On the dynamics of capillary gas trapping: implications for the charging and leakage of gas reservoirs

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Abstract: Capillary leakage of gas from buried structures can be quantified using Darcy migration concepts together with formulations for cap-rock permeability, relative permeability and entry pressures at low gas saturations. Capillary trapping has a static component defined by the entry pressure of the cap rock and a dynamic component defined by Darcy migration velocities and rates of migration into the trap. The importance of the dynamic trapping component increases with burial due to a corresponding reduction in cap-rock permeability. The low gas migration velocities through buried cap rocks make it unlikely that gas escape from these traps will be focused above their tops. Barriers within the cap-rock sequence may increase the gas saturation and increase the lateral width of the leakage zone. This may result in complex leakage routes into shallower structures.

Source rocks that supply gas to deeply buried traps will start to become exhausted as the temperatures increase. This reduces the rate of gas supply into the traps. Dynamic traps which have trapped gas columns that exceed the capacity of the cap-rock entry pressures can then no longer support the same column heights, and they are reduced in size. The reduction in column heights may continue below the capacity defined by cap-rock entry pressures because of hysteresis effects.

The reduction in seal capacity for deeply buried traps can be estimated if the gas fill history of the trap is known. Traps with a low vertical relief can be shielded from the dynamic seal destruction mechanism by the spill process. During periods of reduced or halted gas generation from the source rocks, dynamic traps will continue to leak for million of years. This delayed leakage may be an important source for the filling of shallower traps with gas long after the source rocks have been buried too deeply for generation to take place.

Keywords: capillary gas leakage, Darcy flow, dynamic leakage, cap rock, sealing times, gas saturations, migration velocities, permeability

The concept of entry (i.e. displacement) pressures (Berg 1975) has been used for many years to describe the sealing potential of traps. The use of entry pressures results in a static assessment of cap-rock sealing potential (Watts 1987). In this sense, static means that the oil and/or gas column that can be supported by a cap rock is considered to be constant as long as the properties of the cap rock do not change. Such changes can occur during geological time as results of burial and associated compaction and diagenesis, but not as a result of the hydrocarbon flow itself. Thus, leakage does not change the sealing potential of a cap rock. One important consequence of this approach to cap-rock assessment is that a trap will either spill hydrocarbons laterally along a carrier system or leak vertically through the cap rock. Once the entry pressures of the cap rock have been exceeded by a hydrocarbon column, the trap will be unable to support any additional column and all hydrocarbons subsequently supplied to the trap will leak out of it.

The use of entry pressures and displacement pressures to describe the leakage of hydrocarbons out of traps is taken from the reservoir technology concept of capillary pressures in multi-phase systems. According to this concept, which has been shown to apply to reservoir oil and gas systems, there will be a difference in phase pressure between the wetting and non-wetting phase of a multi-phase system that is defined as the capillary pressure between the two phases (Leverett 1941). The capillary pressure can be measured in the laboratory for different hydrocarbon mixtures and rocks and is typically related to the effective water or hydrocarbon saturation of the pore space.

During the last 15 years, new insights into modelling approaches of basin-scale hydrocarbon migration processes have made it possible to derive filling histories of traps (Burrus *et al.* 1991; Sylta 1993; Johannesen *et al.* 2002). It is, therefore, only logical to now consider the influence of hydrocarbon trap-filling histories on hydrocarbon leakage in more detail than an entry pressure analysis allows. A natural extension of the analysis is then to incorporate the full capillary pressure description into the leakage description and study the consequences of this improvement. As exploration for gas reserves probes deeper into basins and unconventional deep basin centre gas resources are more frequently sought, an understanding of charging histories and cap-rock leakage mechanisms will prove to be a key tool. Applying this understanding in the exploration for deep gas resources may help avoiding prospects where leakage has caused most of the gas to escape, whereas gas traps with larger columns may be identified.

Process description

Vassenden *et al.* (2003) used a laboratory experiment to study migration into and filling of a synthetic trap, followed by leakage of oil out of the same trap. A glass bead pack was filled into a 2D glass container of 47 × 67 cm and video cameras were placed in front of the model. The reservoir rocks were represented with glass beads of 200–300 μm, while the cap rock was represented with bead sizes of 70–110 μm. Vassenden *et al.* (2003) showed results from the experiments as snapshots over six time steps (Fig. 1). The sequence of snapshots and plotted injection and production volumes documented that the trap started to leak as soon as the oil column exceeded the entry pressure of the cap rock (Slide 3 in Fig. 1). Thereafter, the oil column continued to increase in height, but at a much slower rate. When the supply was stopped, the column started to shrink, until it stabilized at a column significantly below the column at which it started to leak.

Vassenden *et al.* (2003) suggested a snap-off theory to describe this reduction of the oil column after the supply was stopped. Just as important, however, is the fact that the column was observed to increase slightly beyond the column defined by the entry pressure of the cap rock when leakage started. They also observed that

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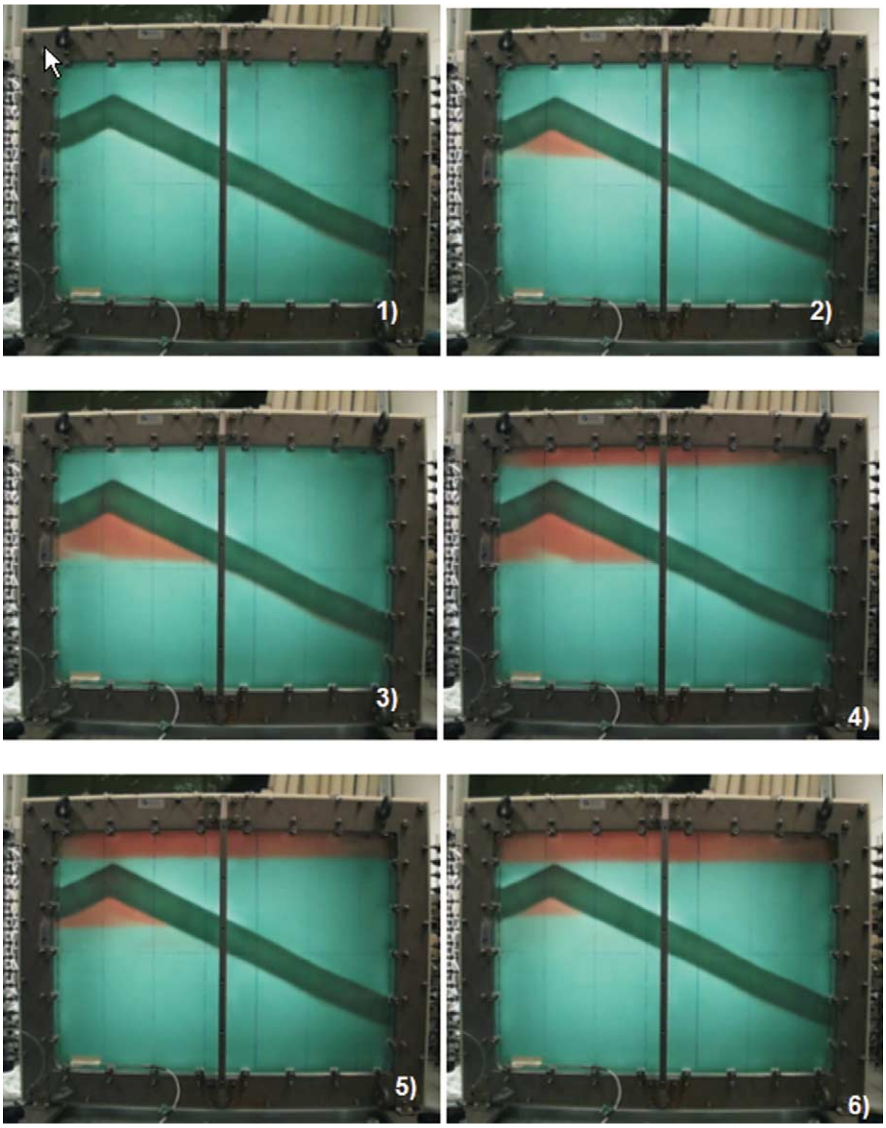

Fig. 1. Six frames showing experimental results after 0.8, 4.6, 13, 29, 44 and 309 hours. Blue is water filled. Dark colour shows the seal. Red areas are oil saturated (from Vassenden *et al.* 2003).

the leakage within the cap rock was not concentrated in a single focused migration pathway. Leakage was observed in a broad zone around the topmost point of the trap (Fig. 2).

Sylta (2002) analysed the flow properties of cap rocks with the aim of determining which type of modelling technology would be applicable to simulate the leakage process, Darcy flow or percolation techniques. Percolation has been shown to work well in the simulation of secondary migration of single-phase systems in carrier systems (Carruthers & Ringrose 1998), at least for two-phase systems with static geometries. Sylta (2002) argued that percolation could not be used for simulating leakage processes through low-permeability mud-rocks because the effective permeability of most cap-rocks is too low. The saturations modelled for hydrocarbon leakage through the mudrocks are very low and capillary pressures of the non-wetting phase are not much higher than the entry pressures of the cap rocks. Therefore, leakage has to be modelled over a fairly large cross-sectional area for most traps. Leakage areas should typically exceed 1 km^2 for most North Sea reservoir if capillary migration in cap rocks is observed above the reservoir.

Sylta (2002) used a classical buoyancy drive to define the capillary pressure at the interface between the seal and the reservoir:

$$P_c = P_e + \Delta\rho g H \qquad (1)$$

where P_c is the capillary pressure of the cap rock, P_e is the entry pressure, H is the height of the oil column and $\Delta\rho$ is the density contrast between the non-wetting and wetting phases (e.g. gas and oil). Variables used in this paper are described in Table 1. P_c can be related to the effective water saturation (equation (2)) via a lithology parameter L and P_e. L represents the sorting of rocks and controls the shape of the P_c versus effective water saturation, S_{wt} (equation (3)), curve. The functional dependency of relative permeability can be related to the same parameters as P_c (see equation (2)). The relationship between permeability and entry pressure (equation (2)) has been plotted by several authors (Fig. 3) and constitutes the last part of equation (2):

$$k_r = f(S_{wt}, P_e, L), \quad P_c = f(S_{wt}, P_e, L), \quad k = f(P_e) \qquad (2)$$

$S_{hc} = (1 - S_{wt})$ is the effective hydrocarbon saturation. Effective saturations represent those parts of the fluids that are movable:

$$S_{wt} = \frac{S_w - S_{wi} - S_{gi}}{1 - S_{wi} - S_{gi}} \qquad (3)$$

The hydrocarbon leakage flow was described for buoyancy-driven migration:

$$q = \frac{Q}{A} = \frac{k k_r \Delta\rho g}{\mu} \qquad (4)$$

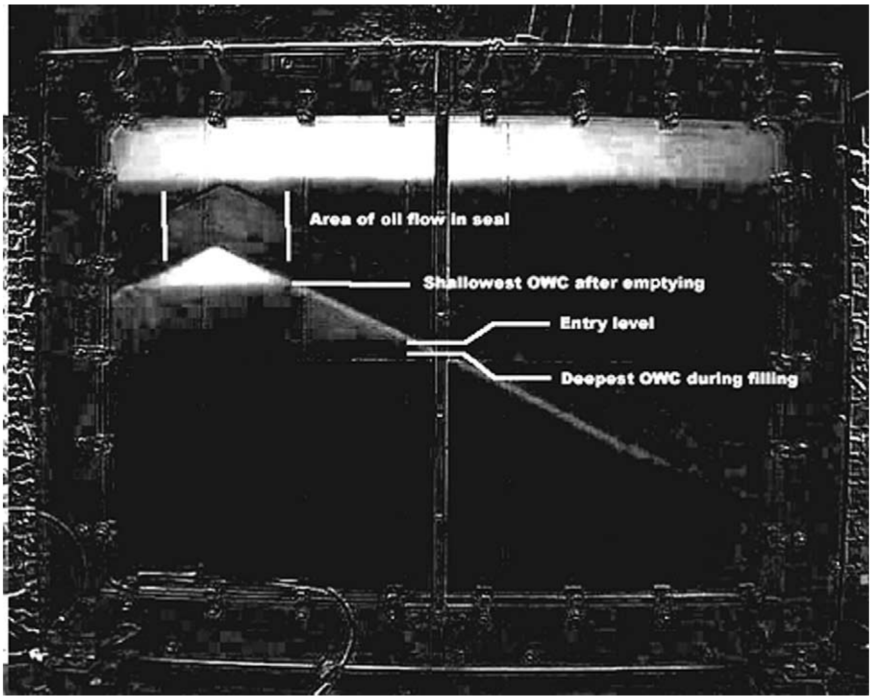

Fig. 2. Difference picture for the last time-step shown in Figure 1, highlighting the different zones (from Vassenden *et al.* 2003).

Q is the rate of supply into the trap from the source rocks, A is the area through which hydrocarbons leak. It is possible to estimate typical values for: Q, k, $\Delta\rho$, μ while g is known. Q can be estimated from hydrocarbon generation and expulsion modelling, while k can be estimated from Figure 3 or from laboratory measurements of permeability and/or entry pressures. The equations above can be solved for the unknowns, assuming a lithology (L) and the results can be plotted as q versus k and H. Figure 5 shows this relationship using the (Standing 1975) formulations for P_c and k_r:

$$S_{wt} = \left(\frac{P_c}{P_e}\right)^{-L} \tag{5}$$

$$k_r = k_r^o(1 - S_{wt})^2\left(1 - S_{wt}^{((2+L)/L)}\right) \tag{6}$$

Table 1. Description of variables used in this paper

Q	flow ($m^3\,s^{-1}$)
q	flow rate ($m^3\,m^{-2}\,s^{-1}$)
H	total height of gas column defined by entry pressure (m)
h	height of gas column below H (m)
k	absolute permeability (Darcy or m^2)
k_r	relative permeability (0–1)
k_r^o	relative permeability at maximum hydrocarbon saturation ($S_w = 1 - S_{oi}$)
$\Delta\rho$	density contrast between hydrocarbon phase and water ($kg\,m^{-3}$)
S_g	gas saturation (average from $h = O$ to $h = H$)
S_{gi}	minimum gas saturation for flow to occur
S_w	water saturation (between S_{wi} and $1 - S_{gi}$)
S_{wi}	irreducible water saturation
μ	viscosity of hydrocarbon phase (Pa s)
S_{w*}	effective water saturation (0–1) in Corey equation
ϕ	porosity of carrier bed, isotropic medium
P_e	entry pressure (Pa)
P_c	capillary pressure (Pa)
L	lamda describes the sorting of rocks in k_r and P_c curves

Sylta (2002) used Figure 4 to conclude that percolation modelling is not an appropriate process description for modelling leakage through low-permeability mudrocks because it is not representative of the process when trap filling rates are significant, for example, greater than $10^6\,Rm^3\,Ma^{-1}$ of oil and/or gas and the permeability of the cap rock is below 3 mD. When these conditions are met, a dynamic hydrocarbon column will be created below the static entry pressure column. The height of the dynamic hydrocarbon column is completely dependent on the filling history and of the flow properties of the seal. These properties can be described and quantified using equations (1) to (6) above, once the geometry of the trap is known.

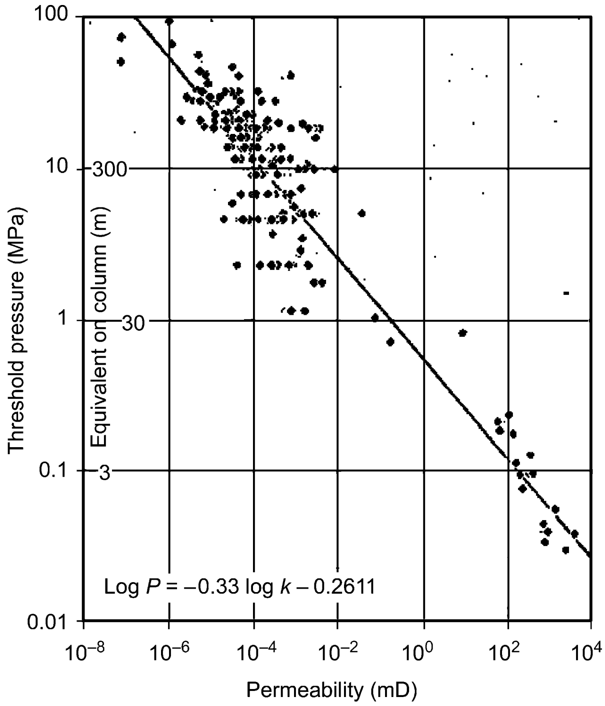

Fig. 3. Threshold pressures (MPa Hg) versus permeabilities (mD) for a wide range of undifferentiated lithologies (from Ingram *et al.* 1997).

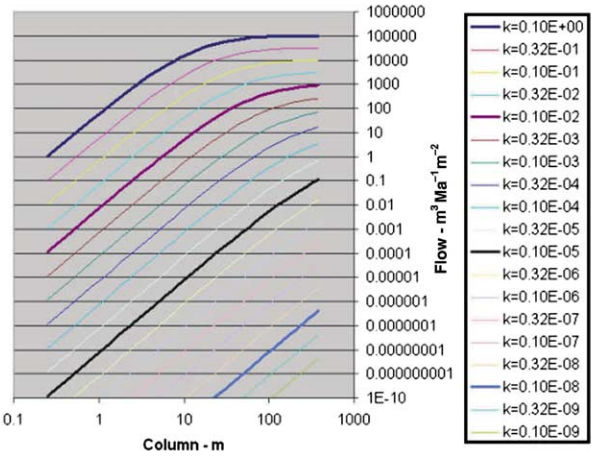

Fig. 4. Leakage flow versus dynamic Darcy hydrocarbon column height for different permeabilities. Permeabilities are in mD (from Sylta 2002).

The analysis of Sylta (2002) assumed a simplified geological model in which the cap rock was assigned the same properties over the entire trap. This was a required assumption in the analysis and it will not hold true for many traps. When traps fill below the entry seal point, capillary leakage will typically start at the very top of the trap. Initially, a very small part of the cap rock will experience leakage, but when a dynamic column builds beyond a few metres in height, then capillary leakage will occur over a larger volume within the cap rock. The properties of actual cap rocks may then be expected to vary and it is not evident that all arguments presented above will apply unmodified to an upscaled version of the process description. Heterogeneity in the cap rocks will result in leakage occurring in the most permeable parts of the cap rock first. It is, however, deduced from the arguments of Sylta (2002) that the flow properties of the most permeable parts of the cap rocks may not be able to transport all the gas that becomes available for leakage and the less permeable parts of the cap rock will be invaded by gas. The analysis presented in this paper makes significant simplifications to the cap rock properties. The interpretation of the experimental results may need to be modified when the process is upscaled for heterogeneous cap rocks. However, the conclusions on dynamic gas columns presented herein need only be modified: the columns may decrease or increase in size, but will not become zero.

Quantifying leakage

In order to assess the leakage properties of a trap, the geometry of the trap must be known. The area of leakage above the trap has to be known to compute the leakage volumes and, therefore, a starting point is to describe the area as a function of column height, H:

$$A = f(H) \tag{7}$$

This relationship can be obtained for any mapped structure, either manually, or by numerical integration in a mapping package.

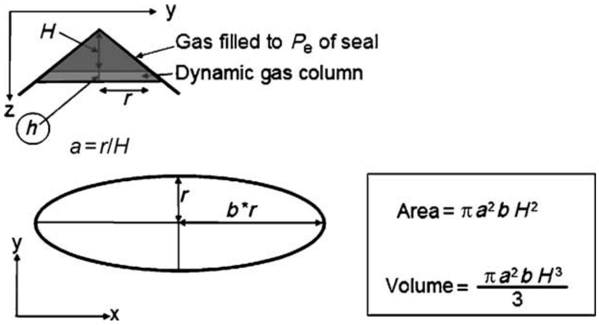

Fig. 5. A coned trap with an elliptical horizontal.

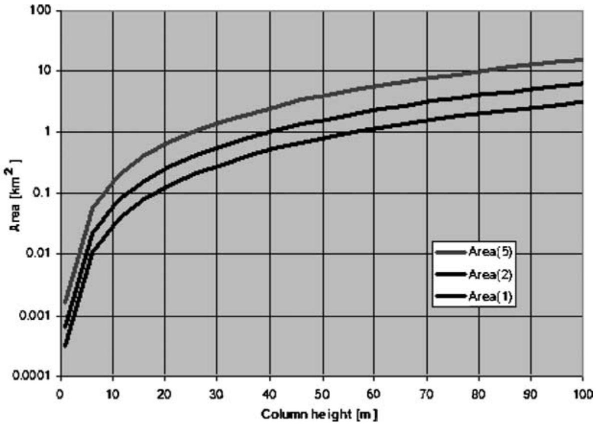

Fig. 6. Area versus column heights for elliptic cone with $a = 10$ and $b = 1$, 2 and 5. Uppermost curve is for $b = 5$ (Fig. 5 explains 'a' and 'b').

A very simple approach is used here to derive A for a synthetic trap. Figure 5 shows a cone-shaped trap filled with gas down to the static entry pressure column of H and with a dynamic column of height h below. A horizontal slice shows an elliptical shape with the long axis length being '$b \times r$' where r is the smallest radius in the ellipse. The value of 'r' is related to the column H by $r = aH$. For this simple trap, the area of the trap at column H is:

$$A = \pi(aH)(abH) = \pi a^2 bH^2 \tag{8}$$

The hydrocarbon pore-space volume of the cone down to H is:

$$V = \phi_{\text{eff}} \frac{1}{3} \pi a^2 bH^3 \tag{9}$$

where ϕ_{eff} is the effective pore-space fraction available for the gas, $N/G\phi(1 - S_w)$.

The advantage of this formulation is that it is extremely easy to approximate 'a' and 'b' for a trap and generate $A(H)$ and $V(H)$ as graphs from a spreadsheet. Figure 6 shows the area versus column height for $a = 10$ and $b = 1$, 2 and 5. The curve for $b = 5$ will be used in the following quantification of leakage for this trap. Once the area versus gas column height has been determined, the procedure shown in Figure 7 can be used to iteratively find the correct value for A and h for given values of Q, and k. Q is the maximum filling rate when the trap is filled beyond the entry column seal and k is the permeability. Q is taken from an assessment of the generation and expulsion history of the source of a trap, while k can be taken from, for example, Figure 3. Here, the permeability versus entry pressure values are picked from Figure 3 for a trap that can seal a 300 m column of oil. This corresponds to a 450 m gas column due the difference in interfacial tension and density between oil and gas. The chosen permeabilities are

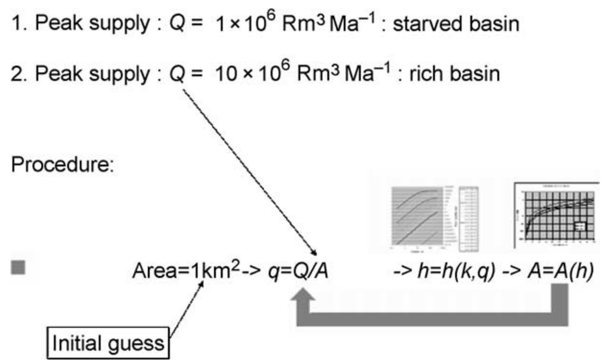

Fig. 7. Procedure used to estimate h from Q and k. An initial guess of A is used to calculate $q = Q/A$ (∗) and then h is picked from the graph. A is calculated from h and this gives a new value of $q = Q/A$. Iteration continues from (∗).

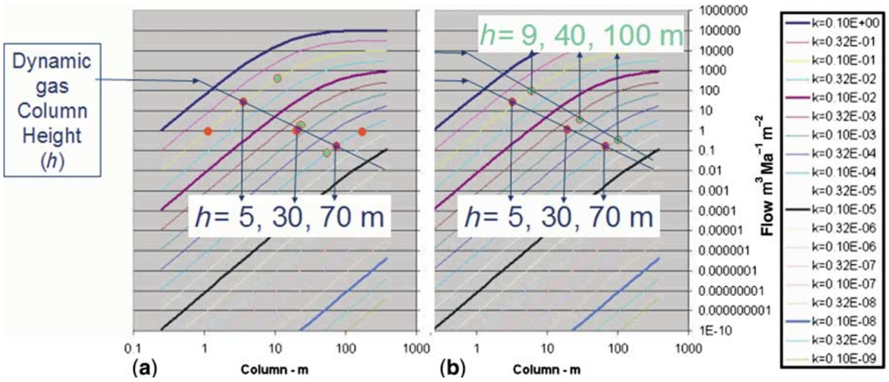

Fig. 8. (**a**) Interpolation of correct column heights from initial values (red dots), via intermediate values (green) to correct column heights (purple) for high, middle and low cap-rock permeability (k_h, k_m, k_l) using $Q = 1 \times 10^6\,\mathrm{Rm^3\,Ma^{-1}}$. (**b**) Interpolated values for $Q = 1$ and $Q = 10$ (green) for same values of k.

10^{-5} mD, 2×10^{-4} mD and 10^{-2} mD for a low, middle and high permeability case. Note that these permeabilities are quite high for typical cap rocks. The three permeability cases are referred to as the k_l, k_m and k_h cases in the following analysis. These values are only chosen as an illustrative example. The results of the following analysis would not change dramatically if, for instance, the gas column entry pressure seal was reduced for the same permeability due to larger density differences between oil and gas.

For each of the three k-cases, a value of Q is first chosen ($Q = 1$ here) and the procedure in Figure 7 is used to arrive at first an initial value for the dynamic column heights h (red dots in Fig. 8). Next, iterative values for h (green points in Fig. 8a) are found by following the loop in Figure 7. The final values (purple dots in Fig. 8) are determined by repeating the loop until the values of h do not change between each loop. In our case, a total of three loops are sufficient to find a stable solution. Figure 8a shows that the three values for h line up on a straight line. The range of the final values is significantly less than the initial estimates of h. The difference between k_h and k_l decreases from 110 m to 65 m for $Q = 1$.

The uppermost data points in Figure 8b show the final estimates of h for $Q = 10$. The gas columns increase approximately 40% when the flow rate increases ten times. This means that the process is, to a certain degree, very robust with respect to the filling history of a trap. When the supply rates increase, the gas column increases. The increased gas column results in higher capillary pressures in the cap rock. This increases both the relative permeability within the cap rock and the area of cap rock that will have capillary pressures that are greater than the entry pressures. As a result, the volume of gas that can be transported through the cap rock increases dramatically and the column height does not increase as fast as the supply rate.

Discussion

The analysis presented here shows that cap rocks that experience a dynamic leakage process will increase column heights. The maximum dynamic gas column heights for buried traps can easily reach 100 m in source-rich basins, where the peak supply rates of traps can exceed $10^7\,\mathrm{Rm^3\,Ma^{-1}}$. A steady gas supply rate of $10 \times 10^6\,\mathrm{Rm^3\,Ma^{-1}}$ would fill a 20 m thick trap with the properties used above, with a 500 m dynamic gas column with $400 \times 10^6\,\mathrm{Rm^3}$ gas in 40 Ma. Figure 9 shows the trapped volumes for such a trap versus gas column (using equation (9)). If the supply continued at the same rate beyond the 40 Ma, the trap would leak continuously with a volume rate corresponding to the supply rate, thus, sourcing shallower traps with gas. If the supply from the source rock is stopped, then the leakage would decrease. It would take a minimum of 10 Ma to decrease the gas column from 500 m to 450 m because the trapped volume would have to decrease from 400 $\mathrm{Rm^3}$ to $300 \times 10^6\,\mathrm{Rm^3}$ (Fig. 9).

The 10 Ma of continued leakage of gas from the trap will increase if cap-rock hysteresis causes the snap-off pressure to be significantly lower than the entry pressure of the cap rock. A reduction in snap-off to one third of the entry pressure column would result in the gas column being reduced from 500 m to 150 m. This would mean that a total volume of $350 \times 10^6\,\mathrm{Rm^3}$ could leak from the trap after the supply was stopped and, thus, leakage would be maintained for more than 35 Ma. If the reservoir thickness is greater than 20 m, the leakage times could be even longer.

Table 2 lists column heights and corresponding trap volumes calculated for the model trap using no limitations in reservoir thickness (the base lies below the gas–water contact). The delay times shown in the rightmost column are calculated by dividing the volumes of gas trapped by the dynamic seal with the maximum supply rates (Q). This gives estimates of how long the trap will be able to leak gas after the supply has been stopped. The leakage can continue from 2 Ma to more than 100 Ma. The greater value of Q gives the shorter duration times for leakage because high values of Q result in thicker columns. Thicker dynamic columns lead to higher gas saturations in the cap rock and, therefore, higher relative permeabilities and flow rates. These higher flow rates will be maintained for some time after the supply has stopped. However, the exact behaviour of the relative permeability and capillary pressures of cap rocks during hysteresis is unknown. The relative permeability is expected to slowly reduce until it reaches zero at the snap-off pressure. Therefore, the leakage rates will most likely show exponential decrease rates after the supply has been stopped, thus, extending the leakage period beyond those given in the rightmost column of Table 2.

In the case of a heterogeneous cap rock with entry pressures and permeability changing throughout, the dynamic seal column may not be determined as easily as in the model example here. A fully upscaled process description that can account for these features is not yet available. Most likely, both dynamic seal columns and

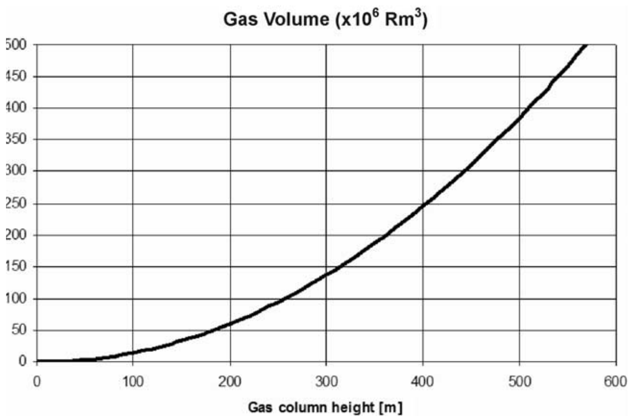

Fig. 9. Gas volumes versus column height for a 20 m thick reservoir in an elliptical coned trap with 10% effective porosity (from equation (9)).

Table 2. Calculated dynamic cap rock sealing for three permeability and two filling cases

Q ($\times 10^6$ Rm^3 Ma^{-1})	Permeability (mD)	h (m)	Area (m^2)	q (m^3 Ma^{-1} m^{-2})	V dynamic ($\times 10^6$ Rm^3)	V dynamic/Q(Ma)
1	0.01	5	0.04	25	7	7
	0.0002	30	1.5	1	44	44
	0.00001	70	7.9	0.12	106	106
10	0.01	9	0.1	100	14	1.4
	0.0002	40	2.6	3.8	59	5.9
	0.00001	100	36	0.28	157	15.7

leakage times may be in the lower ranges of values presented in Table 2 when the process is upscaled. This is because the gas will typically first fill the low entry pressure pores and these will also be the ones with the higher permeabilities and the sharpest transition from low relative permeabilities to high relative permeabilities as the dynamic gas column builds up. It is possible to develop a more extensive process description that accounts for these factors, although it may be unrealistic to expect a simple analytical solution. Numerical modelling will most likely be needed to address the problem and it is, therefore, not within the scope of this paper to discuss it in more detail. It is concluded that more work is needed to study these effects properly.

These considerations show that the filling history of traps must be known to compute their leakage history and rates. The maximum value of Q will need to be determined to compute the maximum column of gas that can be supported. The volumes of dynamically trapped gas divided by $Q_{\max}$ can be used to assess the leakage duration once gas supply is exhausted or strongly reduced. Figure 10 demonstrates what a dynamic fill and leakage history of a trap might look like. In this example the entry pressure of the cap rock increases linearly through time. The uppermost curve shows that expulsion peaked some million years ago, possibly because the trap has been buried beyond the peak gas generation window. The trap then starts to leak once the volume of gas migrating into the trap exceeds the volume of the entry pressure seal. Static leakage rates are higher than the dynamic leakage rates for the period before gas expulsion peaks (Fig. 10b). The most dramatic differences between these curves are observed after the expulsion rates are reduced, where the dynamic leakage is maintained at high level until the present day.

There are at least three important effects of this difference:

- the dynamic cap-rock leakage maintains a thicker column of gas for some time;
- the dynamic trap can be emptied more than the static trap;
- the dynamic trap maintains leakage into shallower traps after the supply is reduced.

Source rocks that supply gas to deeply buried traps will gradually become exhausted as temperatures increase. This reduces the rates of gas supply into the traps. Dynamic traps that have trapped gas columns that exceed the capacity of the cap-rock entry pressures can then no longer support the same column heights and the trap is reduced in size. Unfortunately, this reduction in column heights will continue below the capacity defined by the entry pressures. Hysteresis effects will cause relative permeability and capillary pressure curves to be different when the gas column decreases, resulting in a lower seal potential for traps with a dynamic seal history. Gas traps that experience dynamic leakage will act as filters for the leakage process. Gas remains trapped in the deeply buried traps and is slowly reduced during burial. It is likely that a dynamic trap will continue to leak even when diagenesis increases the entry pressure of the cap rock at high temperatures because once the entry pressure has been exceeded and leakage initiated, it will continue. The important step is to get the leakage process started and thereby develop some gas saturation within the pore space of the cap rock.

The mechanism described above may explain why there is a good potential for gas leakage from very deeply buried source rocks even long after they have passed the peak of their gas generation window.

Nature provides an extensive database of drilled traps that can be used to test migration concepts and case studies are, therefore, important contributions to validate and test the concept presented here. One challenge with the 'natural laboratory' is that rarely is there only one process operating in isolation. It is, therefore, extremely difficult to find a case study where capillary leakage is the only unknown parameter. Usually, the amounts of gas generated, expelled and migrated into the traps are poorly constrained, while cap-rock permeabilities and entry pressures are unknown or have to be inferred from well logs. This can be done as part of an exploration study, but the results are inadequate as scientific proof that the process description works or fails. In order to validate the process description with case study data, several cases with differing geological conditions, must be used.

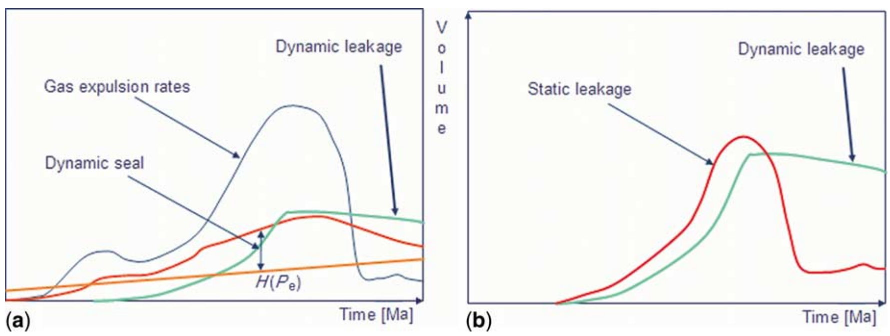

Fig. 10. Fill and leakage history of a trap. (**a**) Straight red line shows static column seal capacity (m) through time. Red curve is total sealed column that could result with the shown filling rates. Green shows the resulting dynamic leakage volumes. (**b**) Resulting dynamic (red) and static (green) leakage volumes versus geological time (see text for discussion).

Traps that have experienced a period of dynamic gas column heights may show signs of early filling that have been deeper than the present-day hydrocarbon–water contact. If the pore pressures are sufficiently low to rule out hydraulic leakage as the leakage mechanism, and tectonic events have not induced leakage, then these traps may be candidates for dynamic capillary leakage. Leith *et al.* (1993) recognized cap-rock leakage above the Snorre Field using geochemical techniques, suggesting that migration of hydrocarbons occurred through larger parts of the cap rock. This would be consistent with expected effects of a dynamic column height, but a more detailed assessment is required before further conclusions can be made.

The reduction in seal capacity for deeply buried traps can be estimated if the gas fill history of the trap is known. The seal capacity reduction is more important for traps with very large structural closures. The effect of the dynamic seal destruction mechanism can be reduced in traps with a lower vertical relief by the spill process. This limits the maximum gas column that can accumulate beneath a trap. Therefore, smaller traps are more likely to be preserved at depth than the large traps. Faults that become more sealing with depth and lead to compartmentalization of traps may increase the probability of dynamic seal creation and destruction because some of the compartments may trap larger columns of gas and lower the spill point.

The low gas migration velocities through deeply buried cap rocks make it unlikely that gas escape from these traps will be focused to thin migration stringers above the traps. Gas at low saturations will tend to fill a large fraction of the cap rock above leaking gas-filled traps. Almost the entire section above the gas trap may become saturated with low-saturation gas. Only if barriers exist within the seal will the saturation increase below the barrier. This increase will be needed to overcome the higher entry pressures of the barrier. Such a barrier may also increase the lateral width of the leakage gas zone if the lateral permeability is sufficient. It does not take much depositional or diagenetic hetereogeneity in the cap rock to disperse gas laterally throughout a larger portion of the section above a deep gas trap. Lenses of silt and/or sand just below tighter portions of the seal may easily act as conduits for localized lateral migration of gas. This may result in very complex filling routes into many small structures above just one deep gas structure.

The methods, procedures and analysis performed in this paper all assume that migration of gas does, in fact, occur at low saturations and at low permeabilities. Low gas saturations in cap rocks are frequently reported from exploration wells. The low relative permeabilities that are assumed here have, however, not been measured and reported for real cap rocks. They are observed for low permeability sands and silts and it does not seem likely that the flow regime should completely change from sands/silts to clays and cap rocks. The assumption made here is, therefore, the most reasonable assumption one can make about flow in cap rocks at the present time. More research is needed on this topic in order to refine the models and determine properties that can lead to more accurate determination of the capillary sealing potential of traps.

Conclusions

This paper discusses the capillary leakage processes that operate in many deep traps when their maximum vertical closure is greater than the capillary entry pressure of the cap rock. It is concluded that gas leakage is typically a dynamic Darcy flow process and that gas-filling rate histories will determine the actual vertical column heights that gas traps can build. Dynamic gas columns can exceed the entry pressure column heights by more than 100 m in many cases, but may also be quite small when the gas supply rate from the source rocks is low.

Column heights and rate of leakage can be quantified from estimates of permeability, entry pressure, lithology and the gas-filling history. Most traps that undergo capillary leakage through a cap rock will experience dynamic capillary leakage and, thus, the gas-filling history of the accumulation has to be determined to quantify capillary leakage. Shallow traps can be fed for a long time by deeper gas traps that continue to leak after the source rocks have stopped generating substantial amounts of gas.

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