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The Impact of Salt Caverns on Stress in the Lotsberg Formation

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Summary

Salt caverns are large cavities mined in salt formations to store hydrocarbons such as natural gas, propane, butane, and crude oil, or to provide a place to dispose of granular oilfield wastes such as produced sand or drill cuttings, or to use the salt directly for industrial feedstock or consumer purposes. In Canada, depending on the cavern purpose and geological setting, they can be up to 150 m in diameter or 120 m in height. Cavities of this size, particularly when there are many close together, can have a significant impact on the stress field within several hundred metres in the surrounding formations.

Salt caverns used to store liquid hydrocarbons always have two liquids present: the product being stored, and saltwater brine which is used to displace the product back to surface. These caverns generally operate at pressures around the brine gradient of 11.8 kPa/m. This is significantly lower than the typical vertical stress gradient of 22.6 kPa/m and requires vertical stresses to be increased some distance from the salt caverns to compensate for the inability of the brine and hydrocarbon to support all of the overburden weight directly above the cavern. This also increases the risk of hydraulic fractures or rock mass failure above and between caverns.

During injection and withdrawal of hydrocarbons, downhole cavern pressures can swing by 5% to 10% of the static brine pressure gradient due to friction in the well tubulars. The resulting elastic uplift and sag of the cavern roof can be observed in adjacent caverns. These dynamic geomechanical effects are often observed by Keyera at its Fort Saskatchewan, Alberta facility when caverns are held at static pressures during mechanical integrity tests which are performed every five years. Caverns need to be within 150 m of each other to initially see this effect, but it is not always guaranteed to be observed.

Case Study

Keyera Corporation operates eighteen salt caverns at its Fort Saskatchewan, Alberta fractionation and storage facility. The caverns are used to store natural gas liquids including C_{2+} and C_{3+} raw feeds, and spec. products including propane (C_3), butane (C_4), and condensate (C_{5+}). The first caverns entered service in 1972. All cavern wells are set in the Lotsberg formation at depths between 1857 and 1871 m. Caverns are mined below the casing shoe and have diameters between 80 and 137 m, and height of 35 to 40 m. The overall Lotsberg formation is 70 to 73 m thick, and the upper two-thirds are noted as being very clean halite

(NaCl) with minimal impurities (Yuan et al, 2022; Toboła & Kukiałka, 2020). However, the lower third contains two brecciated marlstone layers which impede cavern mining and depth.

Several geomechanical modelling studies have been performed to assess operating risks for the caverns. Risks include cavern stability, tensile fracturing, and opening of parting planes between salt caverns. Two-dimensional plane strain vertical cross section finite element models across the entire cavern field and three-dimensional finite difference models of smaller groups of caverns have been completed. Modelling incorporated the elastic-plastic response of brittle (non-salt) rock types and the time-dependent, viscoplastic creep behaviour that dominates the deformation of rock salt.

At the most basic level, due to their low operating pressure relative to the overburden stress gradient, salt caverns cause significant changes in stress in the vicinity of individual caverns, and in the larger volume around a field of salt caverns. Undisturbed vertical stress at the top of the Lotsberg based on density logs is 41 MPa (22.1 kPa/m). Figure 1 shows the reduction of vertical stress immediately above two modelled salt caverns to 22 MPa (11.8 kPa/m). The compressive vertical stress is significantly reduced around a group of caverns. However, a region of vertical stress greater than the undisturbed stress has been observed 150 to 350 m away from a modelled cluster of six caverns. This region is a result of the overburden load being redistributed away from the caverns, creating a stress concentration outside of the cavern cluster. Similar behaviour has also been modelled by Brouard et al (2021).

Salt caverns also create dynamic stress environments. The overall change in bottomhole pressure in the Keyera caverns is from 19 to 25 MPa caused by maximum withdrawal and injection rates. However, the typical operating range is smaller. An impact of the pressure changes and geomechanical response is shown in Figure 2. Cavern A was operating, with pressure changes of 292 to 1,217 kPa caused by variable injection rates. Cavern B was sitting static and isolated from plant operations. Six events were recorded where changes in Cavern A pressure caused a pressure response in the opposite phase in Cavern B in the range of 1.4 to 4.8 kPa. This is a geomechanical response. As pressure increased in Cavern A it bore more of the overburden weight which meant that the surrounding salt and caverns (including Cavern B) observed less vertical stress and vice versa. Caverns A and B have diameters of 130 and 123 m respectively and a centre-to-centre spacing of 252 m. These dynamic geomechanical effects are not always consistent, as can be seen in the figure, likely due to stress relaxation of the rock and salt or the interactions with other adjacent caverns.

In summary, salt caverns have a significant impact on the stresses in their vicinity. Primarily this is due to operating pressures being much lower than the undisturbed stress field. Secondary stress effects caused by storage operations can also be observed.

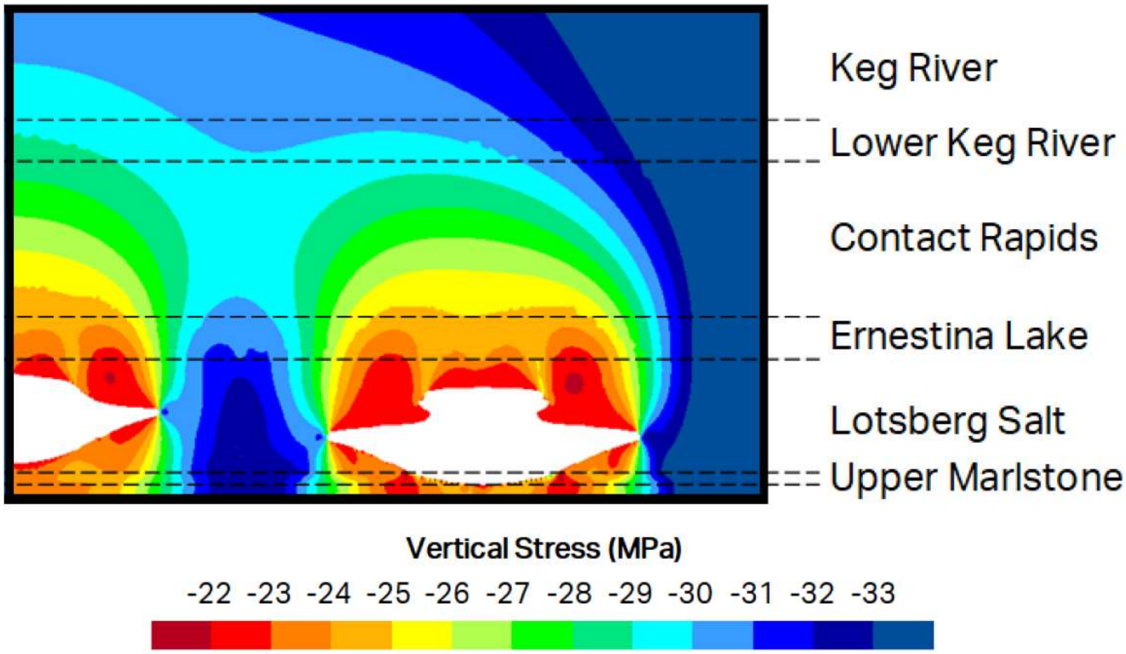

Figure 1: Vertical stresses in immediate vicinity of two caverns (3D model, compression is -ve).

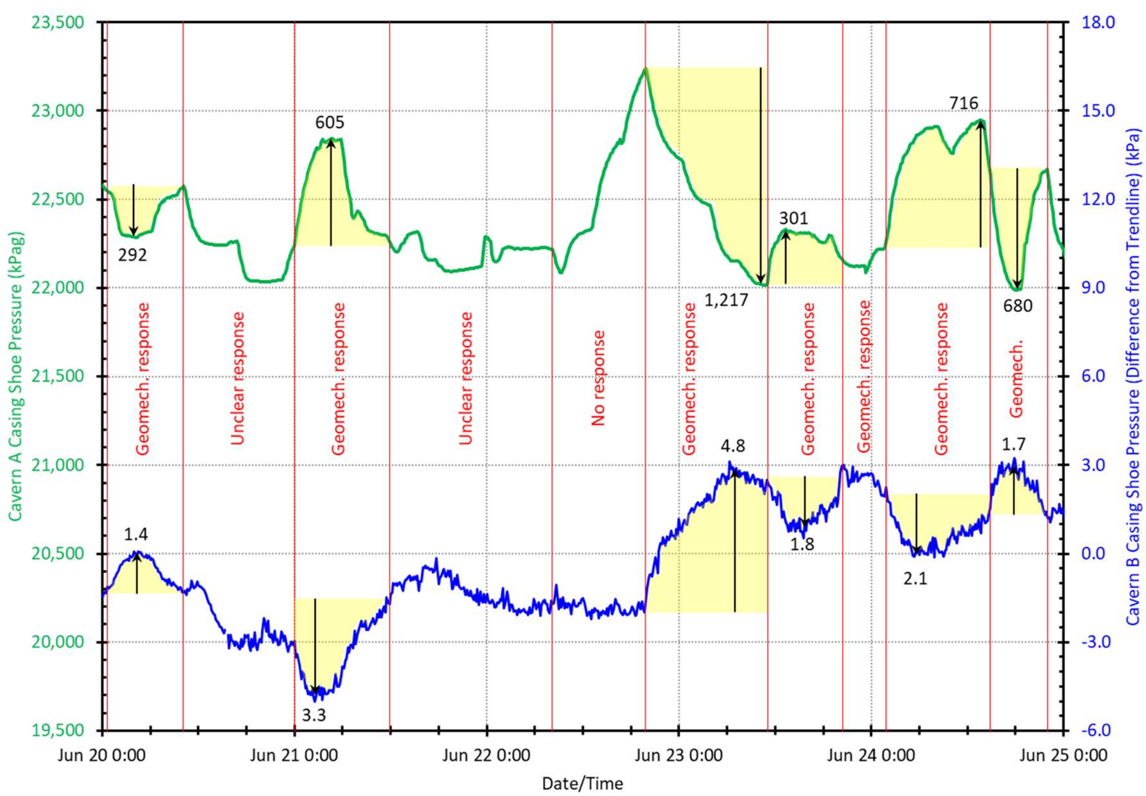

Figure 2: Cavern A operating pressures and geomechanical responses of Cavern B.

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