Naturally occurring underpressure – a global review

T. Birchall1,2*, K. Senger1 and Richard Swarbrick3

1 Department of Arctic Geology, The University Centre in Svalbard, P.O. Box 156, N-9175 Longyearbyen, Svalbard, Norway
2 Department of Geosciences, University of Oslo, Geologibygningen, Sem Sælands vei 1, Oslo 0371, Norway
3 Swarbrick GeoPressure Consultancy and Durham University, UK

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Abstract: Several mechanisms have been suggested as drivers of naturally occurring underpressure. However, the phenomenon is largely underrepresented in literature. Previous studies have focused on individual cases in North America, where challenges due to topography and defining hydrostatic gradients exist. More recent publications from underpressured basins have emerged from other parts of the world, where settings are arguably more favourable to studying the phenomenon. Based on a total of 29 underpressured locations, it is apparent that the magnitudes and depths of underpressure are similar throughout the world.

Pressures of up to 60 bar blow hydrostatic are common in sedimentary basins of North America, China, Russia, and Europe and typically occur at shallow depths (<2500 m). All occurrences of underpressure occur in areas that have been geologically recently uplifted and is predominantly confined to low permeability rocks. Although rarely tested, it appears that mudstone and typically occur at shallow depths (<2500 m). All occurrences of underpressure occur in areas that have been geologically recently uplifted and is predominantly confined to low permeability rocks. Although rarely tested, it appears that mudstone

Underpressure or subnormal pressure is defined as any pore-pressure below hydrostatic (i.e. the pressure exerted by a column of water). Whilst reservoir depletion due to hydrocarbon production is a common cause of anthropogenic underpressure (e.g. Hunt 1990), naturally occurring underpressure is relatively underrepresented in literature. Naturally occurring underpressure can broadly be split into gravity driven processes and geology driven processes, though they are not mutually exclusive. Gravity driven processes are common in the science of hydrogeology (e.g. the Great Artesian Basin in Central Australia; Love et al. 2013), where underpressure is a result of elevation changes, flow rates, and the choice of hydrostatic gradient reference. Geology driven underpressure occurs where geological changes have impacted rock properties or fluid pressure-volume-temperature (PVT) conditions, and fluid pressures have been unable to equilibrate with their surroundings. There are some cases in the USA, where both geological processes and gravity may contribute to underpressure. Some of these cases are further complicated where geological drivers have affected flow regimes. The challenges of these areas are discussed in the next section of this article. Fortunately, most cases outside the Americas occur in areas of much less topographic relief. Because gravity driven underpressure occurs anywhere there is groundwater flow, and is largely determined by an arbitrary hydrostatic gradient, this contribution focuses on geology driven underpressure. Both mechanisms are considered in the recently uplifted, mountainous areas of the USA where a multitude of studies exist.

Where underpressure has been documented it has typically been on a case-by-case basis or as part of a bigger discussion into abnormal pressures, with a greater focus on overpressure. Swarbrick and Osborne (1998) discussed underpressure in an overview of mechanisms that cause abnormal pressure, while Law and Spencer (1998) provide a summary of cases of abnormal pressure from around the world, including twelve exhibiting underpressure. More recently, Law (2013) showed the prevalence of underpressure in gas reservoirs throughout the USA. In this contribution we have identified and quantified underpressure in a total 29 basins and regions from around the world that exhibit underpressure in both hydrocarbon-bearing reservoirs and aquifers.

Geologically formed underpressures of up to 100 bar (1450 psi) below hydrostatic have been encountered in sedimentary basins of North and South America, China, Russia, mainland Europe and the Norwegian Barents shelf and Svalbard (Birchall et al. 2020). These underpressures exist in a variety of geological settings although, to our knowledge, all cases occur in regions that have undergone geologically recent and significant uplift.

Underpressure can be problematic. During drilling, the fluid pressure in the wellbore is likely to always be higher than that in an underpressured reservoir (overbalanced), particularly in the offshore environment where seawater is the lightest drilling fluid available. This can lead to drilling mud losses into the formation, as has been well-documented in the Barents shelf (Birchall et al. 2020). If drilling fluid losses are severe it can lead to loss of well control. It may also lead to differential sticking of the drill pipe which, in the worst case, may result in it needing to be cut. Drilling fluid invasion (Fig. 1) can also lead to formation damage and can complicate petrophysical logging and potentially lead to missed pay.

In hydrocarbon exploration a lateral or vertical pressure difference (relative to hydrostatic) may lead to the inference of a very good seal between them. In some settings, on the contrary, it may be indicative of fluid flow. However, if underpressure has developed geologically recently with varying spatial magnitude, it cannot prove a geologically long-lived seal or fluid flow trends. Capillary or hydraulic seal capacity may be negatively affected by underpressure and should be considered for when carrying out seal analysis.

Underpressure impacts the phase and storage capacity of any injected fluids, such as carbon dioxide (Braathen et al. 2012; Senger...
they may be addressed. Underpressure and identify where knowledge gaps exist and how doing this we provide a comprehensive overview of the subject of likelihood of certain mechanisms occurring in different basins. By comparing the geological history of underpressured basins and including its magnitude and depth of underpressured stratigraphy; (2) documenting global cases of underpressure, the currently documented cases of underpressure globally through: of twenty-nine identified underpressure-exhibiting basins or regions observed underpressures. Secondly, they narrow the potential first, give confidence in the identification and magnitude of documented case of the Barents shelf is offshore. These settings, are in basins with very little topographic relief, and the well-studied cases of recently documented occurrences of underpressure from China relief where defining a hydrostatic gradient is challenging. More mountainous areas where locally defined hydrostatic gradients bear definition of the hydrostatic gradient. This is most problematic in practice such as tunnel excavation (Noy et al. 2004). A major challenge in defining and measuring underpressure is the definition of the hydrostatic gradient. This is most problematic in mountainous areas where locally defined hydrostatic gradients bear little relevance to the underlying aquifer. The well-studied cases of underpressure in North America from areas of high topographic relief where defining a hydrostatic gradient is challenging. More recently documented occurrences of underpressure from China are in basins with very little topographic relief, and the well-documented case of the Barents shelf is offshore. These settings, firstly, give confidence in the identification and magnitude of observed underpressures. Secondly, they narrow the potential underpressure causing mechanisms. In this contribution, we investigate the geological characteristics of twenty-nine identified underpressure-exhibiting basins or regions on a case-by-case basis. We aim to provide a systematic review of the currently documented cases of underpressure globally through: (1) synthesising the current state of knowledge on the subject of underpressure; (2) documenting global cases of underpressure, including its magnitude and depth of underpressured stratigraphy; (3) comparing the geological history of underpressured basins and providing case studies; (4) identifying the geological feasibility and likelihood of certain mechanisms occurring in different basins. By doing this we provide a comprehensive overview of the subject of underpressure and identify where knowledge gaps exist and how they may be addressed.

Hydrostatic gradients and mountainous regions

The term ‘hydrostatic gradient’ is something of a misnomer. Fluid columns in the subsurface are anything but static; water tables and sea levels move up and down, and flow regimes change with time. In addition, hydrostatic gradients can be influenced by changes in water density, predominantly caused by variations in salinity (e.g. there is c. 7.5% difference between freshwater and a typical Gulf of Mexico hydrostatic gradient) and, to a lesser extent, temperature (discussed in the Llanos Basin case study).

Onshore, the biggest uncertainty with hydrostatic gradients relates to their starting datum. Offshore, the hydrostatic gradient starting datum is easily defined by the mean sea level. Onshore it is frequently defined by the land surface elevation, and in some cases the top of the water table at the wellbore location. This is not a problem in a basin with little topography, but in vertically confined aquifers in mountainous areas the locally defined hydrostatic gradient can be far detached from the subsurface fluid system.

In complex terrain the shallow subsurface pressure conditions can be perceived differently depending on the application. For hydrocarbon exploration, having a surface (or mudline) defined hydrostatic starting datum is important as it provides a reference when considering drilling fluid densities. Conversely, hydrogeologists typically use hydraulic head elevations at multiple locations to calculate a potentiometric surface to better understand the pressure distribution and flow potential of the entire system. Figure 2 shows the different approaches in three different hypothetical systems. Figure 2a and b are static systems that have reached an equilibrated state with no flow, while Figure 2c is a dynamic system with fluid recharge and discharge. In Figure 2a and b, the fluid systems are hydrostatic and the measured wellbore pressures fall on common respective gradients (also shown by the potentiometric surface with zero gradient). The choice of hydrostatic datum is determined by the elevation, and thus, defines the magnitude and presence of abnormal pressures.

Dynamic settings, where groundwater systems are in a constant state of flux, add an additional level of complexity. While a static system that has equilibrated to a single connected free surface (e.g. Fig. 2a and b), wells in a dynamic system may appear over or underpressured depending on the well elevation and the hydraulic head in the reservoir at that point. A dynamic system can be in equilibrium with sustained recharge and discharge (e.g. Fig. 2c) or may be in the processes of equilibrating with a free surface following a change in conditions (e.g. erosion exposing the reservoir). Distinguishing between an in-equilibrium or out-of-equilibrium system is extremely difficult, and interpretation relies on an understanding of the geological and hydrogeological history. Unsurprisingly, pressures from multiple wells in a dynamic system do not fall on a common hydrostatic gradient. Hydraulic head diminishes in the direction of flow, at a rate known as the hydraulic gradient, which is dependent on a multitude of factors (Toth 2009). These include the reservoir properties of hydraulic conductivity (largely determined by permeability) and specific storage (the volume of water released per unit volume of rock per unit decline in hydraulic head – largely determined by the reservoir and fluid compressibility), in addition to the influence of gravity due to elevation differences and, if not fully saturated, the rate of recharge.

In settings where the reservoir permeability is extraordinarily high, and the sealing lithology low (e.g. paleokarst systems), static conditions may prevail. However, because there is no such thing as zero permeability in nature, most systems are dynamic to some degree, on geological timescales. Aquifers can be connected over hundreds of kilometres with elevation changes of hundreds or thousands of metres. Fundamentally this means there may be large variations between a locally defined hydrostatic gradient and the measured reservoir pressure simply due to the effects of gravity.

With the added uncertainties of reservoir properties and flow rates (including the effects of depth from the surface), assessing the presence and magnitude of abnormal pressure and the proportional contribution of different mechanisms is virtually impossible.

The reason that the matters of topography and hydrostatic gradient are so important in this article is because the historically best-studied cases of underpressure are from North America, located
in areas of major topography. This makes it an extremely challenging place to study the causal mechanisms of underpressure. For example, severe underpressure (35 bar or greater below hydrostatic) can be explained (regardless of whether it is the true driving mechanism or not) by the reservoir being plumbed to a free surface at least 350 m lower than the wellbore location, which is obviously almost impossible to rule out unless the wellbore is already at the lowest elevation in the region.

In this article the challenges of topography with the under-pressure cases of North America remains. We encourage the reader...
to keep this in mind when assessing pressures from the mountainous regions of the USA, Canada, and Colombia. Fortunately, most cases of underpressure from the more recent studies elsewhere in the world occur in basins with no or negligible topographic relief. In these settings other mechanisms are unequivocally at play.

**Causes of underpressure**

Underpressure caused by hydrocarbon production and subsequent depletion is relatively common and well documented (Teufel et al. 1991; Santarelli et al. 1998; Streit and Hillis 2002). Naturally occurring underpressure caused by geological processes is a less well documented and understood phenomenon. Table 1 provides a summary of places where underpressure has been documented and the mechanisms that have been attributed to each location. The fact that some locations are the subject of numerous studies with different proposed underpressure causing mechanisms is probably testament to the complexity of the subject.

Several mechanisms have been hypothesized as a main driver of underpressure (Fig. 3), but fundamentally the phenomenon must relate to a reduction in fluid volume, an increase in connected pore volume, or a change in hydraulic regime.

Thermodynamics dictates that a reduction in temperature will cause an increase in fluid density, and thusly, a reduction in fluid volume (Fig. 3a) which may lead to underpressuring in well-sealed systems. Most cooling probably occurs in association with uplift as rocks are moved upwards through the geothermal gradient, however, it may also occur due to changes in the geothermal gradient (e.g. through widespread magmatism) or changes in the surface temperature (Allis 1978). Fluid volume reduction due to temperature is far more significant in hydrocarbons, particularly gas, than it is in water. It likely contributes to the development of underpressure in basins that are highly saturated with gas. Barker (1972) suggested temperature may cause abnormal pressures in aquifers due to thermal expansion and contraction. However, this assumes a perfectly sealed compartment and no changes in the rocks themselves. In reality, there is no such thing as a perfect seal, and the pore network of a reservoir is never perfectly rigid; cooling results in decreasing porosity at a similar or greater rate than fluid volume reduction (Longuemare et al. 2002; Brotons et al. 2013), meaning it is unlikely to cause significant underpressuring. Temperature increase has largely been discounted as generating aquifer over-pressure (Daines 1982) so it seems unlikely that cooling would cause significant aquifer underpressuring.

The disequilibrium compaction of shales and their propensity to produce overpressure is relatively well understood (Swarbrick and Osborne 1998; Swarbrick et al. 2001). Conversely, decompression and fracturing of shales during uplift (Fig. 3c) is poorly understood, though their elastic properties and rheology mean they are likely to be more sensitive to uplift than reservoir rocks (Neuzil and Pollock 1983; Karig and Hou 1992; Liu and Roaldset 1994). Empirical evidence of this may come from rare direct pressure measurements in low permeability mudrocks in several recently uplifted and glaciated areas where severe underpressures (>35 bar below hydrostatic) were recorded (Neuzil 1993; Vinard 1999; Neuzil and Provost 2014; Birchall et al. 2020). It appears that in some reservoir intervals that decompacting shales have drawn fluid from the reservoir, leaving both the reservoir and seal underpressured (Wilson et al. 1998; Birchall et al. 2020). Poorly connected, and low permeability reservoirs encased within, or juxtaposed against thick shales, are therefore, more susceptible to developing under-pressure. Poorly connected reservoirs, with low overall pore volumes are more sensitive to changes in the surrounding rocks (and are likely better sealed), whereas low permeability reservoirs cannot replace water lost into the adjacent shales at a fast enough rate to remain in equilibrium (Birchall et al. 2020). Decompression is inherently reliant upon uplift and/or erosion.

In an offshore environment, the hydrostatic gradient changes over time due to sea level change (Fig. 3c). Similarly onshore, water tables and drainage systems also evolve and change over relatively short timescales. Therefore, pore pressures in the deep subsurface are likely, to some extent, to be out-of-equilibrium with the ever-changing hydrostatic gradient (Birchall et al. 2020). Although this mechanism is speculative and difficult to ascertain, it is more likely to develop where the reservoir is rigid (i.e. the grain contacts feel the change in stress rather than the fluids) and well-sealed. However, the magnitude of abnormal pressure that this mechanism can cause alone is relatively small; it would take c. 100 m of sea level rise to cause 10 bar of apparent underpressure in a perfectly-sealed, and completely rigid reservoir.

Minor changes in the hydrostatic regime may occur in a variety of ways during permafrost formation. Firstly, if permafrost forms a new top seal, it may change where an underlying aquifer equilibrates or it may completely seal the reservoir where overpressure is likely to develop due to the volume increase of ice formation (Gilbert et al. 2018). Secondly, it likely plays a minor role in changing the thermal properties of the permafrost interval, potentially leading to cooling of the reservoir. Dobrynin and Serebryakov (1989) suggest that the hydrostatic gradient should begin at the permafrost base as it could describe underpressure magnitudes in Siberia, though we dispute and discuss this later.

Differential gas charge (Fig. 3d) requires a relatively complex geological history to generate underpressures and requires a secondary mechanism, typically attributed to cooling (Law and Dickinson 1985). In this mechanism gas is generated in the deep parts of the basin and migrates into nearby, low permeability reservoirs displacing water. This results in an unusual configuration of a gas leg sitting downdip of the water leg, and has been termed ‘basin-centred gas’ (BCG) (Law 2002). Overpressure may initially form, with underpressure developing subsequently if uplift occurs. During this process, it is hypothesized that gas escapes the reservoir at a greater rate than it is generated and can enter the reservoir. Then due to a secondary mechanism, such as cooling, or decompression, may become sub-hydrostatic. A common occurrence in these BCG accumulations is that the gas is rarely at hydrostatic equilibrium (Law and Dickinson 1985; Law 2002). There are numerous global examples of BCG accumulations, but those exhibiting under-pressure are situated in the Midwest USA, Canada, the Ordos Basin in China, and two basins in the former USSR (Law 2002).

Abnormal pressures may develop through osmotic processes across a shale membrane if there is a very high contrast in total dissolved solids (i.e. salinity) on either side of the shale (Fig. 3e). To our knowledge, only two studies have suggested osmosis as a potential cause of underpressure (Breeze 1973; Neuzil 2000). This causes a decrease in fluid density, and thusly, a reduction in fluid volume, or a change in hydraulic regime.

Table 1. A summary of locations exhibiting underpressure and the underpressure generating mechanisms proposed for each location in previous studies. See Table 2 for a full references list

<table>
<thead>
<tr>
<th>Mechanism attributed by author</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal effects (cooling)</td>
<td>Switzerland, Michigan Basin, Barents shelf, China, W. Canada, USA, Former USSR</td>
</tr>
<tr>
<td>Decomposition</td>
<td>Switzerland, Michigan Basin, Barents shelf, China, W. Canada, Midwest USA, Appalachians, Hungary</td>
</tr>
<tr>
<td>Change in hydrostatic regime</td>
<td>Barents shelf, Russian Arctic</td>
</tr>
<tr>
<td>Differential gas charge</td>
<td>USA, China, Former USSR, Canada</td>
</tr>
<tr>
<td>Osmosis</td>
<td>USA</td>
</tr>
<tr>
<td>Geology induced water flow</td>
<td>USA, Canada, Colombia, Hungary</td>
</tr>
</tbody>
</table>

Table 1.

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Table 2. The global occurrences of underpressure, their key parameters and existing studies of each location

<table>
<thead>
<tr>
<th>Basin</th>
<th>Map ID</th>
<th>Age of underpressured strata</th>
<th>Depth of underpressure</th>
<th>Max. magnitude of underpressure bar and (% of hydrostatic)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bohai Bay Basin</td>
<td>20</td>
<td>Oligocene</td>
<td>1700–3400 m.</td>
<td>63 Bar (64%)</td>
<td>Li et al. (2010); Meng et al. (2016); Wang et al. (2019)</td>
</tr>
<tr>
<td>Ordos Basin</td>
<td>18</td>
<td>Carboniferous to Cretaceous</td>
<td>2300–3600 m.</td>
<td>66.5 Bar (81%)</td>
<td>Hao et al. (2012); Shixiang et al. (2013)</td>
</tr>
<tr>
<td>Qaidam Basin</td>
<td>17</td>
<td>Paleocene to Pliocene</td>
<td>500–1200 m.</td>
<td>32 Bar (68%)</td>
<td>Hao et al. (2011)</td>
</tr>
<tr>
<td>Qinshui Basin</td>
<td>19</td>
<td>Carboniferous to Permian</td>
<td>300–480 m.</td>
<td>11 Bar (74%)</td>
<td>Meng et al. (2011)</td>
</tr>
<tr>
<td>Santanghu Basin</td>
<td>16</td>
<td>Permian to Triassic</td>
<td>720–2075 m.</td>
<td>40 Bar (74%)</td>
<td>Xu et al. (2013); Zhang et al. (2009)</td>
</tr>
<tr>
<td>Songliao Basin</td>
<td>21</td>
<td>E Cretaceous</td>
<td>1540–3000 m.</td>
<td>65 Bar (58%)</td>
<td>Li et al. (2010); Xie et al. (2003); Zhanghua et al. (1999)</td>
</tr>
<tr>
<td>North America</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alberta Basin</td>
<td>1</td>
<td>Devonian to Eocene</td>
<td>600–2500 m.</td>
<td>53 Bar (25%)</td>
<td>Breeze (1973); Jiao and Zheng (1998); Nelson and Gianoutsos (2011); Nelson et al. (2015); Sorensen (2005)</td>
</tr>
<tr>
<td>Anadarko Basin</td>
<td>3</td>
<td>Permian</td>
<td>700–2100 m.</td>
<td>52 Bar (36%)</td>
<td>de Witt Jr (1986); Law (2013); Russell (1972)</td>
</tr>
<tr>
<td>Appalachian Basin</td>
<td>5</td>
<td>Silurian to Carboniferous</td>
<td>Shallow to 3000 m.</td>
<td>Only gradients provided: (35% in Shale 80% in Sandstones)</td>
<td></td>
</tr>
<tr>
<td>Denver Basin</td>
<td>3</td>
<td>Carboniferous to Cretaceous</td>
<td>600–2400 m.</td>
<td>135 Bar (34%)</td>
<td>Belitz and Bredehoeft (1988); Law (2013); Nelson et al. (2015)</td>
</tr>
<tr>
<td>Eastern Ohio</td>
<td>5</td>
<td>Silurian to Cretaceous</td>
<td>1200 m</td>
<td>17 Bar (86%)</td>
<td>Davis (1984)</td>
</tr>
<tr>
<td>Green River Basin</td>
<td>3</td>
<td>Cretaceous</td>
<td>1200 to ~2500 m</td>
<td>Not quantified</td>
<td>Law and Dickinson (1985); Law (2013)</td>
</tr>
<tr>
<td>Michigan Basin</td>
<td>4</td>
<td>Ordovician</td>
<td>500–800 m</td>
<td>32 Bar (47%)</td>
<td>Bahr et al. (1994); Khader and Novakovski (2014); Nasir et al. (2011); Neuzil and Provost (2014)</td>
</tr>
<tr>
<td>Palo Duro Basin</td>
<td>3</td>
<td>Cambrian to Permian</td>
<td>670–2750 m</td>
<td>41 Bar (57%)</td>
<td>Orr and Kreitler (1985)</td>
</tr>
<tr>
<td>Piceance Basin</td>
<td>3</td>
<td>Cretaceous</td>
<td>2200–3570 m</td>
<td>150 Bar 58%</td>
<td>Law (2013); Senger et al. (1987); Senger and Fogg (1987); Wilson et al. (1998)</td>
</tr>
<tr>
<td>Raton Basin</td>
<td>3</td>
<td>Carboniferous to Paleocene</td>
<td>~270–2800 m</td>
<td>Only gradients provided: at least 30 bar (2%)</td>
<td>Dolly and Meissner (1977); Law (2013); Nelson et al. (2013)</td>
</tr>
<tr>
<td>San Juan Basin</td>
<td>3</td>
<td>Cretaceous</td>
<td>600–1200 m</td>
<td>Only gradients provided:</td>
<td>Dickey and Cox (1977); Law (2013)</td>
</tr>
<tr>
<td>Williston Basin</td>
<td>3</td>
<td>Cretaceous</td>
<td>70–325 m</td>
<td>14 Bar (1%)</td>
<td>Neuzil (1993); Neuzil (2000); Neuzil and Pollock (1983)</td>
</tr>
<tr>
<td>South America</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Llanos Basin</td>
<td>6</td>
<td>Cretaceous to Pliocene</td>
<td>600–4800 m</td>
<td>85 Bar (83%)</td>
<td>Person et al. (2012); Villegas et al. (1994)</td>
</tr>
<tr>
<td>Neuquén Basin</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Europe</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Cis-Carpathian downwarp</td>
<td>11</td>
<td>Jurassic to Miocene</td>
<td>76–2000 m</td>
<td>17 bar (79%)</td>
<td>Law and Spencer (1998); Orlov (1979); Serebryakov et al. (2002)</td>
</tr>
<tr>
<td>North Barents shelf</td>
<td>8</td>
<td>Triassic to Jurassic</td>
<td>700–2000 m</td>
<td>60 Bar (35%)</td>
<td>Birchall et al. (2020); Wangen et al. (2016)</td>
</tr>
<tr>
<td>Hungary–Pannonian Basin</td>
<td>10</td>
<td>Triassic, Eocene to Miocene</td>
<td>Near surface to 2500</td>
<td>28 Bar (80%)</td>
<td>Mádl-Szőnyi et al. (2015)</td>
</tr>
<tr>
<td>Dnieper-Donets Basin</td>
<td>12</td>
<td>Carboniferous</td>
<td>No data</td>
<td>No data</td>
<td>Law et al. (1996); Law and Spencer (1998); Polutranko (1998)</td>
</tr>
<tr>
<td>Wellenberg, Switzerland</td>
<td>9</td>
<td>Cretaceous</td>
<td>350–1100 m</td>
<td>44 Bar (53%)</td>
<td>Mazurek (2000); Vinard (1999); Vinard et al. (1993); Vinard et al. (2001)</td>
</tr>
<tr>
<td>Russia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>East Siberian Plateau</td>
<td>15</td>
<td>Precambrian to Cretaceous</td>
<td>No data</td>
<td>No data</td>
<td>Serebryakov and Chilingar (1995)</td>
</tr>
<tr>
<td>West Siberian Basin</td>
<td>14</td>
<td>Jurassic</td>
<td>500–2500 m</td>
<td>50 Bar (84%)</td>
<td>Dobrynin and Serebryakov (1989); Matsuveich et al. (1997); Kuzin (1982); Serebryakov and Chilingar (1995)</td>
</tr>
<tr>
<td>Timan – Pechora Basin</td>
<td>13</td>
<td>Permian</td>
<td>&gt;300 m</td>
<td>Only gradients provided Min. 5 bar (88%)</td>
<td>Law et al. (1996); Law and Spencer (1998)</td>
</tr>
<tr>
<td>Oceania</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Taranaki Basin, New Zealand</td>
<td>22</td>
<td>Confidential</td>
<td></td>
<td></td>
<td>Mark Webster (Pers. comm. 2020)</td>
</tr>
</tbody>
</table>
may be because it requires extremely low porosities (Neuzil 2000), which therefore makes pressure measurements exceptionally difficult. Swarbrick and Osborne (1998) suggest that any under-pressure formed by osmosis is likely to be small, and that it cannot occur if the shale contains microfractures.

Geological processes can change hydrogeological systems on a regional scale. For example, if a fully sealed reservoir under hydrostatic conditions becomes exhumed at a downdip location. A hypothetical example is in Figure 3f, where glacial erosion has caused uncorking of the reservoir, leading to the reservoir draining. Sorenson (2005) suggests this as a cause of underpressure in the Hugoton Field in the Oklahoma Panhandle. Tectonic processes may totally change the regional dip and regional flow and equilibrium conditions (Fig. 3g). Every case of underpressure in this study is in an area of either tectonic uplift or deglaciation, which highlights why areas of topography are not optimal places to study underpressure.

**Pressure data**

Pressure analysis is carried out through direct or indirect methods. Direct pressure data comes from measurements of fluid pressure through physical contact with the reservoir. Indirect pressure analysis is an interpretation of pressure based on petrophysical and geophysical properties. Direct pressure measurements are obtained by either involve using a fluid-collecting probe against the interval of interest, or by isolating the interval of interest and allowing it to flow (e.g. a drill stem test). In a small number of cases focusing on the shallow hydrogeology, piezometers have been used to measure the hydraulic head of an aquifer.

Interpreting pressure from wireline log data relies on the interpretation of petrophysical data to identify zones of abnormal mudrock porosity in for a given depth. Such pressure interpretations

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**Fig. 3.** The Mechanisms that generate underpressure are discussed in further detail in the main body of text in this article. (a) Fluid cooling effects; often related to uplift or climatic changes, cooling causes an increase in fluid density and reduction in volume and pressure. This is likely to be important in gas dominated settings, but negligible in water. (b) Decompaction; elastic rebound or brittle fracturing resulting in an increased pore volume with fluid unable to replenish the system. (c) Change in hydrostatic regime, such as sea level change, may occur faster than the subsurface pore pressures can equilibrate with. (d) Differential gas flow is associated with basin-centred gas deposits. Uplift causes underpressure in the gas saturated reservoir and low permeabilities prevents aquifer recharge from the flanks, resulting in underpressures in the basin centre. (e) Osmosis may occur over a shale membrane when there are very high contrasts in salinity on either side of the shale, resulting in overpressure on one side and underpressure on the other. Changes in hydrostatic regimes; including sea level change. (f) and (g) show underpressure caused by changes in hydraulic regimes, where underpressure is caused by gravitational processes. In this study it only applies to cases in the mountainous regions of North America. (f) shows downdip uncorking of a reservoir due to glacial erosion while (g) shows changes in the flow regime through tectonic processes.
can be useful to detect overpressure in basins at maximum burial but is unreliable where rocks are no longer at their maximum stress state. Even in areas with a good understanding of the mudrocks, quantitative pressure interpretation is challenging (Hermanrud and Undertun 2019). For this reason, we have only used direct pressure measurements in this study. However, some of the more recent studies from the basins in China have, wrongly in our opinion, attempted to interpret shale pressure from acoustic logs. This is discussed in more detail in the Songliao Basin case study.

Where hydraulic head is provided instead of pressures, we have converted the data by extrapolating the head along a hydrostatic gradient to the depth of measurement. If the study provided a hydrostatic gradient value, or salinity data, it was used for extrapolation, where it was not provided, a gradient of 0.102 bar m$^{-1}$ was used. Where water table depths are available, they have been used as the hydrostatic gradient datum, where not the land surface has been used. To attempt to quality control the data in this study we have assessed build up plots where these are available. However, in most cases we have taken published data at face value. In many cases, pressure measurements do not fall on clear fluid gradients, whether this is due to challenging reservoir conditions or is more representative of the disequilibrated nature of underpressure is unknown. We have not included pressure data in our global plot where there is excessive spread in data points if they are from the same depth and wellbore.

**Occurrences of natural underpressure**

Table 2 compiles underpressured basins of the world documented in the scientific literature ($n = 80$ key references) and Figure 4 highlights their locations. Except for the Barents shelf (Birchall et al. 2020), and an undocumented case in New Zealand (M. Webster, Pers. comm. 2020), naturally occurring underpressure has only been documented onshore (Fig. 4). While most cases are recorded in petroleum producing provinces, likely due to the proclivity of pressure data acquisition in hydrocarbon exploration and production, there are also cases of severe underpressure in other areas, most notably in Switzerland (Vinard et al. 1993, 2001), Svalbard (Wangen et al. 2016; Birchall et al. 2020), and the Michigan Basin (Normani and Sykes 2012; Khader and Novakowski 2014; Neuzil and Provost 2014).

Figure 5 shows the magnitude and depth of naturally occurring underpressure globally. In contrast to overpressure, underpressure typically occurs at shallow depths, which is probably symptomatic of the geological conditions leading to its development. Furthermore, it may be indicative of the timing and preservation of underpressure.

**China**

Underpressure has been documented in six basins across China, with depths ranging from the deepest global occurrence at c. 3500 m in the Ordos Basin (Xu et al. 2011; Hao et al. 2012; Shixiang et al. 2013), to shallower than 500 m in the Qinshui Basin (Meng et al. 2011).

The Chinese basins in this study have undergone complex and geologically recent inversion, largely related to the ongoing Himalayan orogeny (Table 3 and references therein). Uplift magnitudes can be highly variable within each basin, which makes detailed quantification of uplift in every wellbore location
difficult. Nevertheless, in every documented occurrence of underpressure in China, at least several hundred metres of uplift have occurred (e.g. Wang et al. 2019).

Underpressured reservoirs in China are of various geological ages (Table 3) with no prevalence in any particular stratigraphy, although most occurrences of underpressure occur in low permeability reservoirs. The underpressured Cenozoic reservoirs of Bohai Bay are an exception to this but we note that these occur in deeply buried and well-sealed reservoirs (Qi and Yang 2010; Guo et al. 2013). However, Meng et al. (2016) noted that greater underpressures in Bohai Bay did tend to be in zones that have been more affected by carbonate and silica cementation.

Underpressure in China occurs in both aquifer and hydrocarbon legs, with the possible exception of the gas-dominated Ordos Basin. Pressure data here is in the form of drill-stem tests (DST) from coalbed methane accumulations, and although the fluid type was not specified (Xu et al. 2011; Hao et al. 2012), it is probably the gas-bearing interval. The magnitudes of underpressure are greater at the downdip Sulige Gas field than in the updip Yulin field (Xu et al. 2011) which supports the hypothesis of it being a BCG accumulation (Law 2002).

Several of the studies use acoustic logs to suggest relict or residual overpressure in shale intervals (Xie et al. 2003; Hao et al. 2011, 2012; Zhang 2011; Wang et al. 2019). However in uplifted basins this leads to misinterpretation of pore-pressures and is discussed in more detail in the Songliao Basin case study.

The most proposed mechanism for underpressure in the Chinese basins is uplift associated decompaction and cooling (Xie et al. 2003; Xu et al. 2010, 2011, 2013; Hao et al. 2011, 2012; Shixiang et al. 2013; Wang et al. 2019). No mechanism is studied for the very minor abnormal pressures (assuming the pressure data is correct) in the Qinshui Basin (Meng et al. 2011).

Case study – Songliao Basin

The Songliao Basin is a late Mesozoic intra-cratonic basin located in NE China (Li et al. 2012). The regional topography of the area is almost flat. Underpressure of up to 70 bar occurs in the low permeability syn-rift fluvial and floodplain deposits (Fig. 6). The Gu, Hu, and Su hydrocarbon accumulations are in the Central uplift zone where the most severe underpressure is located, while the Qu accumulation on the flank of the uplift possesses relatively mild underpressures (Fig. 6b).

The Yingchengzi, Shahezi, and Dengloukou Formations are severely underpressured while the higher quality Quantou Formation is near hydrostatic (Fig. 5). The Yingchengzi, Shahezi, and Deng- loukou Formations are heterolithic comprising interbedded shale, siltstone and deltaic sandstones deposited in a lacustrine setting (Xie et al. 2003). The Dengloukou Formation comprises calcareous shales with interbedded sandstones, also deposited in a lacustrine environment. The late Cretaceous Quantou Formation marks the end of rifting and comprises good reservoir quality fluvial and flood plain deposits.

Fig. 5. Pressure depth plot of the global occurrences of underpressure. Underpressured measurements with a high degree of confidence are shown. Pressures have been normalized to the water table where possible, (where not available the land surface is used as the datum point). A hydrostatic gradient of 0.1006 bar/m has been used which is most broadly representative of the cases herein. See Table 2 for key references containing pressure data for each location.
Table 3. An overview of uplift magnitudes and the generally poor reservoir properties of the underpressured sedimentary units in China

<table>
<thead>
<tr>
<th>Basins</th>
<th>Uplift</th>
<th>Depth</th>
<th>Permeability</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bohai Bay</td>
<td>200–600 m</td>
<td>1600–3700 m</td>
<td>8.1–117 mD</td>
<td>Wang et al. (2009), Guo et al. (2013)</td>
</tr>
<tr>
<td></td>
<td>600–1200 m</td>
<td>2300–3700 m</td>
<td>0.1–10 mD</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt;1 mD</td>
<td></td>
</tr>
<tr>
<td>Qinhuai</td>
<td>500–1000 m</td>
<td>490–1250 m</td>
<td>0.01–9 mD</td>
<td>Wang et al. (2001), Guo et al. (2012)</td>
</tr>
<tr>
<td>Shanxi</td>
<td>2500 m</td>
<td>300–1100 m</td>
<td>0.1–0.001 mD</td>
<td></td>
</tr>
<tr>
<td>Songliao</td>
<td>150–1100 m</td>
<td>1100–2800 m</td>
<td>2.5–11 mD*</td>
<td></td>
</tr>
</tbody>
</table>

*Normal pressured reservoirs in this area: 20–3000 m.

From the end of the Cretaceous the basin underwent uplift that is ongoing at present (Fig. 6d inset).

It is not surprising that underpressure is stronger in the lower permeability reservoirs although whether it is due to the causal mechanism of underpressure or simply because it takes longer for pressures to equilibrate is hard to determine. The lack of present-day topography, any major changes in the recharge and discharge zones and the distribution of underpressure (e.g. underpressure is not always greatest updip) appear to argue against the differential hydrodynamic flow as the main mechanism. Significant cooling due to both uplift and the geothermal regime has affected the basin (Zhou and Littke 1999), as in the other under pressured basins of China. Cooling should impact hydrocarbons but underpressure here also occurs in the aquifer. Decompaction is a potential cause and is more likely to occur in the mud-rich rocks, which makes it difficult to assess.

Figure 7 shows pressures and the acoustic response in the Su oil and gas pool. Xie et al. (2003) suggest that the acoustic slowness in the Shahezi formation is from undercompaction due to residual overpressure. However, because the basin has undergone complex inversion, the rocks are no longer under their maximum stress state, making ascertaining fluid pressures from the complex relationship between rock properties and stress impossible. There is as much evidence that the shales of the Shahezi Formation are anomalously slow due to overpressure as there is that the slowness is due to compaction and/or fracturing. This would arguably, better explain the presence of underpressure in the juxtapose reservoir.

The Americas

Underpressures in North America have been well studied with 36 studies spread over 12 basins (Table 2 and references therein). Most of these basins are located around the southern Rocky Mountains in the Texas and Oklahoma Panhandle, New Mexico, Colorado, Utah, and SW Wyoming. The prolific petroleum province of the Alberta Basin has been extensively studied and eight publications document underpressure in the Appalachian and Michigan basins. The magnitude and depth of underpressure shows a similar variation to other global cases with pressures rarely exceeding fifty bar below hydrostatic. Most of these basins are in mountainous areas which is problematic for reasons already discussed.

The Alberta, Michigan and Appalachian basins have undergone uplift and erosion recently due to Quaternary glacial cycles and erosion (Khader and Novakowski 2014; Neuzil and Provost 2014). Uplift in the underpressured areas of the southern Rocky Mountains is more complex with the Sevier–Laramide orogeny contributing to regional uplift until the Paleogene (Yonkee and Weil 2015). Erosion continued throughout the Cenozoic and accelerated in the Quaternary by glaciation and the associated increased river flow (Carter et al. 1998). Post-Laramide uplift associated with the Rio Grande Rift also occurred in NW New Mexico and SW Colorado (Miggins et al. 2002).

Documented occurrences of underpressure in North America are not restricted to reservoir intervals. Severe underpressure has been directly measured in shales in the Ficocene, Williston, and Michigan Basins (Neuzil 1993; Wilson et al. 1998; Khader and Novakowski 2014; Neuzil and Provost 2014) and we discuss these later. In Appalachia, under pressurized lenticular channel-like reservoirs are typically stratigraphically trapped within shales and contain almost no water (Russell 1972; de Witt Jr 1986).

Eight basins studied in North America have been identified as BCG accumulations (Law 2002), although in the Raton Basin Nelson et al. (2013) note that whilst a BCG accumulation is possible, the presence of underpressure cannot be used as evidence for one as the basin is water saturated, with recently formed underpressure being situated in the aquifer. Underpressures in BCG accumulations
are encountered in low permeability reservoirs below 1 mD except for the previously mentioned Raton Basin (up to 28 mD) and the Anadarko Basin (up to 100 mD). Underpressures in BCG accumulations are postulated to occur due to cooling and/or decompaction due to erosion during uplift (Dickey and Cox 1977; Law and Dickinson 1985; Law 2002). Another explanation for the proposed BCG accumulations of the Raton and Anadarko basins are that under-pressure is the result of topographic effects (Sorenson 2005; Nelson and Gianoutsos 2011). The contrast in the suggested causal mechanisms of underpressure is testament to the challenges of analysing underpressure in areas of topography.

Topographic effects and changes in flow regimes have been proposed to explain underpressure in many of the basins in the Southern Rocky Mountains area (Nelson et al. 2013) and the Anadarko Basin, in the Oklahoma-Texas Panhandle region (Orr and Kreitler 1985; Senger and Fogg 1987; Sorenson 2005; Nelson and Gianoutsos 2011). Figure 8 shows a cross-section (redrawn from Sorenson 2005), explaining underpressures in the Hugoton field in the Texas–Oklahoma–Kansas Panhandle. The Wolfcampian carbonate reservoir appears underpressured at the Hugoton Field relative to the land surface but outcrops some 280 km to the NE. The hydraulic head in the reservoir at the wellsite is very similar to the elevation of the reservoir outcrop suggesting the system has flowed and achieved equilibrium with this downdip discharge point. Sorenson (2005) and Nelson and Gianoutsos (2011) suggest this began during high rates of erosion during the Quaternary ‘uncorked’ the reservoir, while updip the reservoir is sealed from recharge. This study shows why developing local hydrostatic gradients in mountainous regions can little relevance to the underlying reservoir conditions.

In addition to the BCG accumulations, several other occurrences of underpressure have been attributed to unloading and associated cooling. Russell (1972) suggests that the strongly underpressured lenticular reservoirs likely occurred due to decompaction of the surrounding shales, essentially drawing fluids from the reservoir like a sponge. Breeze (1973) notes that stratigraphic traps of Oklahoma are often underpressured in the reservoir, though they suggest wireline logs indicate the surrounding shales are over-pressured, and suggest osmosis may explain this. However, this is unlikely. We have already discussed why interpreting pressure from wireline logs in uplifted areas is impossible, and doubt that the shale here is overpressured, based on the geological history. Neuzil (2000) also suggested osmosis could be at play in the Williston Basin of South Dakota, though also notes that this mechanism requires extremely low porosities and very high contrasts in the amount of total dissolved solids. Nearly all documentations of underpressure in the Alberta and Michigan basins suggest it formed due to erosion and post-glacial rebound (Parks and Toth 1995; Michael et al. 2000; Chan et al. 2005; Khader and Novakowski 2014; Neuzil and Provost 2014).

Perhaps the most compelling evidence of decompaction comes from direct pressure measurements within shale intervals. There are three cases in North America where these measurements have been carried out: (1) the Niobrara Shale in the Piceance Basin (Wilson et al. 1998), (2) the Pierre Shale in the Williston Basin of South Dakota (Neuzil and Pollock 1983; Neuzil 1993), and (3) the Michigan Basin (Bahr et al. 1994; Normani and Sykes 2012; Khader and Novakowski 2014; Neuzil and Provost 2014), with the latter discussed as a case study. Five long term pressure measurements from different intervals of the Pierre Shale were taken over approximately four years (Neuzil 1993) and demonstrated severe underpressure.

The Pierre Shale is regionally extensive and acts as a cap rock in many of the underpressured basins, it is also one of the few global
cases of direct pressure measurements in a shale, which show it to be underpressured (Neuzil 1993). In the Piceance Basin, a gas influx occurred while drilling through a fractured interval of the Niobrara Shale, a subsequent drill-stem test of the interval found it to be underpressured by c. 70 bar (Wilson et al. 1998). The Piceance Basin hosts a BCG accumulation (Law and Spencer 1998; Law 2002), with both overpressure and underpressure associated with the Niobrara shale and the underlying reservoirs. Furthermore, Wilson

Fig. 7. (a) Direct pressure measurements through drill-stem tests from the Su oil and gas pool in the Songliao Basin. Data from Xie et al. (2003). (b) Acoustic log data (Xie et al. 2003) from the Direct pressures and acoustic log from the Su oil and gas pool. Xie et al. (2003) suggest the deviation from the normal compaction trend in the Shahezi Formation is caused by overpressure in mudrocks, despite underpressure being measured in the reservoir intervals of the same formation.

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Fig. 8. A cross-section from the Hugoton Field area in the Oklahoma Panhandle region (figure redrawn after Sorenson 2005). Here the Hugoton Field exhibits major underpressure which Sorenson (2005) suggests can be explained by a downdip discharge point some 280 km to the NE. It is suggested the reservoir became exhumed and exposed at this point due to Quaternary glaciation.
et al. (1998) note that the strongest underpressure correlates to areas where overlying Eocene plateaus have been eroded. In the Pierre Shale of South Dakota, and the Ordovician shale of the Michigan Basin, underpressures are greatest in the vertical mid-point of the shales, with higher permeability reservoirs above and below exhibiting normal or overpressures. In the Piceance Basin, both the shale and the underlying low permeability reservoir are severely underpressured and gas saturated (Wilson et al. 1998). The greatest underpressure in the middle part of these shales may be indicative of fluid flow from outside (i.e. the reservoirs) inwards into the shales (Neuzil 1993).

Case study – the Michigan Basin
The Michigan Basin offers a unique study into pressures in shales that are rarely measured in the hydrocarbon industry. Hydraulically tight rocks are, however, important in the disposal of nuclear waste, where radioactive material needs to be isolated for thousands of years to prevent contamination. Four boreholes were drilled and tested by the Nuclear Waste Management Organization in Bruce County, Ontario, to investigate the potential for nuclear waste storage in Paleozoic sedimentary rocks (Khader and Novakowski 2014; Neuzil and Provost 2014) (Fig. 9). Underpressure in the shales is problematic for storing nuclear waste as it may act to draw fluids in from surrounding aquifers at much faster timescales than previously envisioned. Long term pressure tests (Fig. 9b) designed for low permeability settings (Fig. 9c), were carried out between 2006 and 2010 (Khader and Novakowski 2014; Neuzil and Provost 2014).

Tectonic uplift of the region has not occurred since the Jurassic (Cercone 1984), but the basin has undergone significant glacial loading and unloading during the Quaternary (Tarasov and Peltier 2007). Severe underpressure is observed in the ultra-low permeability shale and marl intervals but normal and slight overpressures persist in the over and underlying units which have permeability that are several orders of magnitude higher. It is hypothesized that during glacial loading water is squeezed from the shale into bounding aquifers which then return to near hydrostatic while the shale becomes underpressured during deglaciations (Neuzil and Provost 2014).

Case study – the Llanos Basin, Colombia
The Llanos Basin is a prolific petroleum producing basin (Cazier et al. 1995), and one of only two basins where underpressure has been recorded in South America. Underpressures here are very minor (Fig. 10) but persist to great depth. Person et al. (2012) and Villegas et al. (1994) attribute these underpressures to ongoing flow conditions within the basin, though interestingly, both suggest opposite fluid flow directions. Because the magnitude of underpressure is very low, and it is situated in relatively deep reservoirs, variations in the hydrostatic gradient will play a more important role in defining underpressure. We have demonstrated this in Figure 10b by including a hydrostatic gradient calculated on a 30°C km⁻¹ geothermal gradient.

Throughout the Cretaceous and Cenozoic the Llanos Basin was under marine and marginal marine depositional settings (Cooper et al. 1995). From around 10.5 Ma, several kilometres of uplift on the NW margins of the basin occurred in associated with the collision of Panama (Cooper et al. 1995). The uplift is still ongoing and may contribute to altering basin flow regimes or other underpressure forming mechanisms. Geothermal gradients are highly varied throughout the basin, with lower gradients in the west and higher to the east (Person et al. 2012).

Europe and former USSR
In western Europe, we document two occurrences of underpressure, both of which offer relatively rare and high-quality data. Data from eastern Europe and the former USSR are sparser, date back several decades and often lack information on specific locations. In Wellenberg, Switzerland, underpressure is observed in ultra-low
permeability Cretaceous Marl that was tested as a potential nuclear waste storage site. Another occurrence of underpressure in Switzerland is documented in similar settings, and was acquired during the construction of a tunnel through a claystone (Noy et al. 2004). The other occurrence of underpressure reported in western Europe is from the Norwegian Barents shelf and in Svalbard in the High Arctic. Here, severe underpressures were encountered offshore during hydrocarbon exploration. They were also encountered onshore Svalbard as part of a carbon dioxide sequestration study (Braathen et al. 2012; Olaussen et al. 2019). We investigate both cases in more detail as case studies. In Hungary, underpressure was encountered in deep carbonates of the Pannonian Basin where glacial erosion and decompaction has led to underpressuring (Mádl-Szőnyi et al. 2015), though the area is complicated by changing groundwater conditions due to differential uplift of the basin.

Several occurrences of underpressure have been documented in the Carpathian region and West Siberia (Orlov 1979; Serebryakov and Chilingar 1995; Chilingarian and Gurevich 1996). Underpressures in these regions appear to be moderate, but this may be due to the lack of data. Underpressures are typically on the order of ten to twenty bar and all occurrences are shallower than 1500 m. Underpressure of c. 10 bar has also been documented in the BCG accumulation of the Timan-Pechora Basin (Law et al. 1996) and in some gas fields of the Dniper-Donets Basin (Polutranko 1998).

A range of mechanisms have been proposed for the formation of underpressure in the former USSR basins. The regions have undergone significant recent geological and post-glacial uplift (Kuzin 1982; Chilingarian and Gurevich 1996). Dobrynin and Serebryakov (1989) suggested underpressure in these basins formed due to fluid shrinkage due to temperature reduction and the lowering of the hydrostatic to the base of permafrost. Kuzin (1982) suggests glaciation and deglaciation as a cause of underpressure but also introduces the impact of the associated sea level change as a contributing factor. It is also possible that in Siberia intra-permafrost natural gas hydrates (Chuvilin et al. 2000) form underpressure during their formation, where the surrounding permafrost seal may prevent equilibration. If this mechanism does exist it probably has an upper limit, as decreasing pressure would lead to destabilization of the gas hydrate.

**Case study – the Barents shelf**

The Barents shelf is unique in this study because it is the only case where the hydrostatic gradient is easily and clearly defined by the present-day sea level (Fig. 11). This is the only documented case where underpressure occurs offshore. Underpressure was also encountered onshore Svalbard in the same stratigraphy, but again, a sea-level defined hydrostatic was applied as the near-coastal wellbore is 6 m above mean sea level and the underpressured interval outcrops beneath a fjord approximately fifteen kilometres to the north (Birchall et al. 2020). Underpressure was first encountered in the offshore part of the northern Norwegian Barents shelf (Fig. 11a) in the 1980s during exploration of the Fingerdjupet Subbasin where underpressures of up to 23 bar were encountered in a Jurassic reservoir (Fig. 11b). Severe underpressure of c. 50 bar was encountered in Triassic reservoirs during exploration of the Greater Hoop area over the past twenty years (Birchall et al. 2020). Similarly severe underpressure was encountered in 2009 during drilling for a carbon dioxide sequestration feasibility study in the onshore equivalent Jurassic and Triassic intervals (Braathen et al. 2012; Olaussen et al. 2019; Birchall et al. 2020).

In Svalbard, high quality pressure tests were carried out over several years, which enabled subtle pressure changes to be
monitored. Following drilling, pressures continued to fall for several days, while pressures following injection tests took more than two years to return pre-test conditions (Birchall et al. 2020). This may suggest that supercharging is more profound than previously thought, because the very slow adjustment times may not be detectable in conventional offshore pressure tests. It should be noted that supercharged measurements represent a maximum pressure, so do not raise questions about the presence of underpressure, rather its maximum magnitude.

In addition to underpressure in the reservoir, it was also encountered in the cap rock in Svalbard and in the Fjordjupet Subbasin. In the latter, it is demonstrated by severe mud losses while drilling with seawater through 800 m of the shale-dominated top seal (Anadrill-Schlumberger 1988). In Svalbard pressure in the top seal was directly measured, albeit unintentionally when drilling fluid was lost into the shale formation and subsequently gas entered and filled the closed wellbore. A pressure sensor installed in the wellbore measured pressures well below hydrostatic at a similar magnitude to that to that encountered in the reservoir intervals (Fig. 11b, d). Overlying the shale interval is a slightly overpressured sandstone artesian aquifer (Braathen et al. 2012). Strontium isotope analysis by Huq et al. (2017) from the same wellbore in Svalbard, show that mixing of fluids has occurred between the underlying reservoir and the cap rock (Fig. 12), which is consistent with underpressure also extending from the reservoir to the cap rock.

Adjustment time modelling between the wellbore location to the outcrop location some fifteen kilometres away (represented in by section B-B’ in Fig. 11a, d) suggests that underpressure must have been formed geologically recently and is being retained by the low reservoir permeability (Birchall et al. 2020). The Barents shelf has undergone both Cenozoic tectonic uplift and Quaternary glacial loading and unloading (Henriksen et al. 2011; Kienas et al. 2017; Lasabuda et al. 2021), similarly to underpressure occurrences in Canada. The evidence and consensus is that underpressure has been caused by glacial erosion and unloading potentially aided by fractures and an additional but smaller influence of sea level rise (Wangen et al. 2016; Birchall et al. 2020).

Case study – Wellenberg, Switzerland

Wellenberg in Switzerland is a potential site for nuclear waste disposal and subsequently has undergone extensive pressure testing in hydraulically tight rocks. Unlike other areas, it is not in a typical sedimentary basin, but an area that has undergone alpine compressional tectonics as evident by repeated sections and a complex stratigraphy (Fig. 13). Two drill sites pressure tested multiple intervals, using methods designed for low permeability rocks (Vinard et al. 1993). Severe underpressure was encountered in the Cretaceous Vitznau Marl.

Determining the exact magnitude of underpressure here is difficult to ascertain due to the challenges associated with hydrostatic gradients in mountainous areas. However, what is clear is that the underpressure magnitude is greatest in the vertical centre of the Vizea Marl interval and becomes progressively nearer to hydrostatic towards and into the bounding reservoir units. The bounding intervals have much higher permeabilities with overpressure in these likely being artesian (Vinard et al. 1993). The greatest underpressure in the middle part of the shale indicates that it is out of equilibrium with the neighbouring reservoirs. The shallow depths of underpressure suggest a relatively short adjustment time (Neuzil 2012) meaning underpressure must have been formed geologically recently.

Switzerland, like many of the examples here, underwent extensive glaciation throughout the Quaternary with repeated loading, unloading and erosion of overburden in addition to the effects of the Alpine orogeny. The studies of the Wellenberg site suggest glacial unloading and rebound has caused the underpressure (Vinard et al. 1993, 2001; Vinard 1999). Although we have stated that mountainous areas can add uncertainty associated with flow, here the greatest underpressures are the equivalent of a hydraulic head less than 10 m above sea level (Vinard et al. 1993). It would be virtually impossible for these low permeability rocks in the Swiss Alps to be plumbed to a distant outcrop at 10 m elevation. We note that the underpressure distribution and magnitude in the Wellenberg case is very similar to that of the Michigan Basin case study, which
features a very similar geological setting and history, with the only major difference being topography.

**Discussion**

**Magnitudes and distribution of underpressure**

Although the range of depths varies, most examples occur in the upper two kilometres of strata, with no known cases existing deeper than 3700 m. The magnitude and range of underpressure is significantly lower than that of overpressure (Swarbrick et al. 2001). While the limits of overpressure are generally well understood and depend on the strength of the rock through geological time (Winefield et al. 2005), the controls on the limits of underpressure are unknown.

**Retention of underpressure**

The retention of underpressure is important to understand as most cases occur at shallow depths. These shallow underpressures usually lack a lateral seal and should not be able to support abnormal pressures on long geological timescales. The vast majority of cases occur in very low permeability rocks, although there are exceptions. Where higher permeability intervals demonstrate underpressures they often occur in deeper and well-sealed reservoirs, such as the Bohai Bay Basin in China, the Fingerdjupet Subbasin on the Barents shelf, and the lenticular sandstones of the Appalachian Basin. However, shallow, high permeability intervals without evidence of lateral seals do exist in basins of the USA. These cases have been associated with the effects of topography and fluid flow, and include the Raton, Palo Duro and Anadarko basins (Orr and Kreitler 1985; Sorenson 2005; Nelson and Gianoutsos 2011; Nelson et al. 2013, 2015), although it should also be noted that these carbonate reservoirs can be highly heterogeneous (Rall and Loeffler 1994). Arguably, it may be that reservoir permeability is the best indicator to separate gravitationally controlled underpressure and other geological drivers. High permeability rocks are more conducive to flow and are more likely to be in equilibrium with downdip free surfaces. Low permeability rocks, on the contrary, restrict flow and maybe preserve underpressure formed through other processes.

Based on the depth, settings, and geological histories, underpressure in the majority of cases from around the world, must have been caused geologically recently and is in a state of disequilibrium. Low permeabilities appear to be restricting equilibration in most
cases particularly where underpressure occurs in shales, where fracture networks may play an important role (Magara 1981; Neuzil 2012; Larsen 2013).

**Underpressure in shales**

Whilst direct pressure measurements in shales are rare in the hydrocarbon industry, other studies have proved extremely useful in demonstrating the occurrence of underpressure in ultra-low permeability rocks. These studies not only demonstrate that underpressure does occur in such seals (or aquitards), but also that underpressure is not synonymous with hydrocarbon provinces. Figure 14 shows five cases of underpressure in mudrocks, and in some cases, demonstrate that the greatest underpressure is toward the centre of the mudrock interval. The pressure gradients from maximum underpressure in the centre, to normal pressures at the boundaries of the mudrock–reservoir interface, may be indicative of flow into the shale from the bounding aquifers. Isotope data in Svalbard (Fig. 12) also supports the hypothesis of flow into the mudrock interval from the underlying reservoir. In the Piceance Basin and in Svalbard (Wilson et al. 1998; Birchall et al. 2020), the reservoirs underlying the shale are underpressured and extremely low permeability. It is likely that the underpressure observed in these reservoirs was first generated in the shale rocks and fluid has been drawn from the reservoir at a rate faster than it has been replenished.

Hermanrud and Undertun (2019) demonstrate that using wireline logs to quantitively predict pore pressure in shales is challenging even with good data and rocks at maximum burial. Uplifted basins are no longer under their maximum stress, which means the link between pore-pressure, effective stress and rock physics has been broken, and petrophysical properties cannot be used to interpret pore pressure. In some cases in basins in China, acoustic petrophysical data has been interpreted to show overpressure in shales that bound reservoirs that have directly measured underpressure (e.g. Xie et al. 2003; Wang et al. 2019). However, numerous geological processes could explain abnormal slowness in rocks in basins that have undergone uplift. One of many such examples is fracturing and decompaction (Ogata et al. 2014).

**Mechanisms generating underpressure**

**The role of uplift**

To our knowledge, all documented cases of underpressure have undergone geologically recent uplift. Uplift has occurred either through tectonics, including the Himalaya and Rockies-Andes influenced basins of China and the Americas, while many cases further north are influenced by glacial erosion and rebound. Because underpressure is synonymous with uplift and erosion, some processes are hypothetically easier to determine than others. For example, underpressure due to cooling, permafrost formation, or osmosis should also exist in areas where uplift has not occurred. Conversely, mechanisms that are intrinsically linked to uplift such as decompaction are difficult to disprove. Uplift brings reservoirs that have been undergone physical and chemical compaction to shallower depths. This can help retain abnormal pore pressures and, arguably, explains the prevalence of underpressure in low permeability intervals at relatively shallow depths.

**Temperature effects**

Temperature can influence PVT conditions in the reservoir in addition to the overall hydrostatic gradient. The impact of temperature on hydrostatic gradients is relatively minor compared to salinity variations. While salinity can potentially influence the entire hydrostatic column, temperature has a gradually increasing
influence with depth, depending on the geothermal gradient. Because temperature increases with depth, the aquifer density decrease due to temperature is somewhat depressed due to the increasing pressure. Nevertheless, in some situations, subtle underpressure may be apparent if temperature is not considered when constructing the hydrostatic gradient. The Llanos Basin may be such a case, Figure 10b from The Llanos Basin shows that applying a temperature adjusted hydrostatic gradient may provide another explanation for apparent underpressures.

Climate-driven surface variations of 20°C or more on kyr scales are common in Earth’s history, as demonstrated by ice-core geochemical studies (e.g. Johnsen et al. 1995). Cooling on these timescales does influence subsurface conditions and is evident in the cryostratigraphy of permafrost (Gilbert et al. 2018). A 20°C change is not insignificant; many of the basins of China likely encountered similar magnitudes through uplift (Table 3 and Feng et al. 1994). Empirically speaking, if cooling is a widespread and major cause of underpressure then one might expect to find underpressure where cooling has occurred without uplift, which we do not observe. We also observe that most cases in this article document underpressure occurring in aquifers where cooling has less impact. Cooling probably is a major driving force in the formation of underpressure in gas-saturated settings such as BCG accumulations.

Decompression

Perhaps the most cited cause of disequilibrium underpressure is erosion and decompression, and the effects of cooling. Unloading is almost always associated with cooling because uplift invariably causes cooling due to geothermal gradients. However, given the underpressures in water legs and in shales it seems likely that decompression is a bigger driver of the two.

It is assumed that shales are more affected by decompression than reservoir rocks due to their rheology and elastic properties (Neuzil and Pollock 1983; Karig and Hou 1992; Liu and Roaldset 1994). It is also important to note that prior to uplift shales have a much smaller interconnected pore volume than reservoir rocks so any increase in pore volume during uplift and decompression will have a much greater impact in pressure reduction than reservoir rocks. Because of these we can expect isolated reservoirs with low interconnected pore volumes to be more affected by decompression induced underpressuring than reservoirs with larger connected pore volumes. Permeability is also important in this mechanism because when water is drawn into the decomposing shales the rate at which water is replenished into the reservoir depends on its permeability. Poorly connected reservoirs with a low permeability encased in, or juxtaposed with, shales are most likely to develop and retain underpressures. Reservoirs with good permeability and connectivity are likely to be able to replenish water at a greater rate than the shale absorbs it and remain normally pressured. We see exactly this in the cases where underpressure is measured within the shales, in the South Williston (Neuzil 1993) and Michigan basins (Neuzil and Provost 2014) and in Switzerland (Vinard et al. 2001). The bounding reservoirs possess good permeability whereas the tight reservoirs underlying the measured pressures in the Piceance Basin and in Svalbard show similar pressures to those in the overlying shale (Fig. 14). Svalbard also demonstrates artesian overpressures in an overlying good permeable sandstone (Birchall et al. 2020).
Ultimately, because underpressure is most frequently observed in aquifers and often in basins with little topography, the most common cause of underpressure seems to be due to compaction associated with uplift, commonly in association with deglaciation. In most cases, particularly those with the best available data, this mechanism is the only one which consistently explains the observations. The effects of topography and gravity alone could be significant in mountainous regions and may be even more profound where regional hydrogeological conditions have undergone changes, such as the midwestern USA. In these settings it would be useful to obtain pressure measurements in the very low permeability mudrock intervals to determine if other processes are prevalent. Underpressure directly measured in shale intervals, locally variable underpressures in low permeability reservoirs juxtaposing shale, and underpressures in reservoirs encapsulated in shale all suggest compaction as a main driver.

Change in hydrostatic regime
Underpressure through sea level change only applies to the Barents shelf case of underpressure where, if it does contribute, can only play a minor role. It is plausible that subtle underpressures exist in undocumented cases, elsewhere offshore in well-sealed rigid reservoirs. Onshore, the equivalent is the change in water tables, which also does not appear to be prevalent in global cases. The vertical movement of the hydrostatic gradient through time were a major cause of underpressure, we would expect it to be common regardless of geological history, yet we do not observe it outside uplifted basins.

Dobrynin and Serebryakov (1989) suggest that permafrost formation causes underpressure due to both cooling and the lowering of the hydrostatic to the base of permafrost. However, we argue that the base of permafrost should not be the datum used as the top of the hydrostatic gradient for several reasons; Firstly, empirical evidence from Canada and Alaska (Kamath et al. 1987; Majorowicz and Hannigan 2000) show pressures at the base permafrost falling on a hydrostatic gradient beginning at the near-surface. In the more mountainous setting of Svalbard, where most wellbores are drilled in the bottom of valleys, the sub-permafrost pressures either demonstrate artesian overpressure or hydrostatic pressures, probably controlled by flow through valley-floor pingos (Gilbert et al. 2018; Birchall et al. 2021). Secondly, the fact that gas hydrates are commonly found at the base of permafrost demonstrates that there must be enough fluid pressure to enable them to form (Majorowicz and Hannigan 2000; Collett et al. 2011; Betlem et al. 2019; Birchall et al. 2021). Thirdly, the concept that the column of permafrost can form and passively sit above the water table with no interaction is flawed. If the permafrost forms a seal, either the hydraulic head will equilibrate to an updip location, or the expansion of ice will generate overpressure; both of these overpressure causing mechanisms are observed in nature (Linell 1973). Hypothetically the hydrostatic may lower if the permafrost formation prevents hydraulic recharge in a dynamic system. But in such a situation it is the free surface at the discharge point that would control the potential magnitude of underpressure, not the base of permafrost.

Osmosis
Breeze (1973) suggested underpressure in stratigraphic traps of Oklahoma was caused by osmosis. This was favoured because wireline logs were interpreted to show shale overpressure whilst the sandstone reservoir is underpressure. However, as previously discussed, inferring overpressure from petrophysical properties in uplifted basins is flawed. In empirical terms, one would expect to see cases of underpressure where uplift has not occurred if this was a prevalent underpressure generating mechanism.

Impacts of flow
Although this paper is focused on the geological drivers of underpressure, it is important to assess whether topographic effects may provide an alternative explanation. The basins of China, and most locations outside the Americas do not have enough topography to generate the levels of underpressure that are observed. In mountainous parts of the North America, a multitude of causes have been suggested for the cause of underpressure (Table 2 and references therein). However, studies from the SE Rocky Mountain area and the Texas Panhandle suggest that underpressure can be explained by regional equilibration with discharge points at lower elevations. The reservoirs here typically exhibit higher permeabilities and arguably better connectivity than other occurrences worldwide. However, the area has been recently uplifted so it is difficult to rule out contributions from other mechanisms that cause underpressure elsewhere. It may be coincidental that the Pierre Shale is a major top seal for these basins, and one of the few mudrocks where underpressure has been directly measured, located several hundred kilometres away in the relatively flat Williston Basin. We note that the locations where underpressure is attributed to flow possess significantly higher reservoir permeabilities than any other cases, and likely do reflect underpressure resulting from flow.

Knowledge gaps and future research directions
Although this synthesis helps comparing and contrasting the cases of natural underpressure, further work is required to fundamentally understand the processes that cause it. In contrast to overpressure, the constraints on the maximum magnitudes of underpressure are not known, nor are the rates at which it develops and builds, predominantly because the proposed mechanisms are so fundamentally different. While modelling is very useful for sense-checking systems that we have a reasonable understanding of, the lack of long-term data, particularly in very low permeability rocks makes understanding the entire fluid system very difficult.

More traditional reservoir rock measurements are common and typically present a snapshot of pressures at a given point in time. Long-term pressure measurements through the sealing and reservoir rocks in areas of known underpressure might provide insight into common origins or whether cases are geologically unique. The interaction between the reservoirs and their juxtaposed mudrock seals is arguably critical to understand the how these disequilibrium systems develop. While mudrock underpressures have been demonstrated in previously glaciated areas, they have yet to be linked to uplift of a tectonic origin. The basins of China, perhaps offer a unique opportunity to install long-term pressure monitors in the seal-reservoir systems, rather than the present flawed use of petrophysical data to infer pressures in the shale intervals.

Finally, there needs to be better integration between methods used in the petroleum industry and those used in hydrogeology. The petroleum industry tends to focus on longer-term geological processes and the view that pressure drives flow dominates, while in hydrogeology shorter term changes in the shallower subsurface are more pertinent and the view that flow (and gravity) determines pressure is considered more. However, one cannot understand an underpressured system without understanding its entirety, from its geological history to short-term changes, from regional setting to local reservoir properties, and from the reservoir to the connection with the atmosphere.

Summary and conclusions
In this contribution we have identified naturally occurring disequilibrium underpressure in twenty-nine basins and regions
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throughout the world. The main trends and findings can be summarized as follows:

- Underpressure magnitudes are lower and vary significantly less than those of overpressure.
- Underpressure is most prevalent in the uppermost 2.5 km of the subsurface.
- Underpressure only occurs in basins that have undergone geologically recent uplift.
- Underpressure is more prevalent in low permeability rocks.
- Significant underpressure occurs in mudrocks.
- Underpressure measurements are more reliable in regions of low topography.

Because underpressure is likely a recent phenomenon and out-of-equilibrium within its system, care must be taken using underpressure to infer good seals or flow direction.

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