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Sensitivity of Subsidence Data in the Northeastern Netherlands to Geological Complexities

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Deep reservoir & shallow soils

Since the start of production from the Groningen gas field (northeastern Netherlands) in the early 1960s, considerable land subsidence (up to 35 cm) has occurred above the field (**Figure 1**). Since 1991, the originally tectonically inactive area has also seen production-induced seismicity (up to M_W 3.6; Hettema et al., 2017).

Subsidence above the field has been caused by both deep reservoir compaction, and shallow soil deformation (clay compaction/swell and peat oxidation; see **Figure 2**). Because of the coastal location and low elevation of the area, the subsidence causes water management challenges. Other coastal areas that have experienced similar issues from both deep petroleum extraction and shallow deformation include the Wilmington oil field, California (Mayuga & Allen, 1969) and Houston, Texas (Holzer & Bluntzer, 1984).

This study is part of the DeepNL-Subsidence project. We aim to determine the subsurface drivers of subsidence, by assimilating geodetic time series (like InSAR satellite data of **Figure 1**) into geophysical models. Highly geologically complex models can lead to:

- Long computation times.
- Data assimilation being unable to function (e.g., weight collapse).
- Highly non-uniqueness solutions.

We want model only those features that produce detectable surface signals. Thus, we investigate: *Which model complexities are resolvable in the geodetic time series?*

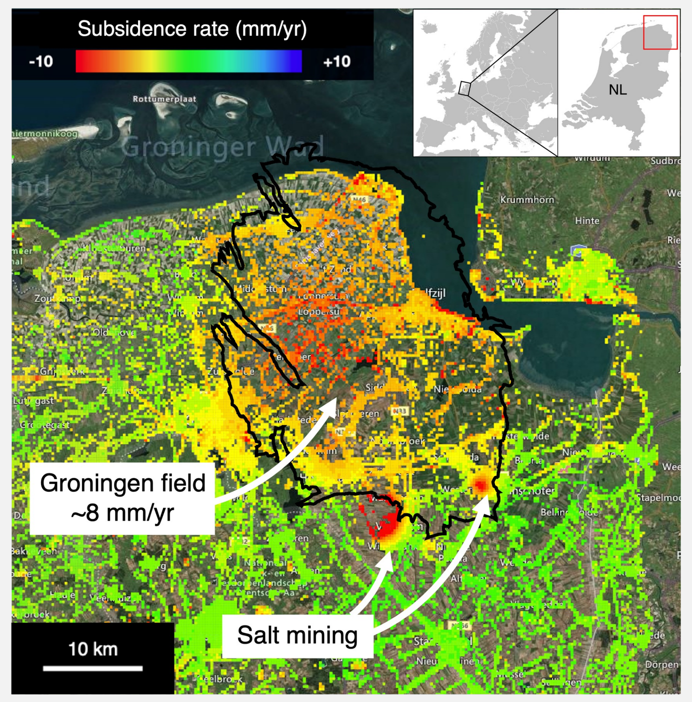

Figure 1: PS-InSAR derived subsidence rates above the study area (modified from bodemdalingkaart.nl). Outline of the Groningen gas field is shown in black.

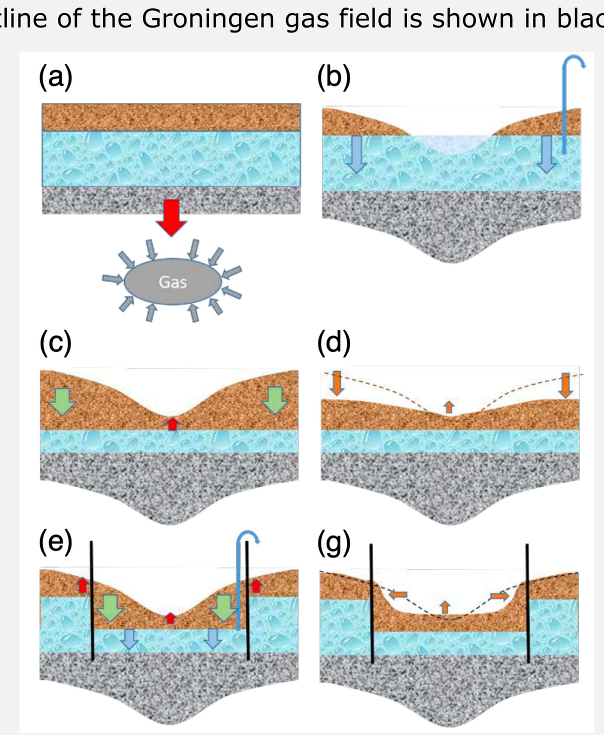

Figure 2: Schematic diagram of the potential impact of deep compaction on the shallow soils. Blue layer represents groundwater.

Model setup

We use the semi-analytical method of a layered elastic half-space by Wang et al. (2006) (**Figure 3**) to simulate surface displacements induced by reservoir compaction. The compaction is modelled using the nucleus of strain (point source) approach (Mogi, 1958), where we discretize the reservoir in triangular cells and represent volume change in each cell by a nucleus of strain (**Figure 3b**).

In the initial setup, uniform annual compaction rate is applied in a homogeneous elastic half-space. We then add complexity in steps to test the model sensitivity to those complexities. Here, we make the conservative estimate that signals smaller than 0.5 mm/yr are not resolvable in the geodetic data sets.

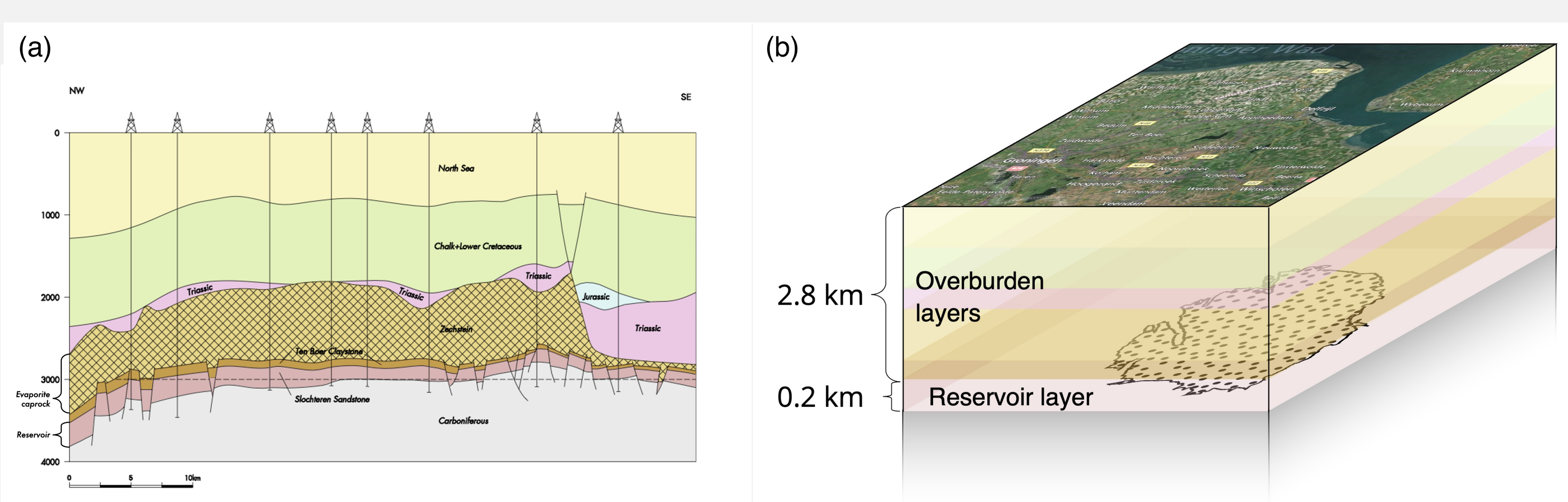

Figure 3: (a) Geological cross section through the Groningen gas field area (modified after Hofmann et al., 2016) and (b) schematic diagram of the layered model setup with point sources located at reservoir depth.

Optimal reservoir complexity

We firstly investigate the resolution (number of point sources) needed to represent the reservoir shape (**Figure 4**).

Figure 5 shows that the imprint of a low reservoir resolution becomes resolvable when the number of points sources is lower than ~200. Since we want to avoid introducing these significant representation errors, the number of point sources needs to be higher than 200. Still, the reservoir complexity can be simplified by more than 2 orders of magnitude.

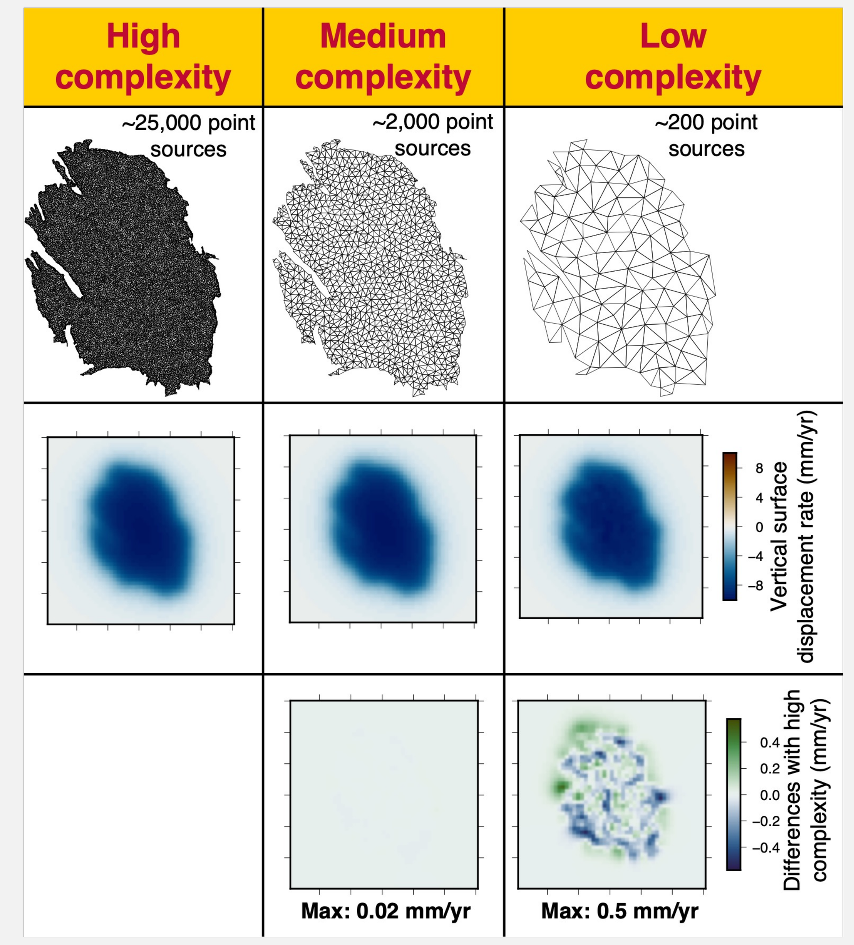

Figure 4: Subsidence results of the reservoir resolution sensitivity tests.

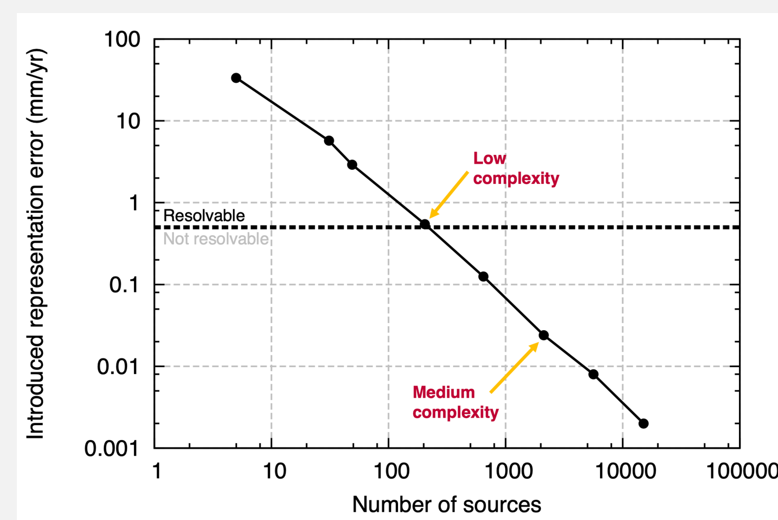

Figure 5: Representation error introduced by the reservoir resolution as a function of number of point sources.

Compaction variability

In models of **Figures 4 & 5** uniform reservoir compaction is applied. In reality, compaction varies throughout the reservoir (**Figure 6**), due to reservoir thickness variations, spatially varying material properties and low-transmissibility faults.

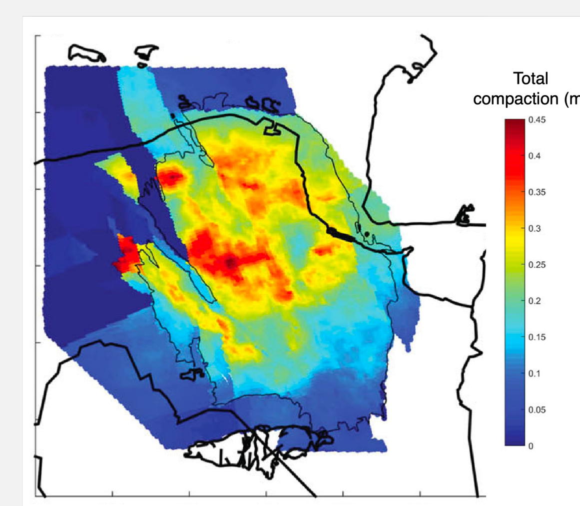

Figure 6: Reservoir compaction model by Van Thienen-Visser & Fokker (2017).

We test the sensitivity of the surface displacements to these compaction contrasts using a checkerboard test (**Figure 7**). This shows that tiles smaller than 4 km^2 do not lead to a resolvable signal at the surface (**Figure 8**). Therefore, when subdividing the reservoir in compartments based on geology, compartments smaller than 4 km^2 should be avoided.

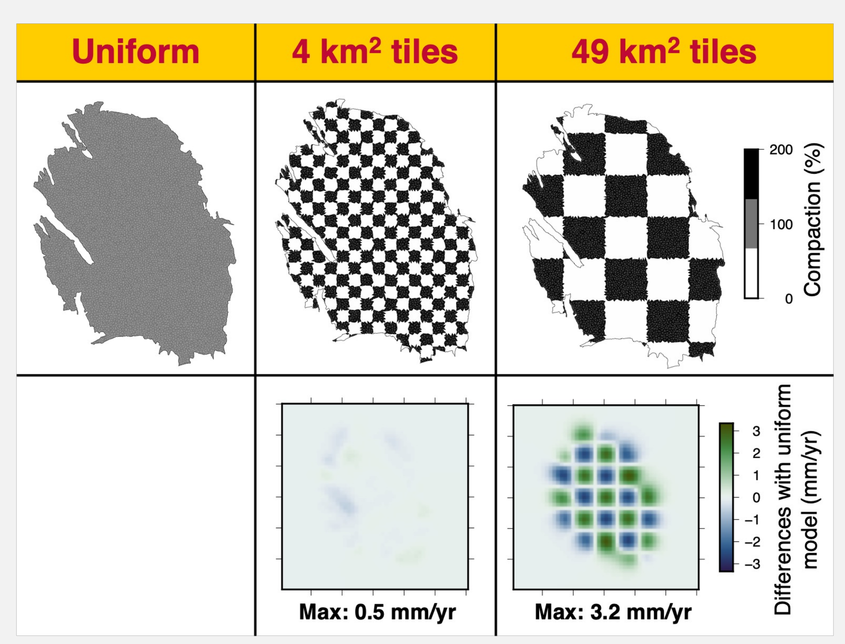

Figure 7: Subsidence results of the compaction variability sensitivity tests.

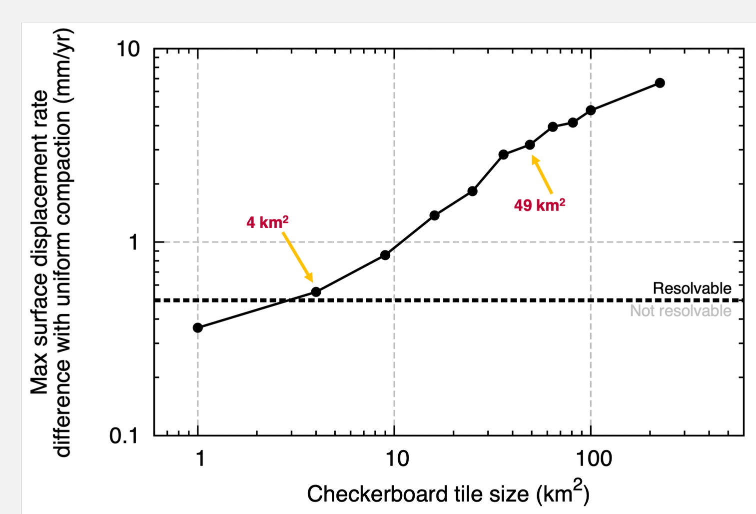

Figure 8: Sensitivity of surface displacements to the size of the checkerboard tiles.

Elastic profile

The previous models all used uniform material properties in throughout the half-space. In reality the elastic properties vary strongly with depth (see example well log data of **Figures 9a-b**) and in space. We aim to develop a layered half-space (**Figure 3b**) that represents the overall response of the subsurface. Therefore, we investigate the sensitivity of the surface displacements to variations in the elastic layer properties. We approximate the well log data with different numbers of layers, and vary the Young's modulus in each of the layers individually.

The difference with the unaltered (reference) profile represents the imprint of the variability in layer elasticity (**Figure 9c**). **Figure 9d** shows that elasticity variations in the top 1 km of the overburden do not lead to resolvable surface signals. Thus, thin layers at the top are unnecessary. In the deeper part of the overburden, layers ~0.3 km and thicker lead to a resolvable surface expression. The surface response is most sensitive to the elastic properties in the reservoir.

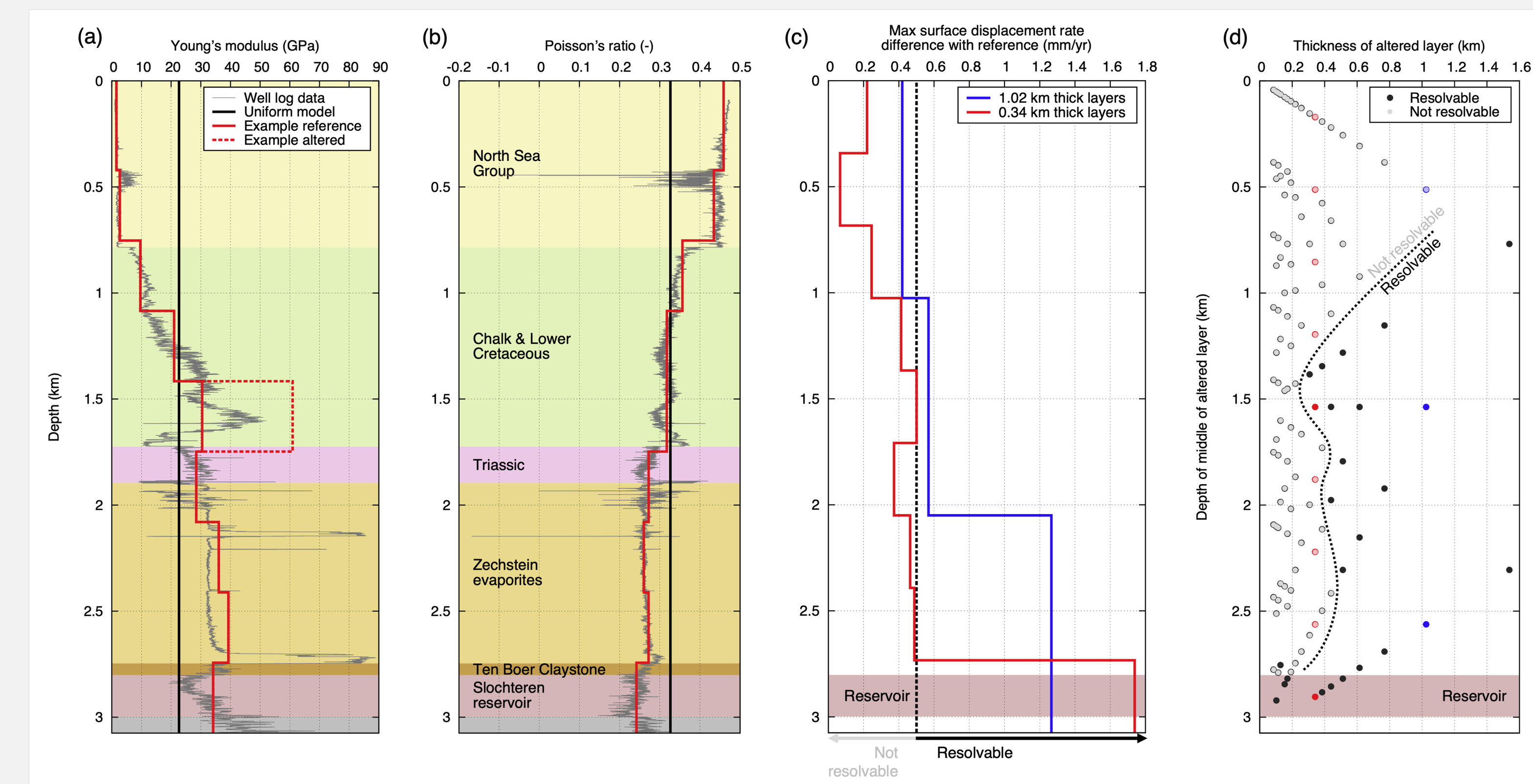

Figure 9: (a,b) Young's modulus and Poisson's ratio profiles of the ZRP-2 sonic well log data. Stratigraphic layering, the uniform model and an example of a layered model are also shown. (c) The surface imprint of elasticity variations for two different layer thicknesses. (d) The resolvability as a function of depth and layer thickness.

Conclusions

In the interest of decreasing computation time and increasing data assimilation performance, we have identified multiple features in the Groningen subsurface model that can be reduced in complexity.

- The reservoir complexity can be simplified by more than 2 orders of magnitude, with ~200 point sources as the minimum.
- Reservoir compartments smaller than 4 km^2 do not lead to a resolvable signal at the surface.
- Surface displacements are relatively insensitive to the elastic properties in the shallowest 1 km of the overburden.
- Deeper parts of the overburden need layers as thin as ~0.3 km.
- The surface displacements are most sensitive to the elastic properties of the reservoir.

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