Location of historic events at Groningen gas field

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SUMMARY

We relocate historic Groningen gas field events that have occurred before year 2000. These events have been recorded by a very small and sparse network of stations in the area with a fairly complicated velocity model. Events are relocated using publicly available P-wave pick arrivals, and a version of the velocity model provided by the operator, the Nederlandse Aardolie Maatchappij (NAM), that we have smoothed. We use station corrections, calculated using a different set of more recent events recorded by a larger array of receivers, to correct the model and diminish apparent biases. The new locations appear to exhibit more structure that suggests presence of active faults.

INTRODUCTION

Due to a recent increase of induced seismicity in the Groningen gas field, a large effort is underway to understand geomechanical processes in the area. It is widely believed (van Thienen-Visser and Breunese, 2015) that compaction due to hydrocarbon production is largely responsible for this seismicity. Modern events occurring after 2015 are recorded by a newly installed dense array of receivers that greatly enhances location reliability. By contrast, historic events, particularly those that occurred before 2000, were recorded by a very sparse network of receivers located far away from one another. The geology of the Groningen gas field that determines seismic velocities is quite complicated which makes event location very difficult. Accurately locating those historic events would nonetheless be extremely useful as it might help reveal seismic history of the region going back 20 years.

We kinematically locate historic events using P-wave arrival picks and a provided velocity model. We did not attempt to pick events on our own, instead we rely on picks made publicly available by KNMI . While seemingly straightforward, the location problem is complicated by the fact that the velocity model is quite complex, the total number of receivers for which picks are available is small, and propagation distances from likely event locations to the stations are quite large (Thurber and Rabinowitz, 2013).

We build a kinematic model based on the velocity model provided by NAM. As we explain below, a couple of ingredients in addition to the provided velocity model are required in order to accurately locate events using available data. The velocity model needs to be smoothed, and station corrections need to be calculated using recent events and then used to locate historic events. Newly obtained historic events locations show relatively small residuals and they reveal an interesting structure that indicate active faults.

MODEL DESCRIPTION

The historic events that we consider occurred between June of 1995 and June of 1999. Figure 1 shows the total number of events for which picks are available as a function of the station.

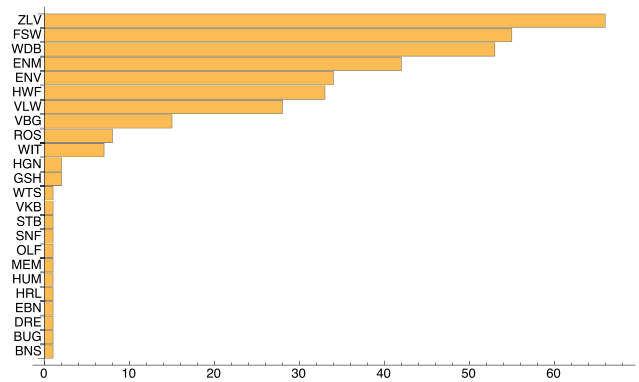

Figure 1: *Number of historic recorded and picked events per station.*

Very few stations have recorded more than a handful of events, and the stations with picks vary from one event to another. The five (5) stations with the largest number of available picks are listed in Table 1. The Rijks-Driehoek (RD) coordinate system, used by the Dutch geographical service, is used throughout this paper. Due to the sparsity of the historic network, distances from catalog event locations to other stations routinely exceed 20 km.

The velocity model provided by NAM is fairly complicated as shown in Figure 2. It contains a large salt body, exhibits large contrast between layers, and it is laterally heterogeneous. These large offsets and the complexity of the velocity model negatively affect the quality of

Station name	x [m]	y [m]
ZLV	246 514	568 121
FSW	270 718	582 155
WDB	245 080	581 028
ENM	227 789	602 786
ENV	238 883	545 977

Table 1: *Station names and coordinates*

event location. Ray tracing through a strongly heterogeneous velocity model like the one that is available for the Groningen area is filled with difficulties. The strong velocity contrasts, particularly for small regions like the anhydrite layer significantly distort ray paths and provide erroneous travel times that are not useful predictions for travel times of finite frequency waves.

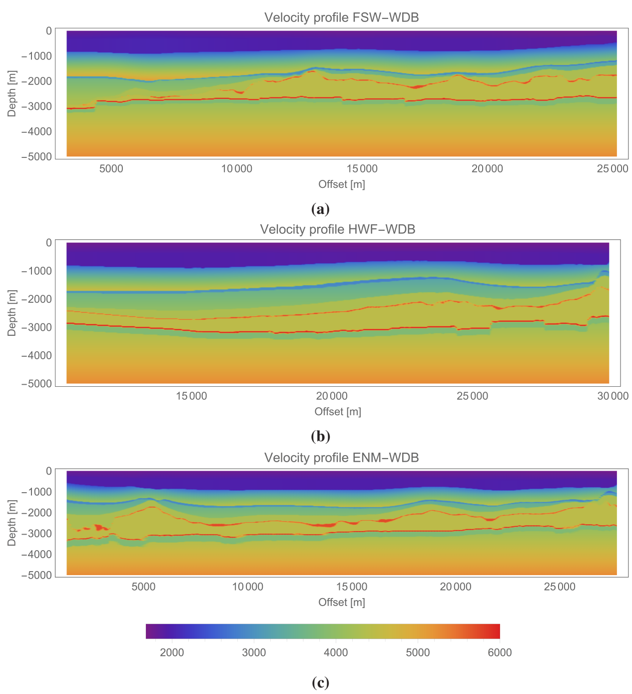

Figure 2: *Examples of P-wave velocity profiles at Groningen. Two-dimensional cross sections of the model along lines joining three station pairs are given.*

In an attempt to obtain more reliable travel times for the waves propagating through the model, we use the approach that has been used to stabilize raytracing in heterogeneous structures for Kirchhoff migration (Versteeg, 1993), which is to smooth the velocity model. We took an empirical approach of simply increasing the spatial scale of smoothing until we get good agreement between finite difference waveform first arrivals and the predicted travel times. This ray-traced smoothed velocity model forms a basis for the event location method discussed below.

EVENT LOCATION

A basic model for arrival time assumes that they can be written as (Myers et al., 2007; Toksöz et al., 2007; Rodi and Myers, 2013):

$$\hat{T}_{ij} = T_i^0 + T(s_i, r_j) + n_{ij}, \tag{1}$$

where $\hat{T}_{ij}$ are picked arrivals from the i-th event at the j-th station, T_i^0 is the unknown origin time of the i-th event, s_i is the unknown event location, r_j is the station location, and n_{ij} is the error term. The function $T(s_i, r_j)$ is the modeled travel time from a hypothetical source location s_i to a station r_j calculated using the provided velocity model smoothed as described above.

Although the smoothed velocity model seems to provide general agreement with waveform simulations, it may still contain travel-time errors that need to be accounted for during event location. While these prediction errors might be automatically cancelled or diminished if a large number of stations with an excellent azimuthal coverage is used, it is unlikely to happen when we locate historic events recorded by a tiny number of stations from far away. Therefore, we would like to first validate our model using more recent events that have been recorded with more stations resulting in a greater number of available arrival time picks.

LOCATION OF RECENT EVENTS AND STATION CORRECTIONS DETERMINATION

We select a suite of more recent event that have occurred between June 2010 and August 2015. We have chosen only events for which picks at all stations listed in Table 1 are available. We locate these events using Equation 1 with all arrival time picks from the currently available stations. We then calculate the residuals for each of the stations. For the five stations, the residuals for each source-receiver pair, grouped by receiver, are shown in Figure 3. A line connecting a station location to an estimated event location represents the residual for that source-receiver pair. The line color represents the residual value according to color legend in the figure title. Error residuals for a given station tend to be quite similar. For example, almost all residuals for station ENV are negative, and almost all residuals for station WDB are positive. These residuals show that the predicted travel times obtained by raytracing a smoothed Groningen velocity model contains systematic biases but these biases are largely (although not en-

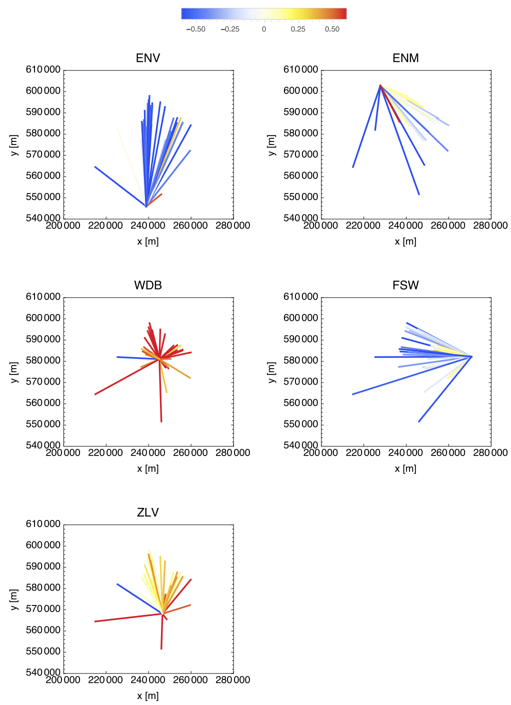

Figure 3: *Travel-time residuals for recent events grouped by station.*

tirely) station-dependent, and hence can be largely removed by applying station corrections.

We calculate the average residual for each station and call that the station correction. We choose an average station correction. Event location with station corrections assumes the following model (Dewey, 1972):

$$\hat{T}_{ij} = T_i^0 + T(s_i, r_j) + c_j + n_{ij}, \tag{2}$$

where c_j is an unknown station correction that naturally depends on a station but is the same for all events. While use of station corrections is ubiquitous in the literature, their physical meaning in Groningen is difficult to relate to local structure in the vicinity of each station.

Location results obtained using Equation 1 1 (i.e., location without station correction applied) and Equation 2 (applying the station correction) using all arrival times are shown in Figure 4. New residuals for the five stations are shown in Figure 5. The mean residuals obtained without and with station corrections are compared in Figure 6. We can see that using stations corrections leads to considerable reduction in the magnitude of residuals, meaning a better fit of the observed arrival times.

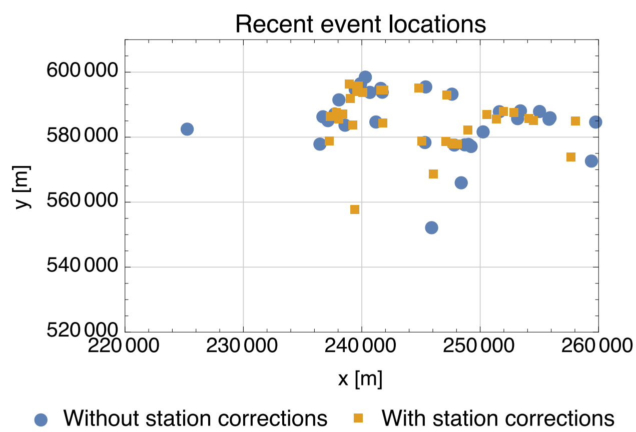

Figure 4: *Locations of recent events estimated with no station corrections and using station corrections.*

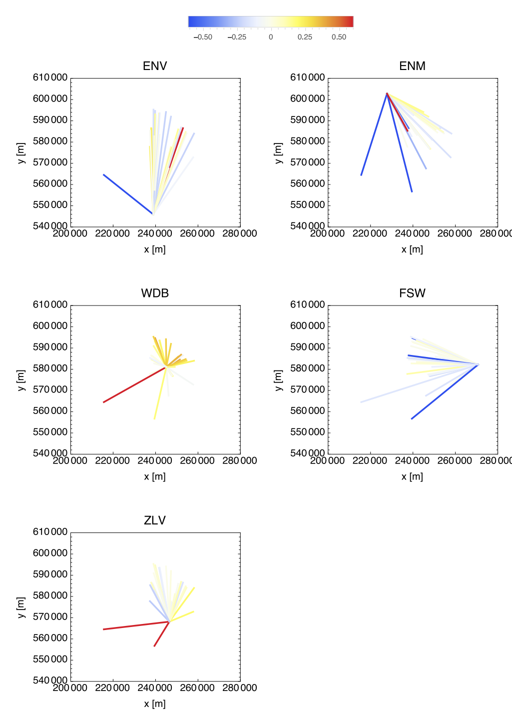

Figure 5: *Travel-time residuals for recent events after applying station-corrections. Compare with Figure 3.*

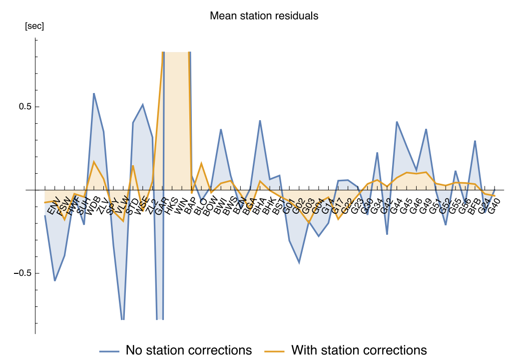

Figure 6: *Mean station residuals for recent events.*

HISTORIC EVENTS LOCATION

We now return to the problem of locating the historic events. We use Equation 2 to fit arrival time picks, but the station corrections c_j are now assumed known and taken to be the mean residuals shown in blue in Figure 6. This is equivalent to locating events using Equation 1 with corrected modeled travel time functions

$$\tilde{T}(s_i, r_j) \equiv T(s_i, r_j) + c_j. \tag{3}$$

The relocated historic events are shown in Figure 7. The mean residuals for stations whose data was used to locate those events are showin in Figure 8. Including the station corrections results in much smaller residuals or, equivalently, better data fit (orange curve in Figure 8). The relocated historic events also seem to display more linear structures that may help identify active faults in the area at the time of those events.

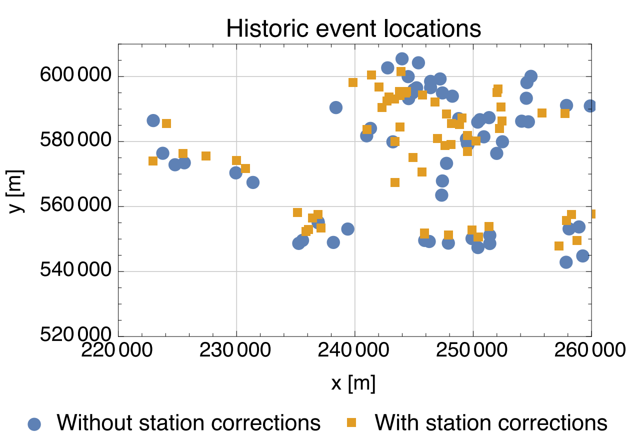

Figure 7: *Locations of historic events estimated without station corrections and using station corrections.*

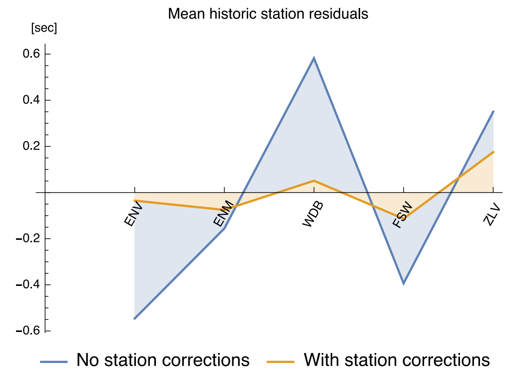

Figure 8: *Mean station residuals for historic events.*

CONCLUSIONS

We have relocated events in the Groningen field using picked P-wave arrivals and a provided velocity model. Modeled travel times used to match observed arrivals were obtained by raytracing a smoothed velocity model and adding station corrections derived using more recent events. The relocated historic events have residuals of average about 0.1 s with little obvious systematic bias. They also seem to exhibit more structure that could be used to infer fault activity in the area during the time of the events. More work is needed to quantify uncertainty of these locations.

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REFERENCES

Dewey, J., 1972, Seismicity and tectonics of Western Venezuela: Bulletin of the Seismological Society of America, **62**, 1711–1751.

Myers, S. C., G. Johannesson, and W. Hanley, 2007, A bayesian hierarchical method for multiple-event seismic location: Geophysical Journal International, **171**, 1049–1063.

Rodi, W. L., and S. C. Myers, 2013, Computation of traveltime covariances based on stochastic models of velocity heterogeneity: Geophysical Journal International, **194**, 1582–1595.

Thurber, C. H., and N. Rabinowitz, 2013, Advances in seismic event location: Springer Science & Business Media, **18**.

Toksöz, M. N., W. Rodi, and S. Sarkar, 2007, Grid-search techniques for seismic event location and phase association: Technical Report DTRA01-00-C-0102, MIT, Massachusetts Institute of Technology, Department of Earth, Atmospheric and Planetary Sciences, Earth Resources Laboratory Cambridge, MA 02139.

van Thienen-Visser, K., and J. N. Breunese, 2015, Induced seismicity of the Groningen gas field: History and recent developments: The Leading Edge, **34**, 664–671.

Versteeg, R. J., 1993, Sensitivity of prestack depth migration to the velocity model: Geophysics, **58**, 873–882.