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Focused fluid-flow structures potentially caused by solitary porosity waves

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ABSTRACT

Gas chimneys, fluid-escape pipes, and diffused gas clouds are common geohazards above or below most petroleum reservoirs and in some CO_2 storage sites. However, the processes driving the formation of such structures are poorly understood, as are the time scales associated with their growth or their role as long-term preferential fluid-migration pathways in sedimentary basins. We present results from a multidisciplinary study integrating advanced seismic processing techniques with high-resolution simulations of geological processes. Our analyses indicate that time-dependent rock (de)compaction yields ascending solitary porosity waves forming high-porosity and high-permeability vertical chimneys that will reach the surface. The size and location of chimneys depend on the reservoir topology and compaction length. Our simulation results suggest that chimneys in the studied area could have been formed and then lost their connection to the reservoir on a time scale of a few months.

INTRODUCTION

Recent observations show that fluids in the subsurface tend to migrate along preferential flow pathways (Berndt, 2005). Most evidence comes from seismic reflection data, where focused fluid flow is imaged as near-vertical zones of highly attenuated chaotic reflections interpreted to represent fluid-escape structures called chimneys or pipes (Judd and Hovland, 2007; Moss and Cartwright, 2010; Bunz et al., 2012). In many cases, chimney structures are rooted in petroleum-generating source rocks and gas- or oil-rich reservoirs and end at the seafloor to form craters or pockmarks often associated with active degassing. As such, chimney structures above closures are considered to be direct hydrocarbon indicators (Heggland, 1998). Chimneys propagate vertically through thick sand units as well as through nearly impermeable shale sequences. However, quantification of fluid-flow processes and the dimensions of chimney structures from seismic data is challenging due to the absence of clear reflectors inside and around a chimney (Nourollah et al., 2010). Manual mapping of chimneys has been improved using new high-resolution three-dimensional (3-D) and four-dimensional (4-D) seismic data (Waage et al., 2019). Seismic chimneys and pockmarks have also been interpreted from seismic data covering several potential carbon storage sites, including Snøhvit (Norwegian Sea) and Sleipner, Troll, Golden Eye, and P-18 (all in the North Sea; Mazzini et al., 2017; Tasianas et al., 2016; Verdon et al., 2013). These vertical conduits are potential migration pathways for the injected CO_2 to escape back to the atmosphere. Despite being an obvious risk to the integrity of storage sites, little is known about their internal structure and hydraulic properties or the factors controlling the generation of seismic chimneys.

We present results of a multidisciplinary study of seismic chimney structures showing that spontaneous flow self-localization due to a solitary porosity wave is a viable mechanism of forming focused fluid flow in realistic geological environments. These results cast new light on the nature of seismic chimneys and their formation processes, with implications for petroleum exploration and subsurface waste storage. Although we based our study on a specific area, the study focused on creating a general model for chimney development.

STUDY AREA

Our study area is in the Ringhorne Oil Field, in the central part of the North Sea over the Heimdal Terrace and the Utsira High (Fig. 1). There, hydrocarbons are found in Middle to Upper Jurassic and Paleocene reservoirs characterized by fluvial sand deposits and marine sandstones interbedded with shales, thin siltstones, and dolomitic limestone units (Johnston and Laugier, 2012; Norwegian Petroleum Directorate, https://factpages.npd.no/en/field/PageView/Producing/3505505). Our interpretation of the geophysical data suggests that the oil in the reservoir is sourced from Jurassic shales in the adjacent Viking graben. Thus, hydrocarbon migration likely occurs laterally from the Viking graben and vertically on the flanks of the Utsira High to charge the reservoirs. The reservoir units sit above a crystalline basement and are directly sealed by marine shales and mudstones. The overburden above the major seal units consists of several intervals dominated by sand, sand injectites, and highly mobile shale. Water depth in the studied area varies between 90 m and 160 m. We used a 3-D broadband seismic data set acquired by PGS (Oslo, Norway) in 2009–2011 with GeoStreamer technology covering ~3000 km^2 (Fig. 1). Prestack depth migration (PSDM) technology was used for data reprocessing in 2016 (see Table S1 in the Supplemental Material[1] for the technical specification of the survey). Processing of seismic data, including seismic sequence stratigraphic interpretation and PSDM, was performed to

[1]Supplemental Material. Additional details on chimney detection and modeling methods, four supplemental figures, and a supplemental table with survey specification. Please visit https://doi.org/10.1130/GEOL.S.16746247 to access the supplemental material, and contact editing@geosociety.org with any questions.

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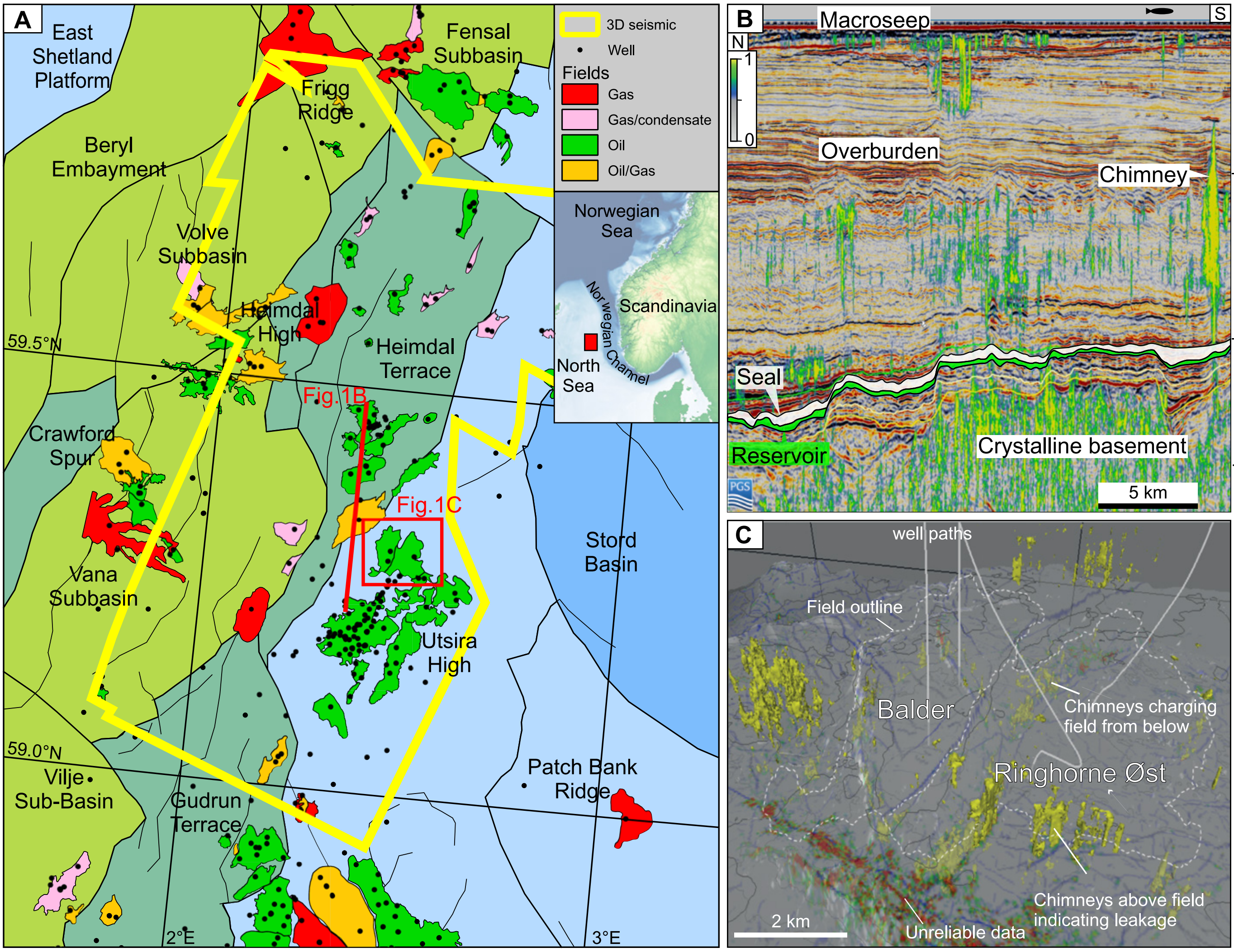

Figure 1. Study area in the North Sea and detected chimneys. (A) Location of the study area, where yellow line shows three-dimensional (3-D) data coverage. Red line is location of two-dimensional (2-D) profile in B. Red box indicates location of reservoir shown in C. (B) Distribution of gas clouds and seismic chimneys on the flank of the Utsira High, likely originating from the Viking graben. Colors show probability of chimneys from seismic attributes. (C) 3-D view of high-probability gas chimneys (yellow) in the vicinity of the Balder/Ringhorne Ost oil fields (white dashed line). Bright yellow chimneys above the Top Statford reservoir horizon (gray) show flank leakage from the reservoir. Gray-yellow chimneys show chimneys below the mapped horizon providing hydrocarbon charge into the main reservoir. Blue linear features—high-probability faults.

support chimney interpretation and modeling. The stratigraphic sequence was tied to the seismic data by several boreholes drilled through the area. We used geophysical, petrophysical, and geological data to build a geological model of the site.

CHIMNEY STRUCTURES

The identification of chimney structures was based on supervised self-educating neural networks to provide chimney probability values, which could be displayed on 2-D seismic sections extracted from a 3-D volume as in Figure 1B, or in 3-D views as in Figure 1C (Tingdahl et al., 2001; Connolly, 2015). We identified chimneys using a set of multidimensional seismic attributes that highlight these features (see the Supplemental Material). Our data show that, in 3-D, chimney structures form nearly cylindrical vertical pipes that cut through formations of different ages without significant changes in the propagation direction. Chimneys can also have a more amorphous shape, often described as a gas cloud (Fig. 1C). However, our chimney processing results on a horizon slice through a suspected gas cloud showed that these features consist of clusters of distinct pipes, which cannot be resolved on seismic sections. Some chimneys are closely related to faults, while others occur below or originate directly above the reservoir (Fig. 1C). The chimneys below the reservoir may represent the migration pathways of hydrocarbons to charge the reservoir (Connolly, 2015). In our study area, there are several high-porosity areas overlaid by low-permeability seals. Yet, despite these low-permeability seals, abundant chimneys are present over them.

CHIMNEY FORMATION PROCESSES AND MODELING FRAMEWORK

Chimney structures are usually interpreted to be the result of overpressure release in areas that experienced high sedimentation rates, oil and gas generation, temperature- and/or pressure-driven diagenetic reactions, or glaciation-deglaciation cycles (Plaza-Faverola et al., 2015; Portnov et al., 2016; Wangen, 2020). However, very few studies have attempted to conduct numerical modeling of seismic chimneys and other reservoir leakage pathways. Most of them consider only preexisting geological structures such as faults or fractures that might be sealed or conductive, depending on pressure fluctuations in the reservoir (Duran et al., 2013; Tasianas et al., 2016). A few exceptions are the works of Wangen (2020), Räss et al. (2018), and Yarushina et al. (2020), who modeled a chimney-generation process in intact rock. Wangen (2020) assumed that chimneys were formed as a result of hydraulic fracturing, while Räss et al. (2018) and Yarushina et al. (2020) proposed that solitary porosity waves produced chimneys.

Fracturing might be expected in hard, brittle rocks when fluid pressure rapidly rises beyond minimum horizontal stress. Fracturing generates planar structures, which are always connected to the initial reservoir, and their orientations are controlled by principal stresses. Solitary porosity waves would be expected in soft deformable formations at lower fluid pressures when effective stresses in the rock meet the failure criterion (see the Supplemental Material). Flow localization due to porosity waves produces elongated cylindrical conduits with a nearly circular cross section (Räss et al., 2018). These conduits propagate upward as self-sustained bodies that then lose their initial connection to the feeding reservoir. Our data show an abundance of nearly cylindrical channels rather than planar fractures (Fig. 1C). Thus, we considered flow self-localization due to solitary porosity waves to be the mechanism of gas chimney formation observed in our data.

The model input requires several dimensionless ratios or numbers derived from known physical quantities and laboratory experiments (see the Supplemental Material). One of them is the compaction length, $L = \sqrt{\frac{\eta k}{\mu}}$, which depends on rock background permeability (k), bulk viscosity of the rock (η), and fluid viscosity (μ). The compaction length is a parameter that describes a drainage area needed for each separate channel to grow. Another relevant parameter is the characteristic compaction time, $T = \frac{\eta}{\Delta\rho g L}$, which depends on the difference between solid and fluid densities, $\Delta\rho$, η, L, and the gravitational acceleration constant, g. For our study area, we inferred that $L = 300$ m, and $T = 1$ yr (see the Supplemental Material).

Our model covered a 2-D seismic section with a lateral extent of 24 km and a depth of 3 km below the seafloor (Figs. 1B and 2A), extracted from the 3-D data set described above. The location of the section is shown in Figure 1A. The initial conditions in our model included a fluid-filled reservoir with high porosity of 30% (+random noise) (Räss et al., 2019), overlying cap rock, and an underlying basement with a porosity of 7.5% (+random noise). Due to buoyancy forces, the fluid in the reservoir migrates upward in diffused clouds (see Video S1 [in the Supplemental Material], which shows the chimney growth). Interaction of flow and viscous matrix deformation leads to flow instability and the generation of separate channels with time (Figs. 2B and 2C).

RESULTS AND DISCUSSION

Our simulation results showed that 0.14–0.22 nondimensional time units are needed for a chimney to form and reach the seafloor (Figs. 2–4). This corresponds to 1.68–2.64 mo in dimensional numbers, given the inferred characteristic scale $T = 1$ yr. The distribution of chimneys is controlled by changes in reservoir topology, thickness, and compaction length. In areas where the reservoir has significant changes in its thickness, chimney formation might be expected. The upward propagation of a chimney is associated with the continuous growth of porosity and permeability. The porosity of the chimney is up to twice the value of background porosity, and its permeability is at least one order of magnitude larger than the value of background permeability. In clay-rich rocks and shales, where permeability has a stronger dependence on pressure, this increase may be several orders of magnitude. Apart from large chimneys, the model can reproduce many smaller fluid-flow features that do not reach the seafloor. The horizontal migration of the fluid is minimal unless the chimneys meet a major lithological boundary, which is modeled as sudden changes in mechanical properties and permeability. First, a competent and thick horizontal layer is set up at the overburden, mimicking the transition from clay-rich cap rock to shales at the upper layers (Fig. 2B). The viscosity of the competent layer is nine times higher than the viscosity of the rest of the cap rock. Simulations show that the fluid ponds below the base of the competent layer for a short time before chimneys pierce through (see Video S1). The chimney in the competent layer becomes slightly wider than the chimney beneath due to the change of the compaction length sensitive to bulk viscosity. We further investigated the effect of a thin competent seal with irregular geometry located right above the reservoir (Fig. 2C). Results showed widening of the channels within and above the seal. The chimneys then become discontinuous, so that their relation to the underlying reservoir may not be visible.

Different sedimentary rocks are also characterized by different permeabilities, which significantly affect subsurface fluid flow. The presence

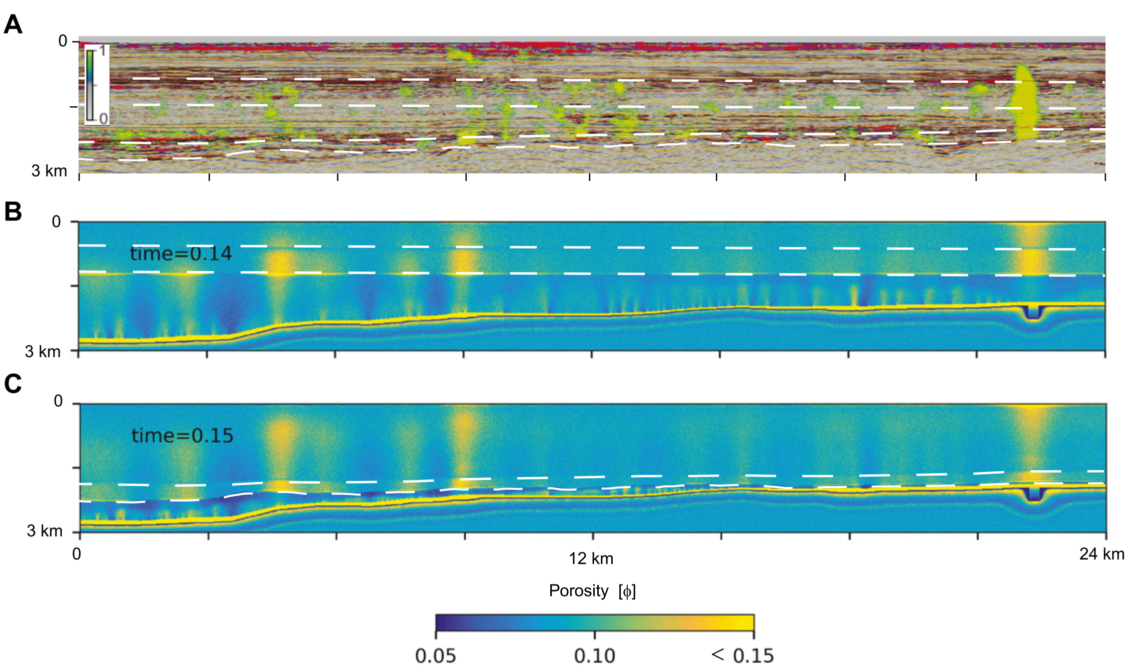

Figure 2. Observed and simulated fluid migration features in the study area (North Sea). (A) Seismic profile of area with identified chimneys from Figure 1B. White dashed lines are boundaries between different geological layers. Colors show the probability of chimneys from seismic attributes. (B) Simulation results showing chimney formation in a setting with a competent thick layer in cap rock. (C) Simulation results showing chimney formation in a setting with a competent thin seal right above the reservoir.

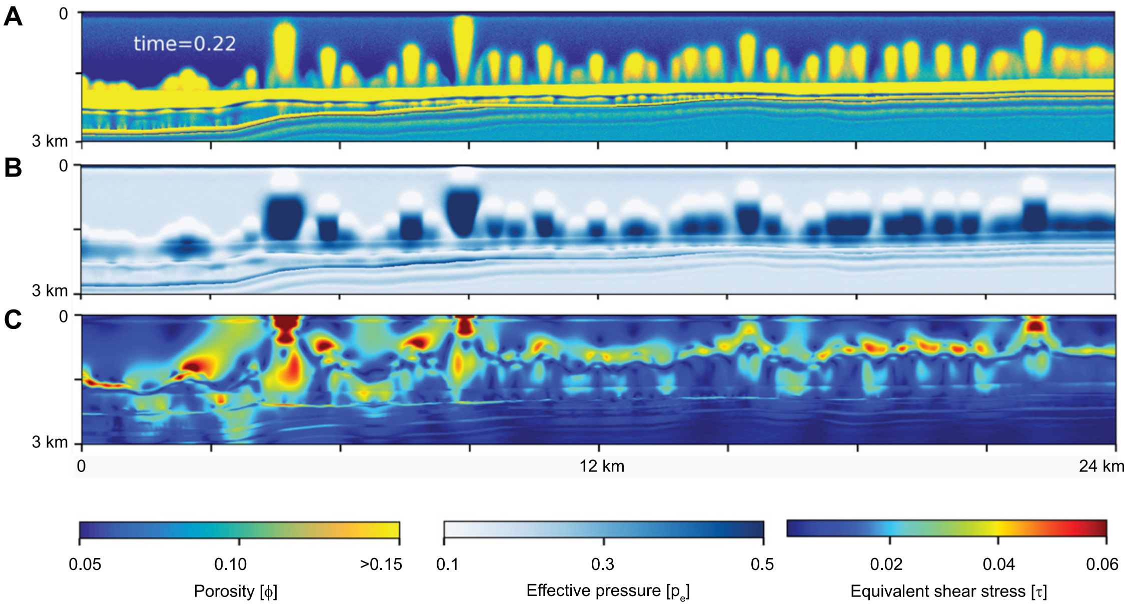

Figure 3. Results of simulations showing chimneys that formed in a setting with a tight thin seal: (A) porosity, (B) effective pressure, and (C) shear stresses associated with growth of chimney structures.

of tight shales with low permeability prevents immediate leakage from reservoirs. Yet, shales are very ductile, and thus their permeability is very sensitive to pressure buildup, increasing by orders of magnitude in response to minor pressure changes (Dong et al., 2010; van Noort and Yarushina, 2019). The presence of a tight seal (Fig. 3) delays the development of the fluid channel. First, fluid accumulates at the base of the tight seal without migrating further into the cap rock (Fig. 4; see Videos S2 and S3). However, as fluid eventually reaches the higher-permeability layers above, multiple chimneys rise above the cap rock. Their spacing is controlled by the compaction length of the low-permeability layer, which is smaller than the compaction length of the reservoir or the rest of the cap rock. Therefore, chimneys that rise atop the tight seal are much more densely distributed than those in previous models. A much higher porosity characterizes these chimneys. They grow by draining fluids from surrounding rocks, with this process reducing background porosity almost by a factor of 2. Due to a sharp gradient in porosity, these chimneys form clear carrot-shaped seismic anomalies that are gradually detached from the original reservoir and seal. Some of these chimneys merge when their growth directions deviate slightly from the vertical. These results explain the presence of chimneys above tight seals seen

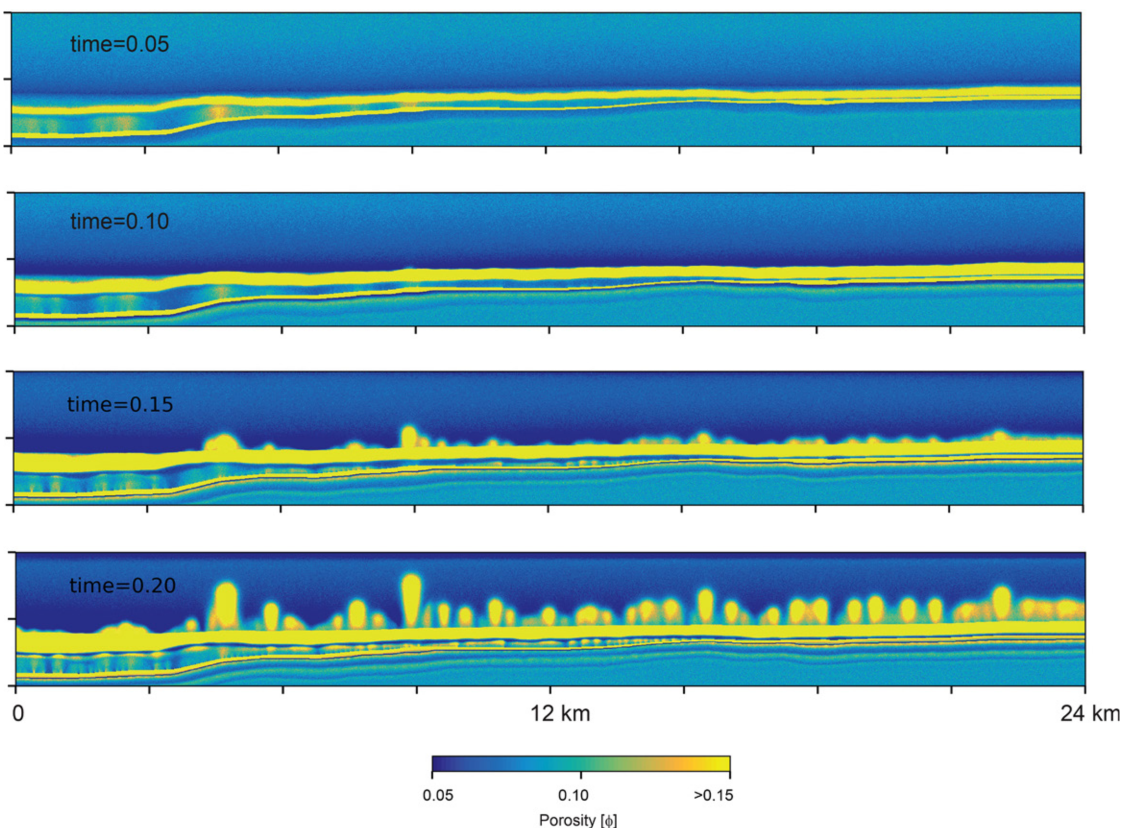

Figure 4. Time evolution of chimneys from Figure 3.

in the seismic data. Chimney formation is driven by viscoplastic deformation, which is an irreversible process. The fluid pressure gradient decreases from regions outside the chimneys toward their center, resulting in fluid drainage from surrounding rocks. This causes compaction of the chimney walls, which sustains them as distinct structures for many years. The roles of material parameters, various layers, and model limitations are explored further in the Supplemental Material.

In all our models, secondary smaller channels were formed above the reservoir after the formation of the larger chimneys (Figs. 2–4), but their buoyancy-driven rise was much slower. These smaller channels may be individually below seismic resolution. Instead, they could be collectively imaged as amplitude anomalies caused by the presence of gas/fluid in the form of a gas cloud (Fig. 1C). Propagation of chimneys is associated with complex disturbances to the fluid pressure and stresses in the rock (Fig. 3). Thus, chimney growth could be accompanied by microseismicity and thus be potentially detected by passive seismic surveys (Yarushina et al., 2017).

Porous sandstone bodies overlain by thick shale cap rock are considered to be suitable CO_2 storage candidates. Our results show that stress-dependent permeability and viscosity of shales and sandstones might lead to chimney formation. This may positively impact the injectivity and storage capacity of the site by eliminating minor reservoir compartmentalization. However, the possible generation of flow channels in the cap rock may compromise storage integrity and lead to CO_2 leakage. Given the fast rates of chimney formation, mitigation measures in case of leakage over CO_2 storage sites must be in place as soon as injection starts, and the seabed should be monitored for potential leakage. We recommend including the stress dependency of permeability and the time-dependent response of a cap rock in a baseline characterization of potential CO_2 storage sites. Less viscous shale units might represent better seals.

CONCLUSIONS

In summary, we propose that seismic chimneys are focused porous fluid-flow structures formed by a time-dependent rock deformation process. Their size and time of formation depend on the material parameters of the rock and the fluid and are controlled by characteristic compaction length and time. The modeling results, seafloor expression, and chimney formation process results suggest that gas clouds often comprise distinct channels and may not necessarily be widespread. The detection of seismic chimneys based on supervised self-educating neural networks combined with simulations of geological processes, leading to the formation of focused fluid-flow structures, is a new promising technique for top seal and charge risk assessment in play evaluation and prospect delineation.

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