to containment. The most important is the previously discussed in-situ stress. The containment depends on the relationship between the in-situ stress and the fracturing pressure. If the in-situ stress is higher in the neighboring formation, the fracture will be contained. But if the stress contrast is smaller, then some degree of fracture growth can be expected. [4]

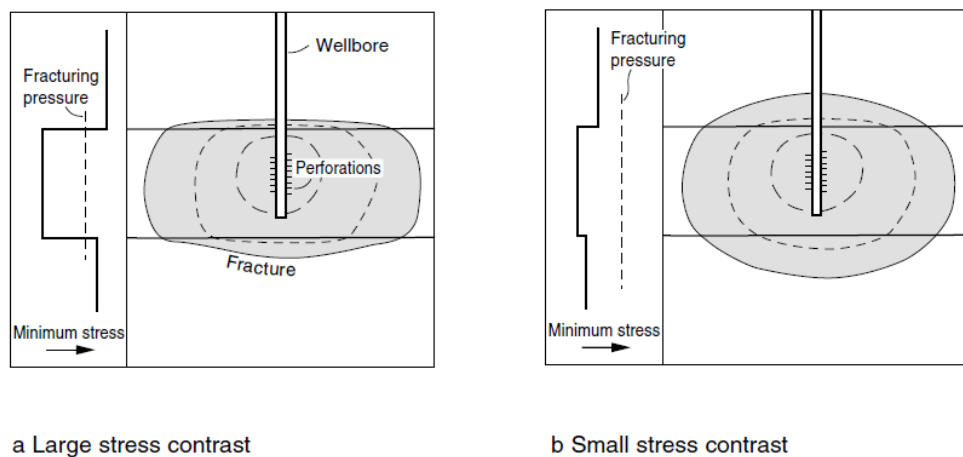


Figure 6: Fracture containment
(Source: Shell: Hydraulic fracturing manual)

The fracture containment is also influenced by:

- Young’s modulus. The bigger its value in the neighboring layers, the easier the containment is.
- Poisson’s ratio. Increased values of Poisson’s ratio lead to more difficult fracture propagation.
- High leak-off. If the fracture reaches a highly permeable zone it may become impossible to rip it.

1.4 Productivity improvement factor

A commonly used measure of the ability of the well to produce is the Productivity Index (PI). The productivity improvement factor is the fraction of the fractured well’s PI and the original PI. Its value depends on two factors: the dimensionless fracture conductivity and the dimensionless length.

These are defined as:

$$L_D = \frac{L}{r_e}$$

Where: L is fracture length (m)

r_e is drainage radius (m)

$$F_{CD} = \frac{k_f * w}{k * L}$$

Where: k_f is fracture permeability (mD)

w is fracture width (m)

k is formation permeability (mD)

The following figure represents the relation of these two factors.

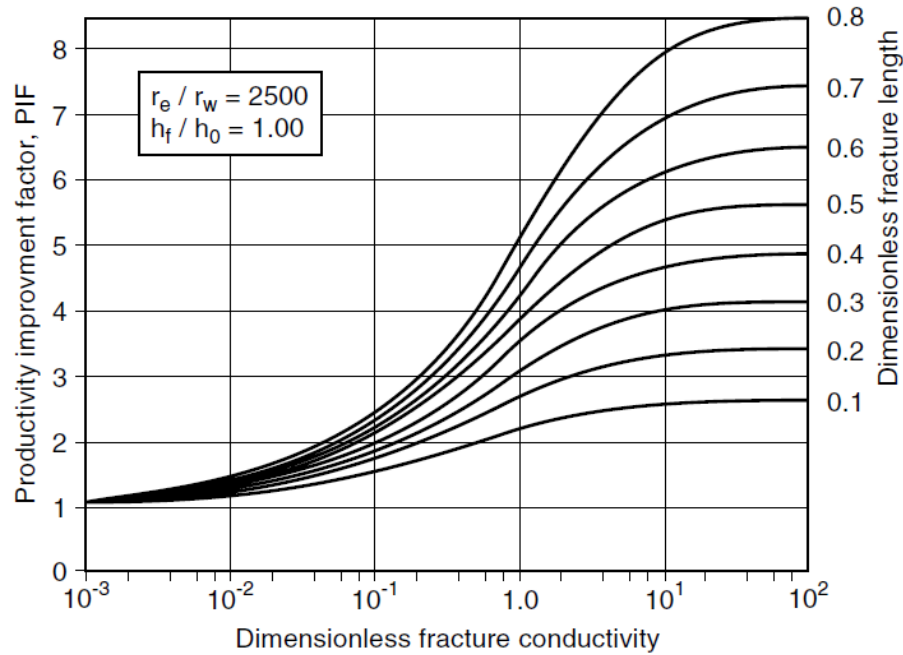


Figure 7: Representation of the Dimensionless productivity index by McGuire-Sikora

(Source: Economides: Modern fracturing)

From the figure, the following conclusions can be made:

- Productivity improvement factor increases with length
- The productivity improvement factor increases with increasing fracture conductivity. However, the maximum improvement is already obtained at a dimensionless fracture conductivity of about 15. Thereafter no further improvement is possible.

These conclusions are valid for all ratios of wellbore and drainage radius. These factors are particularly emphatic in fracture designs. Generally the fracture length is determined by economic criteria, and then the dimensionless fracture conductivity is selected accordingly. In practice, a balance between fracture length and conductivity must be found to ensure the perfect well deliverability.

2 Formation integrity tests

The term formation integrity is widely used in the industry. It usually indicates a test to determine the formation's strength. These tests are as follows:

- Limit test: A test carried out to a pre-defined value, which is smaller than the formation pressure.
- Leak-off test (LOT). A test carried out to the leak-off point, but not further.
- Fracture gradient test. A test carried out to the leak-off point and beyond, until the formation breaks.

Since I analyzed mainly Leak-off test data (except a few well data), I am going to write solely about LOT.

2.1 Leak-off test

“A test to determine the strength or fracture pressure of the open formation, usually conducted immediately after drilling below a new casing shoe. During the test, the well is shut in and fluid is pumped into the wellbore to gradually increase the pressure that the formation experiences. At some pressure, fluid will enter the formation, or leak off, either moving through permeable paths in the rock or by creating a space by fracturing the rock. The results of the leak-off test dictate the maximum pressure or mud weight that may be applied to the well during following drilling operations. To maintain a small safety factor to permit safe well control operations, the maximum operating pressure is usually slightly below the leak-off test result.” [5]

The guide line procedure of a Leak-off test is as follows:

1. When the casing shoe is set, we drill ahead a few feet (10-15 ft). This is the open hole where the test will be performed.
2. Mud circulation is necessary until it gets uniform in the well. When it is reached, the drill bit is pulled into the casing shoe.
3. Pumping of high pressure fluid is started, on a low rate. The Blowout preventer is closed.

4. Constant pump stroke is maintained, while the corresponding volume vs pressure data is registered.
5. Plot a graph between strokes pumped and the pressure.
6. When change in the pressure curve is noticed, the pumping must be stopped immediately.
7. Record the pressure data, which is the leak-off pressure.

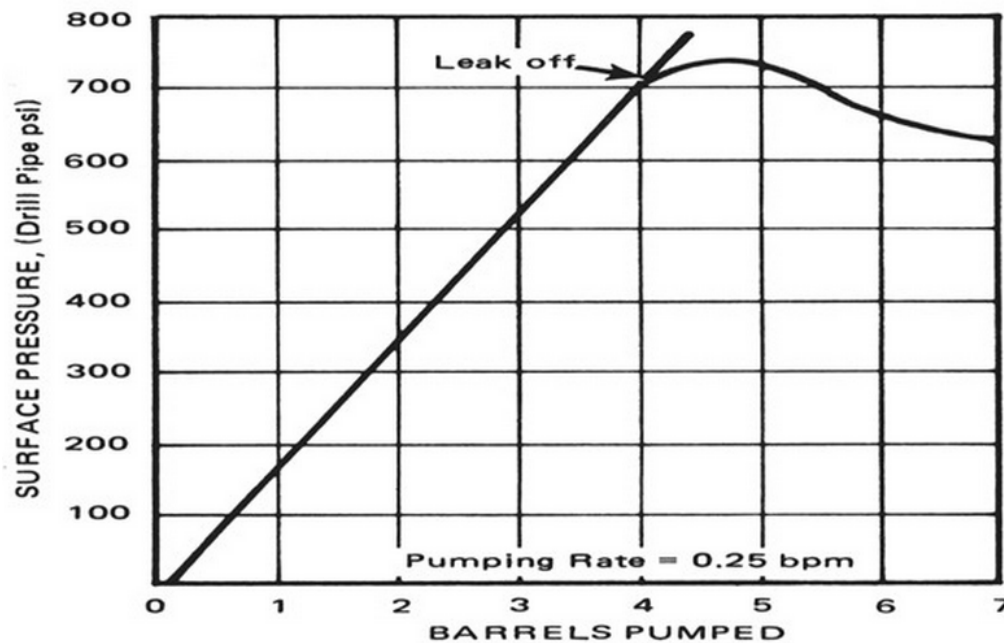


Figure 8: Leak-off test

(Source: <http://slideplayer.us/slide/1712863/#>)

2.2 Fracture gradient determination

A number of theoretical and field-developed equations have been used to approximate fracture gradients. Many of these are suitable for immediate application in a given area, while others require measurements taken after the well has been drilled.

Accurate knowledge of the fracture gradient enables:

- Planning of a drilling program, casing depths and maximum mud weights
- Calculation of the maximum annular pressure (MAASP) when controlling a kick

- Calculation of kick tolerances while drilling
- Estimation of pressures required for stimulating by hydraulic fracturing

2.2.1 Hubbert and Willis method

This method is based on the assumption, that fracturing occurs when the fluid pressure overcomes the formation pressure. They believed this stress relationship to be in the range of 1/3 to 1/2 of the total overburden. Therefore fracture gradient determination would be as follows:

$$F_{max} = \frac{1}{2} \left(1 + \frac{P}{D} \right) \quad F_{min} = \frac{1}{3} \left(1 + \frac{2P}{D} \right)$$

Where: F is fracturing gradient [psi/ft]

P is pore pressure [psi]

D is depth [ft]

2.2.2 Eaton's Method

Eaton's method builds on the theory established by Hubbert and Willis and assumes that rock deformation is plastic. On the basis that Poisson's ratio and overburden vary with depth, Poisson's ratio has to be derived from regional data for the fracture gradient, formation pressure and overburden gradient.

$$F = \left(\frac{S - P}{D} \right) * \left(\frac{v}{1 - v} \right) + \frac{P}{D}$$

Where: S is overburden pressure [psi]

v is Poisson's ratio

3 Calculation

For the calculations I used the above listed methods. Both, Willis and Eaton's method gave equal results, assuming the Poisson's ratio to be 0.25. This ratio is the average value in the literature. To achieve higher accuracy for the different type of rocks, I modified the corresponding Poisson ratio what resulted in more accurate results. Let us see the calculation itself.

First, the examined wells and the gathered data are shown in Table 1. 176 wells' data are listed below. All these wells are located in Hungary; their distribution can be seen on the map attached.

Pressure and Total vertical depth data are from the Leak-off tests, the other parameters are calculations. I used the value of the normal formation gradient for the pore pressure calculations. In Hungary, it is 0.442 psi/ft. The sum of the formation pressure and the Leak-off pressure gives the fracture pressure. We can observe that the calculated and the measured values are fairly equal, aside from formations, where abnormal pressure was present.

To increase the accuracy I used mixed values of Poisson's ratio, where multiple formations were identified. This is why for example a sandstone-sand containing formation has different Poisson value, than a sandstone-siltstone one.

Finally, I created a few gradient diagrams representing some of the most frequent formations.

Table 1: Calculations

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Algyő-Nyugat-2	638	3352,16	1481,6547	2105,156	2105,15	2209,0734	2119,654	siltstone sand	0,28	0,659
Algyő DK-1	1015	3378,4	1493,2528	2121,635	2121,63	2226,3656	2508,252	sandstone sand	0,28	0,659
Álmosd É-1	1160	3548,96	1568,6403	2228,747	2228,74	2127,1920	2728,640	sandstone	0,22	0,599385
Bak-Dél-1	159,5	3348,88	1480,2049	2103,097	2103,09	2038,3806	1639,704	sandstone, siltstone	0,23	0,608675
Bak-Délnyugat-1	1595,4	3526	1558,4920	2214,328	2214,32	2146,1891	3153,892	siltstone, sandstone	0,23	0,608675
Baracska-1	725	2296	1014,8320	1441,888	1441,88	1704,6916	1739,832	claystone	0,35	0,742462

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Belezna M-1	2175	7429,2	3283,7064	4665,538	4665,53	4452,9481	5458,706	sandstone	0,22	0,599385
Belezna-24	1957,5	7189,76	3177,8739	4515,169	4515,16	4980,3154	5135,373	marl, clay marl	0,31	0,692696
Belezna-Kelet-1	3074,8	9279,12	4101,3710	5827,287	5827,28	5647,9713	7176,171	sandstone, conglomerate	0,23	0,608675
Belezna-Kelet-1	1073,3	7268,48	3212,6681	4564,605	4564,60	5034,8444	4285,968	marl, clay marl	0,31	0,692696
Belezna-Kelet-1	826,5	3312,8	1464,2576	2080,438	2080,43	1985,6413	2290,757	sandstone	0,22	0,599385
Belezna-Kelet-2	1522,9	7258,64	3208,3188	4558,426	4558,42	5028,0283	4731,218	marl, clay marl	0,31	0,692696

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Belezna-Kelet-2	899,2	3309,52	1462,8078	2078,379	2078,37	2145,8383	2362,007	marl, sandstone	0,27	0,648384
Bér-1	754	4008,16	1771,6067	2517,124	2517,12	2776,4350	2525,606	marl	0,31	0,692696
Berettyószentmárton-Dél-1	1798	7491,52	3311,2518	4704,675	4704,67	4936,9116	5109,251	claymarl,siltstone	0,28	0,659
Berettyószentmárton-Dél-1	1580,5	7462	3298,2040	4686,136	4686,13	4917,458	4878,704	clay marl, siltstone	0,28	0,659
Berettyószentmárton-Dél-1	1261,5	7053,41	3117,6074	4429,542	4429,54	4648,1974	4379,107	clay marl, siltstone	0,28	0,659
Beru-1	362,5	3424,32	1513,5494	2150,473	2150,47	2256,6268	1876,049	clay , sandstone	0,28	0,659

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Beru-1	2030	7314,4	3232,9648	4593,443	4593,44	4820,1896	5262,964	siltstone, clay marl	0,28	0,659
Beru-2	362,5	3270,16	1445,4107	2053,66	2053,66	2155,0354	1807,910	siltstone, clay	0,28	0,659
Beru-2	1232,5	6724	2972,01	4222,672	4222,67	4580,0045	4204,508	siltstone, claystone	0,3	0,681143
Beru-2	1450	9256,16	4091,22	5812,868	5812,86	6304,7672	5541,222	siltstone, claystone	0,3	0,681143
Beru-6	1435,5	4942,96	2184,79	3104,179	3104,17	3543,2907	3620,288	clay	0,33	0,716836
Beru-6	1972	9662,88	4270,99	6068,289	6068,28	6367,8379	6242,992	siltstone, claymarl	0,28	0,659

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Beru-6	1450	11365,2	5023,42	7137,346	7137,34	7137,3456	6473,418	tuff, marl	0,25	0,628
Berzence-2	1102	3870,4	1710,72	2430,611	2430,61	2509,5037	2812,716	clay marl, sandstone	0,27	0,648384
Borota-2	870	1574,4	695,88	988,7232	988,723	1020,8150	1565,884	clay marl, sandstone	0,27	0,648384
Csanádapáca É-1	1232,5	6733,84	2976,36	4228,852	4228,85	4098,7222	4208,857	sandstone, siltstone	0,23	0,608675
Csanádapáca É-2	507,5	2889,68	1277,24	1814,719	1814,71	1732,0297	1784,738	sandstone	0,22	0,599385
Csévharaszt-2	768	2010,64	888,70	1262,682	1262,68	1466,6704	1656,702	clay, claystone	0,34	0,729455

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Dombegyháza DNY-7	725	2040,16	901,75	1281,22	1281,22	1462,4597	1626,750	clay	0,33	0,716836
Dombegyháza DNY-9	652,5	1826,86	807,47	1147,269	1147,26	1287,1851	1459,972	sand	0,32	0,704588
Földes ÉK-1	797,5	5185,68	2292,07	3256,607	3256,60	3156,3954	3089,570	sandstone, siltstone	0,23	0,608675
Földes-23	942,5	5238,16	2315,27	3289,564	3289,56	3567,9352	3257,766	claystone, siltstone	0,3	0,681143
Földes-23	1812,5	8672,32	3833,17	5446,217	5446,21	5715,0588	5645,665	siltstone, clay marl	0,28	0,659
Gomba-1	1015	4018	1775,96	2523,304	2523,30	2445,6574	2790,956	sandstone, siltstone	0,23	0,608675

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Gomba-2	246,5	1692,48	748,08	1062,877	1062,87	1213,2302	994,5761	clay, sand	0,33	0,716836
Gomba-2	1015	6015,52	2658,86	3777,747	3777,74	3551,1365	3673,859	siltstone, tuff	0,21	0,590329
Gomba-3	1261,5	4526,4	2000,67	2842,579	2842,57	2755,1079	3262,168	sandstone, siltstone	0,23	0,608675
Gomba-4	754	4408,32	1948,48	2768,425	2768,42	2683,2356	2702,477	sandstone, siltstone	0,23	0,608675
Gomba-6	319	1712,16	756,77	1075,236	1075,23	1248,9428	1075,774	clay, claystone	0,34	0,729455
Gomba-6	1160	4726,48	2089,10	2968,229	2968,22	2748,4481	3249,104	tuffy sandstone	0,2	0,5815

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Gomba-8	1769	4657,6	2058,66	2924,973	2924,97	2791,6937	3827,659	sandstone	0,22	0,599385
Gutorfölde-1	1029,5	3345,6	1478,76	2101,037	2101,03	2036,3841	2508,255	siltstone, sandstone	0,23	0,608675
Hahót DNY-1	261	2564,96	1133,71	1610,795	1610,79	1663,0779	1394,712	clay marl, sandstone	0,27	0,648384
Hahót-Ederics-92	870	3066,8	1355,53	1925,95	1925,95	1988,4627	2225,525	clay marl, sandstone	0,27	0,648384
Hajdúbagos-K-1	1464,5	5066,74	2239,50	3181,917	3181,91	3084,0039	3704,002	siltstone, sandstone	0,23	0,608675
Hajdúbagos-K-1	290	2033,6	898,85	1277,101	1277,10	1218,9085	1188,851	sandstone	0,22	0,599385

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Hencida-1	826,5	2637,12	1165,61	1656,111	1656,11	1766,6475	1992,107	clay, siltstone	0,29	0,669915
Heresznye-Dél-1	1232,5	3325,92	1470,06	2088,678	2088,67	2024,4054	2702,556	siltstone, sandstone	0,23	0,608675
Hosszúpályi D-2	754	4526,4	2000,67	2842,579	2842,57	2755,1079	2754,668	siltstone, sandstone	0,23	0,608675
Hosszúpályi D-3	942,5	4214,8	1862,94	2646,894	2646,89	2565,4447	2805,441	siltstone, sandstone	0,23	0,608675
Hosszúpályi D-4	1044	3968,8	1754,21	2492,406	2492,40	2415,7106	2798,209	siltstone, sandstone	0,23	0,608675
Hosszúpályi D-5	623,5	3978,64	1758,56	2498,586	2498,58	2421,6999	2382,058	siltstone, sandstone	0,23	0,608675

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Hosszúpályi D-6	957	3985,2	1761,46	2502,706	2502,70	2714,4905	2718,458	claystone, sandstone	0,3	0,681143
Hosszúpályi D-8	1479	4482,77	1981,39	2815,183	2815,18	2728,5551	3460,386	sandstone, siltstone	0,23	0,608675
Jánoshalma D-1	652,5	1699,04	750,98	1066,997	1066,99	1176,9176	1403,475	clay, clay marl	0,31	0,692696
Jászberény NY-4	290	1728,56	764,02	1085,536	1085,53	1139,1210	1054,023	sand, siltstone	0,28	0,659
Jászberény NY-4	580	6254,96	2764,69	3928,115	3928,11	3530,8486	3344,692	tuff	0,18	0,564488
Kerkabarabás	725	2712,56	1198,95	1703,488	1703,48	1878,9785	1923,951	clay, clay marl	0,31	0,692696

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Komádi NY-2	1218	3919,43	1732,39	2461,406	2461,40	2582,9083	2950,390	sandstone, clay	0,28	0,659
Komádi NY-2	1261,5	8426,32	3724,43	5291,729	5291,72	5552,944	4985,933	siltstone, clay marl	0,28	0,659
Lakócsa-1	942,5	3886,8	1717,97	2440,91	2440,91	2520,1372	2660,465	sand, sandstone	0,27	0,648384
Létavértes-1	652,5	3890,08	1719,42	2442,97	2442,97	2522,2639	2371,915	claystone, sandstone	0,27	0,648384
Magyarbánhegyes D-2	1015	3335,76	1474,41	2094,857	2094,85	2198,2658	2489,405	clay, sandstone	0,28	0,659
Magyarbánhegyes D-2	1073	6113,92	2702,35	3839,542	3839,54	4235,0858	3775,352	marl	0,31	0,692696

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Magyarbánhegyes- K-2	580	2886,4	1275,79	1812,659	1812,65	1871,4943	1855,788	sandstone, clay	0,27	0,648384
Magyarbánhegyes- K-2	1044	6861,76	3032,90	4309,185	4309,18	4753,1113	4076,897	marl, clay marl	0,31	0,692696
Magyarbánhegyes- K-3	1044	6828,36	3018,14	4288,216	4288,21	4729,9819	4062,139	marl, clay marl	0,31	0,692696
Magyarbánhegyes- K-3	507,6	2824,08	1248,24	1773,522	1773,52	1831,0870	1755,843	siltstone, lignite	0,27	0,648384
Makó NY-1	72,5	1079,12	476,97	677,6874	677,687	760,33525	549,4710	sand clay	0,32	0,704588
Makó NY-1	1015	4893,76	2163,04	3073,281	3073,28	3173,0335	3178,041	sandstone, clay marl	0,27	0,648384

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Mezőgyán D-1	928	3371,70	1490,30	2117,433	2117,43	2296,6153	2418,299	claystone, siltstone	0,3	0,681143
Mezőgyán D-1	1696,5	7248,8	3203,97	4552,246	4552,24	4937,4683	4900,469	claystone, siltstone	0,3	0,681143
Mezőhegyes DK-1	435	1590,76	703,12	999,0018	999,001	1120,8358	1138,119	sand	0,32	0,704588
Mezőhegyes DK-2	391,5	1574,23	695,81	988,6202	988,620	1109,1881	1087,312	sand	0,32	0,704588
Mezősas NY-10	2247,5	5041,36	2228,28	3165,974	3165,97	3322,2562	4475,781	siltstone, clay marl	0,28	0,659
Mezősas NY-10	1450	8485,36	3750,53	5328,806	5328,80	5591,8522	5200,529	clay marl, siltstone	0,28	0,659

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Mogyoród-2	754	1794,16	793,02	1126,732	1126,73	1163,3038	1547,018	clay marl, sandstone	0,27	0,648384
Monor ÉK-1	1812,5	4985,6	2203,64	3130,957	3130,95	2988,2919	4016,135	sandstone	0,22	0,599385
Monostorpályi D-1	1247	4598,56	2032,56	2887,896	2887,89	2799,0300	3279,563	siltstone, sandstone	0,23	0,608675
Monostorpályi DK-1	348	3673,6	1623,73	2307,021	2307,02	2420,9024	1971,731	siltstone, clay	0,28	0,659
Monostorpályi K-1	986	3567,65	1576,90	2240,488	2240,48	2351,0853	2562,903	clay marl, siltstone	0,28	0,659
Monostorpályi K-1	3320,5	7746,67	3424,03	4864,91	4864,90	5105,0563	6744,528	clay marl, siltstone	0,28	0,659
Nagykáta-3	725	3768,72	1665,77	2366,756	2366,75	2524,7239	2390,774	clay , siltstone	0,29	0,669915

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Nagykáta-Nyugat- 1	1377,9	8385,94	3706,59	5266,372	5266,37	4876,4259	5084,486	dolomite limestone	0,2	0,5815
Nagykáta-Nyugat- 1	2436,6	6281,03	2776,22	3944,491	3944,49	3944,4906	5212,817	tuff, clay marl	0,25	0,628
Nagykörös-D-3	348	2204,16	974,24	1384,212	1384,21	1384,2124	1322,238	siltstone	0,25	0,628
Nagyrecse M-1	710,5	1722	761,12	1081,416	1081,41	1134,798	1471,624	clay,sandston e	0,28	0,659
Nagyrecse M-1	2320	6937,2	3066,24	4356,562	4356,56	4571,6148	5386,242	clay marl, siltstone	0,28	0,659
Nagyszénás ÉK-1	1392	6504,24	2874,87	4084,663	4084,66	3958,9703	4266,874	siltstone, sandstone	0,23	0,608675

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Nagyszénás ÉK-1	928	9672,03	4275,04	6074,036	6074,03	6074,0355	5203,037	clay, sandstone	0,25	0,628
Nagyszénás ÉK-1	2102,5	10766,8	4758,95	6761,59	6761,58	7586,2045	6861,453	clay marl	0,32	0,704588
Ócsa-4	1131	3447,96	1524,00	2165,324	2165,32	2272,2114	2655,002	siltstone, marl	0,28	0,659
Ortaháza NY-6	826,5	2994,64	1323,63	1880,634	1880,63	1941,6753	2150,130	sandstone, clay marl	0,27	0,648384
Őrtilos-1	1740	4496,88	1987,62	2824,041	2824,04	2663,6209	3727,620	clay marl, siltstone		0,442
Páhi-2	942,5	2043,44	903,20	1283,28	1283,28	1439,7837	1845,700	clay, sand	0,32	0,704588
Péterhida-1	1450	6940,48	3067,69	4358,621	4358,62	4573,7763	4517,692	siltstone, clay marl	0,28	0,659

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Pötréte-2	725	2364,88	1045,28	1485,145	1485,14	1533,3493	1770,276	clay marl, sandstone	0,27	0,648384
Pusztaföldvár É-1	870	3096,32	1368,57	1944,489	1944,48	1884,6535	2238,573	sandstone, siltstone	0,23	0,608675
Pusztaszőlős-57	391,5	1777,76	785,77	1116,433	1116,43	1252,5887	1177,269	sand, clay	0,32	0,704588
Püspökladány K-1	478,5	1640	724,88	1029,92	1029,92	1155,5247	1203,380	sand, clay	0,32	0,704588
Ráckeve-1	797,5	3378,4	1493,25	2121,635	2121,63	2024,9609	2290,752	siltstone, claystone	0,22	0,599385
Ráckeve-Nyugat- 1ST2	1479	3968,8	1754,21	2492,406	2492,40	2378,8376	3233,209	siltstone, claystone	0,22	0,599385

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Ráckeve-Nyugat- 1ST2	2842	8885,48	3927,39	5580,086	5580,08	5761,2038	6769,385	clay marl, sandstone	0,27	0,648384
Rádiháza-1	1580,9	3903,2	1725,21	2451,21	2451,20	2375,7815	3306,114	siltstone, sandstone	0,23	0,608675
Sávoly D-7	870	3509,6	1551,24	2204,029	2204,02	2275,5669	2421,243	clay marl, sandstone	0,27	0,648384
Sávoly D-8	725	3772	1667,22	2368,816	2368,81	2295,9233	2392,224	siltstone, sandstone	0,23	0,608675
Sávoly-Délkelet- 11	1189	3431,50	1516,72	2154,984	2154,98	2261,3606	2705,724	siltstone, sand	0,28	0,659
Sávoly-Délkelet- 12 ST	1450	3391,52	1499,05	2129,875	2129,87	2199,0058	2949,051	clay marl, sandstone	0,27	0,648384

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Sávoly-DK-11	1189	3430,88	1516,45	2154,593	2154,59	2088,2919	2705,448	siltstone, sandstone	0,23	0,608675
Sávoly-DK-12	1450	3391,52	1499,05	2129,875	2129,87	2199,0058	2949,051	clay marl, sandstone	0,27	0,648384
Síkabonyi-1	333,5	1705,6	753,88	1071,117	1071,11	1201,7456	1087,375	clay, sand	0,32	0,704588
Síkabonyi-1	725	5943,36	2626,97	3732,43	3732,43	3354,9542	3351,965	tuff	0,18	0,564488
Sülysáp É-1	1305	4526,4	2000,67	2842,579	2842,57	2982,8976	3305,668	siltstone, clay marl	0,28	0,659
Sülysáp-1	1087,5	5753,12	2542,88	3612,959	3612,95	3448,3316	3630,379	sandstone	0,22	0,599385
Sülysáp-É-2	609	2197,6	971,34	1380,093	1380,09	1548,4031	1580,339	sand	0,32	0,704588

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Sülysáp-Észak-4	609,2	2223,84	982,94	1396,572	1396,57	1514,7527	1592,137	claystone, siltstone	0,3	0,681143
Szank-148	1203,5	6195,92	2738,60	3891,038	3891,03	4291,8868	3942,096	marl	0,31	0,692696
Szentmártonkáta-1	1087,5	3729,36	1648,38	2342,038	2342,03	2074,6025	2735,877	limestone	0,17	0,556289
Szentmihálytelek	2320	6238,56	2757,44	3917,816	3917,81	4111,2110	5077,443	siltstone, clay marl	0,28	0,659
Szőkedencs K-1	551	3342,32	1477,31	2098,977	2098,97	2315,2105	2028,305	clay, clay marl,	0,31	0,692696
Szőkedencs NY-1	870	3850,72	1702,02	2418,252	2418,25	2496,7435	2572,018	clay marl, sandstone	0,27	0,648384

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Szőreg gáztároló- H1	1667,5	5976,16	2641,46	3753,028	3753,02	3637,5411	4308,962	sandstone, siltstone	0,23	0,608675
Szőreg gáztároló- H1	1624	5992,56	2648,71	3763,328	3763,32	3647,5234	4272,711	sandstone, siltstone	0,23	0,608675
Szőreg gáztároló- H10	1812,5	5972,88	2640,01	3750,969	3750,96	3580,0523	4452,512	sandstone	0,22	0,599385
Szőreg gáztároló- H10	1740	5982,72	2644,36	3757,148	3757,14	3585,9503	4384,362	sandstone	0,22	0,599385
Szőreg gáztároló- H2	1769	5959,76	2634,21	3742,729	3742,72	3627,5588	4403,213	sandstone, siltstone	0,23	0,608675
Szőreg gáztároló- H2	1783,5	5966,32	2637,11	3746,849	3746,84	3631,5517	4420,613	sandstone, siltstone	0,23	0,608675

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Szőreg gáztároló- H3	1667,5	5959,76	2634,21	3742,729	3742,72	3627,5588	4301,713	sandstone, siltstone	0,23	0,608675
Szőreg gáztároló- H3	1348,5	5966,32	2637,11	3746,849	3746,84	3631,5517	3985,613	sandstone, siltstone	0,23	0,608675
Szőreg gáztároló- H4	1812,5	5969,6	2638,56	3748,909	3748,90	3633,5482	4451,063	sandstone, siltstone	0,23	0,608675
Szőreg gáztároló- H5	1812,5	5979,44	2642,91	3755,088	3755,08	3639,537	4455,412	sandstone, siltstone	0,23	0,608675
Szőreg gáztároló- H6	1885	5986	2645,81	3759,208	3759,20	3643,5304	4530,812	sandstone, siltstone	0,23	0,608675
Szőreg gáztároló- H6	2030	5986	2645,81	3759,208	3759,20	3643,5304	4675,812	sandstone, siltstone	0,23	0,608675

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Szőreg gáztároló- H7	1116,5	5979,44	2642,91	3755,088	3755,08	3639,5383	3759,412	sandstone, siltstone	0,23	0,608675
Szőreg gáztároló- H7	1087,5	5972,88	2640,01	3750,969	3750,96	3635,5446	3727,512	sandstone, siltstone	0,23	0,608675
Szőreg gáztároló- H8	1566	5969,6	2638,56	3748,909	3748,90	3633,5482	4204,563	sandstone,silts tone	0,23	0,608675
Szőreg gáztároló- H8	1377,5	5963,04	2635,66	3744,789	3744,78	3629,5553	4013,163	sandstone, siltstone	0,23	0,608675
Szőreg gáztároló- H9	942,5	5986	2645,81	3759,208	3759,20	3643,5304	3588,312	sandstone, siltstone	0,23	0,608675
Szőreg gáztároló- H9	1885	5976,16	2641,46	3753,028	3753,02	3637,5411	4526,462	sandstone, siltstone	0,23	0,608675

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Tápióbicske-1	1406,5	6310,72	2789,34	3963,132	3963,13	3841,1795	4195,838	sandstone, siltstone	0,23	0,608675
Tápióság-1	103	1807,28	798,82	1134,972	1134,97	1273,3882	901,8177	sand	0,32	0,704588
Tápióság-1	1493,5	6235,80	2756,23	3916,085	3916,08	3795,5805	4249,725	siltstone, sandstone	0,23	0,608675
Tápióság-1	1348,5	8377,12	3702,69	5260,831	5260,83	5902,4201	5051,187	sand	0,32	0,704588
Tiszaszentimre-2	246,5	2050	906,10	1287,4	1287,4	1228,7384	1152,600	sandstone	0,22	0,599385
Tiszaszentimre-3	681,5	3378,4	1493,25	2121,635	2121,63	2421,7581	2174,752	Claystone clay marl	0,33	0,716836
Tóalmás D-4	1261,5	6418,96	2837,18	4031,107	4031,10	4031,1068	4098,680	siltstone	0,25	0,628

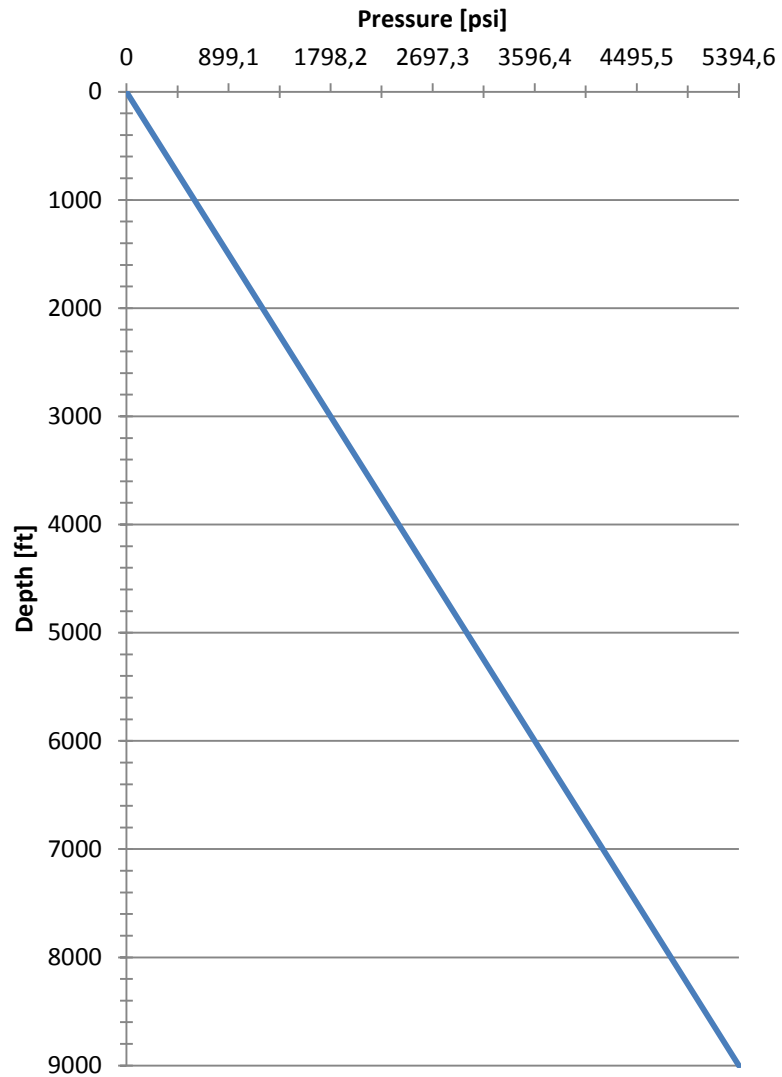
Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Tóalmás D-5	406	1682,60	743,71	1056,677	1056,67	1206,1531	1149,712	clay	0,33	0,716836
Tóalmás D-5	2421,5	5109,45	2258,38	3208,736	3208,73	3662,6387	4679,878	clay	0,33	0,716836
Tóalmás D-6	1812,5	5395,6	2384,86	3388,437	3388,43	3555,7004	4197,355	clay marl, siltstone	0,28	0,659
Tóalmás D-7	420,5	1712,12	756,76	1075,216	1075,21	1227,3141	1177,260	clay	0,33	0,716836
Tóalmás D-7	841	6945,17	3069,77	4361,567	4361,56	3753,6603	3910,765	breccia	0,15	0,540471
Tóalmás D-7	841	8240,63	3642,36	5175,121	5175,12	4453,8231	4483,362	breccia	0,15	0,540471
Tóalmás DK-1	826,5	5871,2	2595,07	3687,114	3687,11	4066,9547	3421,570	clay marl	0,31	0,692696
Tófej-1	1334	3345,46	1478,70	2100,954	2100,95	2204,6639	2812,697	clay marl, siltstone	0,28	0,659

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Tompapuszta-1	391,5	1689,2	746,63	1060,818	1060,81	1190,1904	1138,126	clay, sand	0,32	0,704588
Tormafölde-1	1015	3280	1449,76	2059,84	2059,84	2126,6980	2464,760	clay marl, sandstone	0,27	0,648384
Tormafölde-1	2610	7019,2	3102,49	4408,058	4408,05	4272,4138	5712,486	sandstone, siltstone	0,23	0,608675
Üllés-73	841	7019,2	3102,49	4408,058	4408,05	4625,6528	3943,486	siltstone, clay marl	0,28	0,659
Valkó-1	507,5	2394,4	1058,32	1503,683	1503,68	1577,9096	1565,824	claystone, siltstone	0,28	0,659
Vízvár É-4F	2900	9187,28	4060,78	5769,612	5769,61	6363,9889	6960,777	marl, clay marl	0,31	0,692696

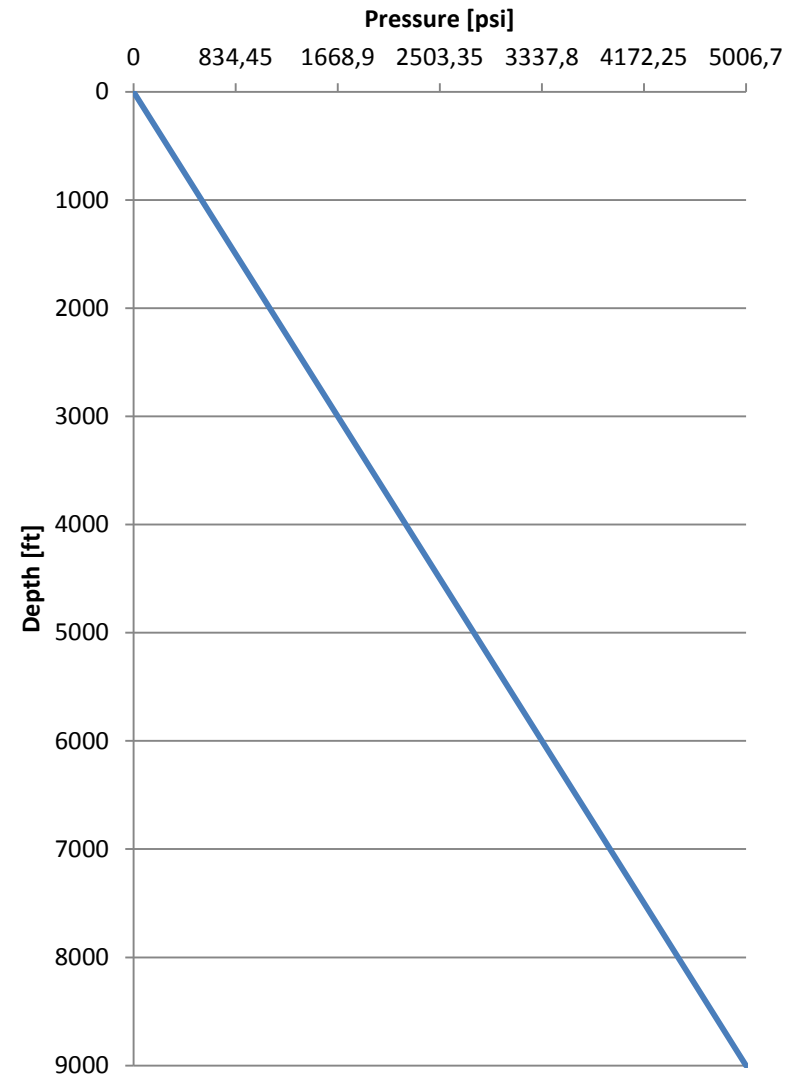
Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Vízhár S-1	2146	4493,6	1986,17	2821,981	2821,98	2735,1434	4132,171	sandstone, siltstone	0,23	0,608675
Vízhár-Dél-1	986,3	3785,64	1673,26	2377,385	2377,38	2304,2285	2659,555	sandstone, siltstone	0,23	0,608675
Vízhár-S-2	667	3348,88	1480,20	2103,097	2103,09	2038,3806	2147,204	sandstone, siltstone	0,23	0,608675
Zalabaksa-1	2175	5444,8	2406,60	3419,334	3419,33	3588,1232	4581,601	clay marl, siltstone	0,28	0,659
Zalakomár É-1	565,5	2870	1268,54	1802,36	1802,36	1891,33	1834,040	clay marl, siltstone	0,28	0,659
Zaláta-1	1667,5	6323,84	2795,14	3971,372	3971,37	3849,1653	4462,637	sandstone, siltstone	0,23	0,608675

Legal Well Name	Pressure [psi]	TVD [ft]	Pore pressure [psi]	Hubbert Willis [psi]	Eaton / 0,25 Poisson [psi]	Eaton / different Poisson [psi]	Fracture pressure [psi]	Formation	Poisson ratio	Gradient [psi/ft]
Zaláta-K-1	2131,5	6325,54	2795,89	3972,443	3972,44	3791,4347	4927,391	sandstone	0,22	0,599385
Zaláta-K-1	638	2092,64	924,95	1314,178	1314,17	1254,2962	1562,946	sandstone	0,22	0,599385
Zomba-1	435	1804	797,37	1132,912	1132,91	1188,836	1232,368	siltstone, clay marl	0,28	0,659
Zsáka-1	942,5	3034	1341,03	1905,352	1905,35	2032,5236	2283,528	siltstone, clay	0,29	0,669915
Zsáka-1	1087,5	7101,2	3138,73	4459,554	4459,55	4679,6908	4226,230	siltstone, marl	0,28	0,659
Zsáka-1	1131	7101,2	3138,73	4459,554	4459,55	4679,6908	4269,730	siltstone, marl	0,28	0,659

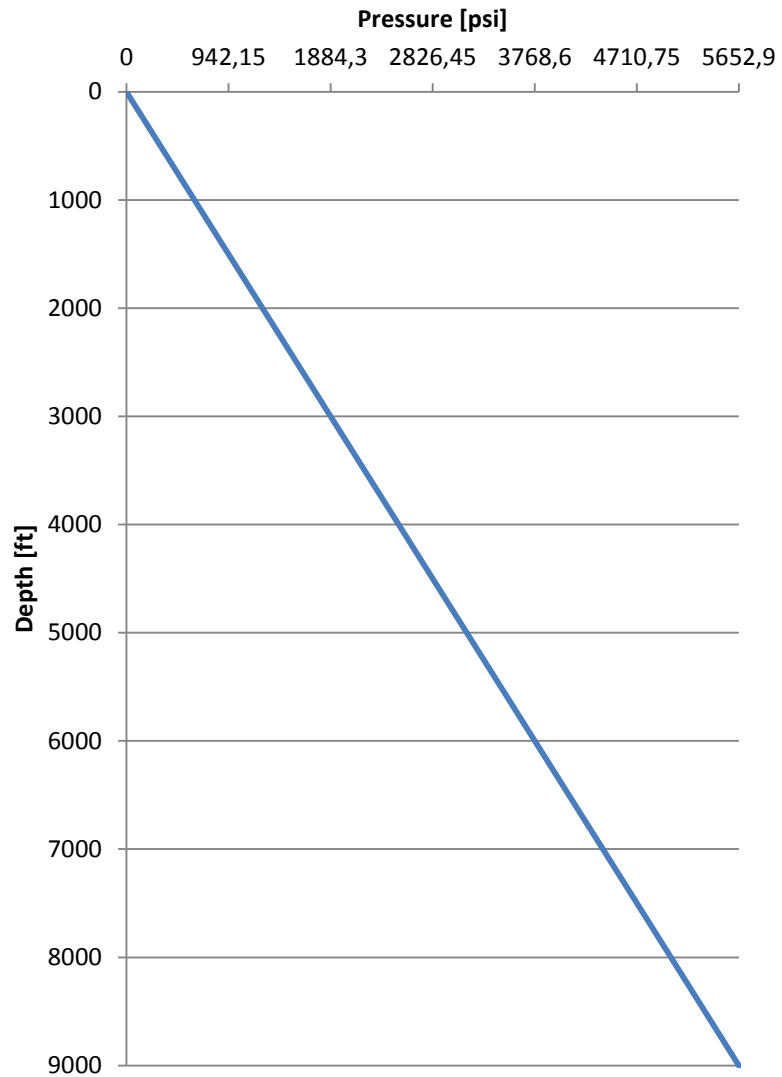
Fracture gradient of sandstones



Fracture gradient of limestones



Fracture gradient of siltstones



Fracture gradients of clay marls

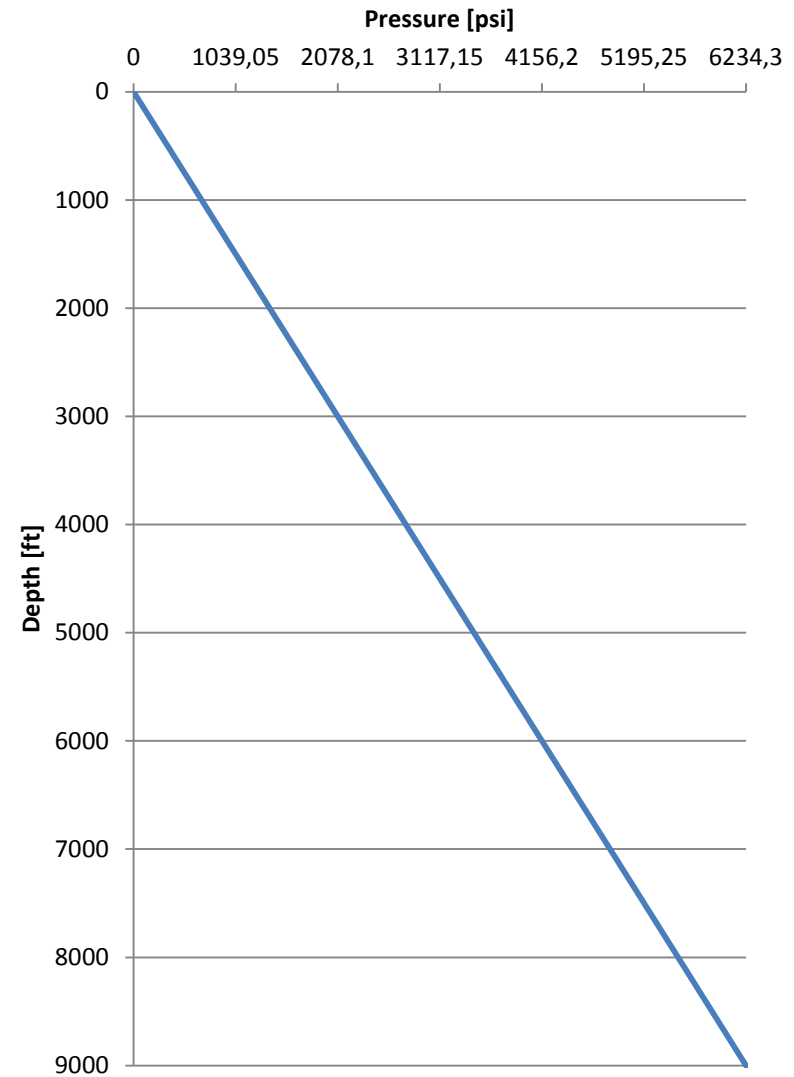




Figure 9: Map of the analysed wells

Literature

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