What maintains high pore pressure in gas shale during exhumation, long after thermal maturation ceases?

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The Ordovician Point Pleasant-Utica shale gas play is economic in large part because it is presently overpressured as is its counterpart the Devonian Marcellus gas shale of the Appalachian Basin (Zhou et al., 2017). Both gas shales maintain a gas reservoir at high pressure despite being exhumed and in some cases exhumation is more than 50% of their maximum depth of burial (Evans, 1995). Capillary pressure at the top and bottom boundaries of these gas shales is an effective seal for keeping gas in place and at well in excess of hydrostatic pressure for as much as 400 My as is the case for the Point Pleasant-Utica gas shale (Engelder et al., 2014). This is a bit of a paradox because exhumation of a gas shale should cause the relaxation of some fraction of the gas pressure generated during maturation, especially after oil has cracked to gas. The mechanism for maintaining pressure even during relaxation accompanying exhumation is known as Skempton’s behavior which is enabled by the relatively high compressibility of gas in pore space. Relaxation of rock stress allows the expansion of pore space but gas expands into this larger pore space without losing much of its pressure because of its high compressibility (Katahara and Corrigan, 2001). During exhumation, Skempton’s behavior maintains pore pressure so that eventually the residual pore pressure exceeds the least stress within the rock, thus leading to late-stage natural hydraulic fracturing (Engelder and Behr, 2017).

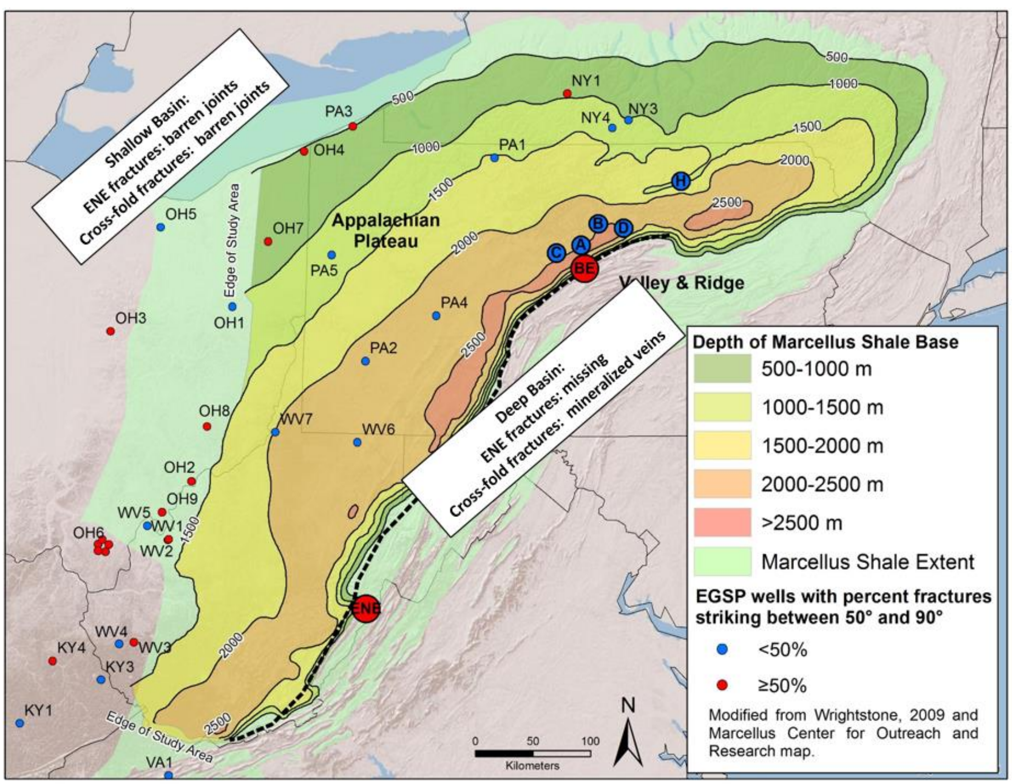

Figure 1. A map of the Appalachian Basin showing the depth to the base of the Middle Devonian Marcellus Gas shale (Wrightstone, 2009). Map shows the general location of the Bald Eagle well (BE), industry wells (A,B,C,D, and H) Wilkins et al., 2014), Eastern Gas Shales Project (EGSP) wells, labeled by state as KY, NY, OH, PA, VA, and WV (Cliffs Minerals, 1982).

The argument that Skempton's behavior regulates pore pressure during exhumation is based on the distribution of fracturing in Appalachian gas shale (Fig. 1). At shallow depths near the NW edge of the Appalachian Basin stacked gas shales including the Marcellus, the Geneseo, the Middlesex, the Rhinestreet, and the Dunkrik-Huron all carry a joint set parallel to the contemporary tectonic stress field (Lash et al., 2004). Sampling in the deeper portion of the Appalachian Basin suggests that this ENE joint set is missing (Evans, 1994; Wilkins et al., 2014). Cross-fold joints are generally without mineralization in the shallow rocks of the foreland portion of the basin whereas they are mineralized in the deeper core in the central basin. The interpretation for shallow but not deep ENE joints is that during exhumation to depths less than 2 km Skempton's behavior maintains a pore pressure sufficiently high to cause natural hydraulic fracturing driven by an evolving gas pressure that eventually exceeds the least stress (Engelder and Behr, 2017). Skempton's coefficient is a poroelastic property dictating the interaction between pore pressure and horizontal rock stress which allows the relaxation of gas pressure but at a fraction of the rate of relaxation of least stress during exhumation (Fig. 2). Because of the stress-pore pressure coupling, least stress does not relax as fast with exhumation as suggested by earlier elastic models (Narr and Currie, 1982; Price, 1974).

Water Density	Biot-Willis	Rock Density	Poisson's Ratio	Onset of Compaction Disequilibrium	Skempton Exhumation	Consolidation Coefficient	% Increase in maturation-related pore pressure	Thermal expansion	Young's Modulus	Geothermal Gradient	Skempton Burial	Onset of Skempton Oil
1029	0.7	2700	0.3	1000	0.7	0.53	0.1	1E-05	26000	0.03	0.7	3000

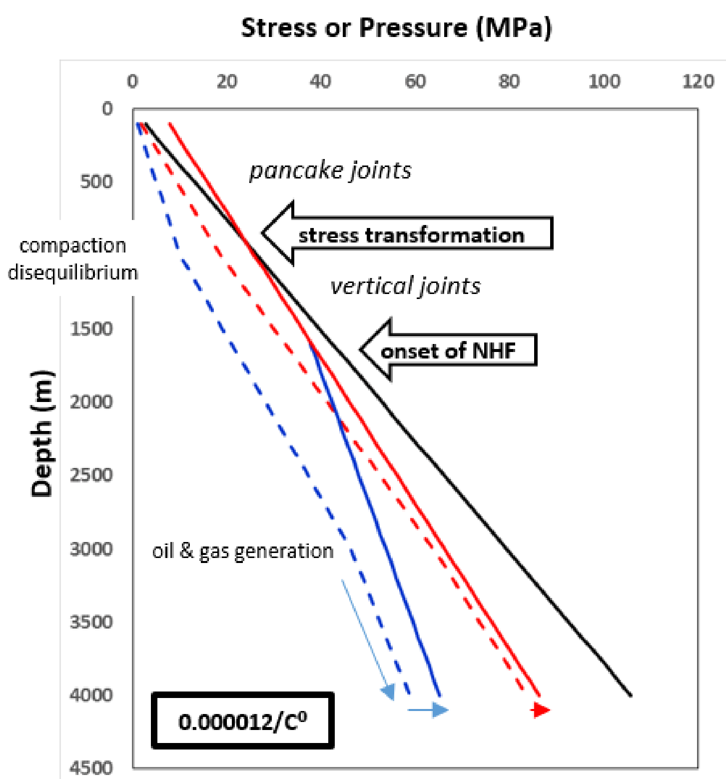

Figure 2. Hypothetical stress-pressure-depth models for Appalachian Basin to 4,000m and completely exhumed. S_v – black line, P_p – blue line. S_{hmin} – red line. The burial portion of this model (dashed lines) is presented in more detail in Engelder and Behr 2017. The exhumation portion of this model is governed by Equations 1 to 3. The intrinsic properties are given in the key to this figure. The coefficient of thermal expansion for a shale (black box) controls the behavior in this Figure.

Sufficient relaxation for natural hydraulic fracturing occurs only after more than 50% of the overburden is removed by exhumation as measured from the maximum depth of burial z_{max} and exhumed to z so that the fraction of the present depth is $(Z_{max} – z)/z_{max}$. The governing equation for poroelastic coupling of the minimum horizontal stress (S_{hmin}) to pore pressure (P_p) during exhumation follows:

$$\Delta S_{hmin} = S_{hmin}^{max} - \left(\frac{v}{1-v}\right)\rho_{rock}g(z_{max} - z) - \frac{\alpha_t E}{1-v}\Delta T + \left(\frac{1-2v}{1-v}\right)\alpha_{bw}\Delta P_p \quad (1)$$

where α_{bw} is the Biot-Willis coefficient, ρ_{rock} is the integrated density of the overburden, ν is Poisson's ratio, E is Young's modulus and α_t is the thermal expansion coefficient for the gas shale in question. The change in pore pressure during relaxation is governed by the Skempton effect according to

$$\Delta P_p = \rho_{rock}g(z - z_{max})\frac{B(1+v)}{3(1-v)}. \quad (2)$$

where B is the Skempton's coefficient. B for black shale is calculated using

$$B = \frac{1}{1+\left(\frac{\beta_f-\beta_\phi}{\beta-\beta_s}\right)} \quad (3)$$

where β is the isothermal bulk compressibility (e.g., 0.000153 MPa^{-1}), β_f is the isothermal pore-fluid compressibility (e.g., 0.00045 MPa^{-1}), β_s is the isothermal solid grain compressibility (e.g., 0.000014 MPa^{-1}), and β_ϕ is the isothermal pore-space compressibility (e.g., 0.00044 MPa^{-1}) (Katahara and Corrigan, 2001; Rice and Cleary, 1976). During exhumation, pore pressure continues to decrease by the Skempton effect until natural hydraulic fracturing is induced (Fig. 2). Above the depth of natural hydraulic fracturing, pore pressure will follow that rock's fracture gradient which is the path that S_{hmin} takes during further exhumation. Even during fracturing, abnormal pore pressure does not drain, a result seen from several gas shales (Gale et al., 2014). This is largely because vertical joints do not rupture through the capillary seal bounding the gas shale (Engelder et al., 2014).

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