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Veendam event, 09-01-2019

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Summary

Most events recorded in the province of Groningen are related to compacting gas reservoirs at around 3 km depth. On January 9, 2019, a seismic event was located at the eastside of Veendam, just outside the area covered by the Groningen and Annerveen gas fields. The event was well detected up till a distance of about 15 km. The incoming waves had a character different from the typical event recorded in the area. In this report a dedicated analysis is done to further constrain the location of the event. The strong presence of guided waves point to a location near the earth's surface. The wavetrain are much longer, however, than for an impulsive event near the Earth's surface. The detected waveforms show similarity with a 2017 event that was located at the flanks of the Heiligerlee salt dome. Both location with a 1D optimized model and a 3D velocity model points to an event location within or at the flanks of the Zuidwending salt dome. The maximum event depth is 1275 m, as found for a P-S delay time observed at a Gasunie instrument near the event. Most likely, the event was located at the southern flank of the Zuidwending salt dome. The mechanism by which the seismic energy is generated remains to be investigated.

1 Introduction

On January 9, 2019, a seismic event occured at the eastside of Veendam, near the Zuidwending salt dome. The event was well detected up till a distance of about 15 km. Both a direct P-wave and a guided wave were observed. This points to a source location within or near the unconsolidated sediments. Also the standard location approach pointed to a location near the Earth's surface. A source at a depth of about 3 km, within the Rotliegend sandstone, could be excluded.

In the following we implement a dedicated processing to find a better constrained location. In Section 1 we provide further evidence for the shallow location of the event and show similarity with a 2017 event that was located at the flanks of the Heiligerlee salt dome. In Section 2 we further constrain the epicenter of the event, and provide the uncertainty thereoff, using both a locally optimized 1D model and a 3D velocity model. In Section 3 we use the recording at the Zuidwending Gasunie office to further constrain the event epicenter and to find a maximum depth.

2 Comparison with previous events

Fig. 1 shows the event gather for the Veendam event; the three-component recordings are shown as function of epicentral distance and with respect to the (first iteration) earthquake origin time. Two clear arrivals can be noted. The green line is fitting the onsets of the

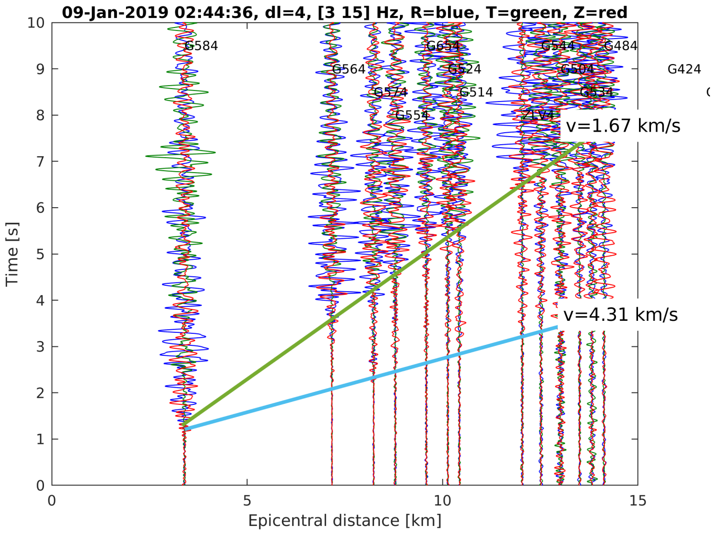

Figure 1: Event gather of Veendam 09-01-2019 event. The 3 colours show recordings over 3 orthogonal components: radial (blue), transverse (green) and vertical (red). The two straight lines depict fits of the two most prominent arrivals. The slope of the lines correspond to the indicated velocities.

most energetic waveforms. This wave is a guided wave. It has a P-wave velocity of about 1.7 km/s, which is an average P-wave velocity of the unconsolidated sediments in the region (North Sea Group; *Van Dalfsen et al.* (2006)). It is further characterized by a polarization in the radial-vertical plane. The blue line is fitting the onsets of the first arrival. This is the first P-wave arrival; note the vertical polarization. It has an average velocity of about 4.3 km/s, which can be explained by propagation over the Chalk Group (*Romijn*, 2017).

The majority of the detected events in Groningen are induced at or near the gasbearing Rotliegend sandstone formation (*Spetzler et al.*, 2018). Fig. 2 shows such a typical event that is induced at about 3 km depth. It has quite different characteristics from the Veendam event (Fig. 1). The first arriving P-wave has velocities of about 5.1 km/s (*Jagt et al.*, 2017). Moreover, a strong S-wave arrival is recorded, which polarization varies over the different source-receiver pairs. It has a typical average velocity just below 3 km/s.

Fig. 3 shows the event gather for a 1 kg charge detonated at 20 m depth. A similar guided wave and refracted wave can be noted as in Fig. 1, though with a much shorter duration. Note the radial polarization of the guided wave.

On 19-11-2017 an event was observed near Winschoten. The event was mapped just above the western flank of the Heiligerlee salt dome (*Ruigrok et al.*, 2018). One untested hypothesis is that, at this location, brittle rock overlying the salt could have moved due to salt creep. Fig. 4 shows the event gather of the most energetic Winschoten event. Note the similarities with the Veendam event (Fig. 1). For both events a similar guided wave and (refracted) P-wave is recorded. Also the direct P-wave has similar velocities. The Winschoten direct P-wave has less signal-to-noise, because it occured when coda of a previous small event was not yet fully attenuated.

For the event comparison, events with similar magnitudes have been chosen. For events at 3 km depth, attenuation relations have been derived for computing local magnitudes (*Dost*

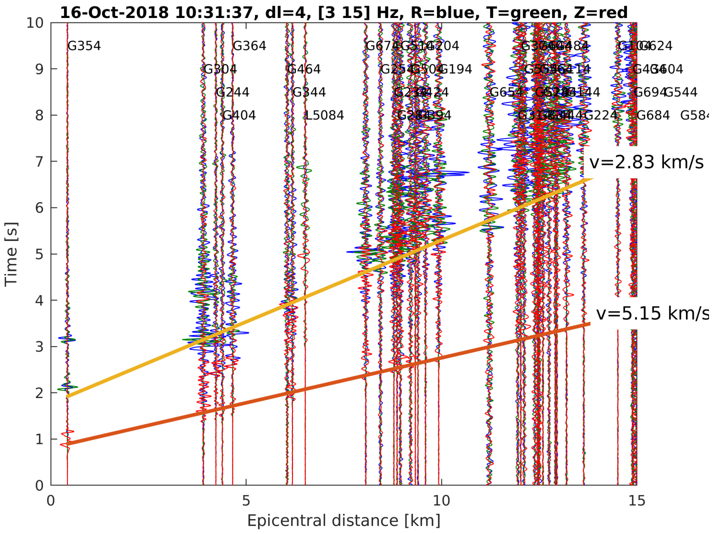

Figure 2: Event gather of Siddeburen 11-07-2018 event. The 3 colours show recordings over 3 orthogonal components: radial (blue), transverse (green) and vertical (red). The two straight lines depict fits of the two most prominent arrivals. The slope of the lines correspond to the indicated velocities.

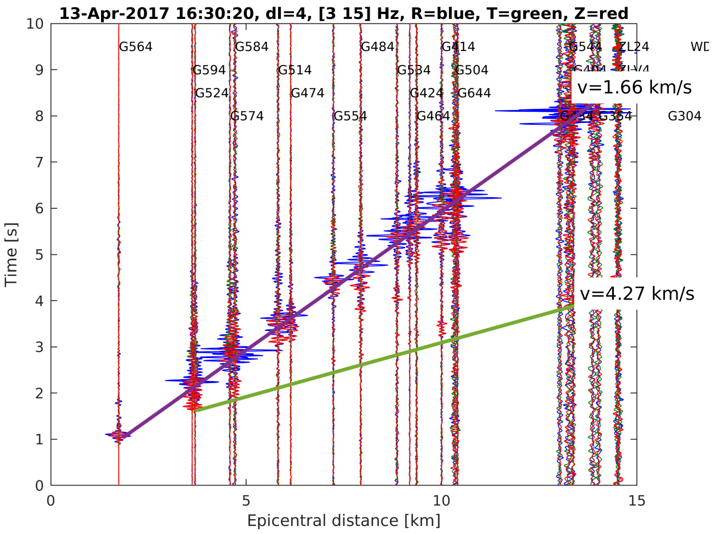

Figure 3: Event gather of a controlled explosion in Groningen. The 3 colours show recordings over 3 orthogonal components: radial (blue), transverse (green) and vertical (red). The two straight lines depict fits of the two most prominent arrivals. The slope of the lines correspond to the indicated velocities.

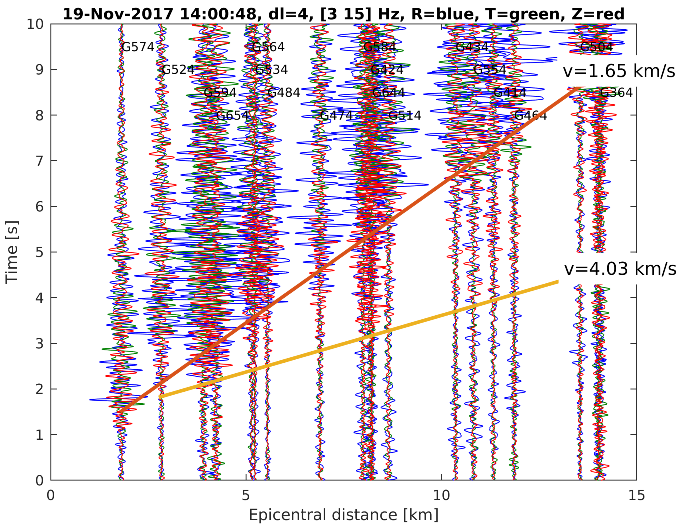

Figure 4: Event gather of Winschoten 19-11-2017 event. The 3 colours show recordings over 3 orthogonal components: radial (blue), transverse (green) and vertical (red). The two straight lines depict fits of the two most prominent arrivals. The slope of the lines correspond to the indicated velocities.

et al., 2018). Only the Siddeburen event is actually at 3 km depth and has a local magnitude of 1.09 ± 0.17. Using the same attenuation relation for the controlled explosion and for the Veendam event results in (biased) magnitudes of 1.18 ± 0.19 and 1.01 ± 0.14, respectively. For the Winschoten event, a moment magnitude was computed of 1.28 ± 0.08.

From the above event-gather comparison of the Veendam event (Fig. 1) with sources between 0 and 3 km depth (Figs. 2-4), it seems likely that Veendam event occured near or within the upper layer of unconsolidated sediments (North Sea Group). From a few kilometers distance onwards, this would yield a first arrival P-wave that refracts over the Chalk Group. Moreover, this would explain the strong presence of guided waves, which are an interference pattern of trapped P-waves in the unconsolidated sediments. The waveforms are much longer than for the explosive source. The source likely has a duration of multiple seconds. Other than for the Winschoten event (Fig. 4) only one clear source pulse can be identified.

3 Location

The Veendam event on 09-01-2019 at 02:44:36.5 was detected by the KNMI network (*Dost et al.*, 2017) and located near-real time with the Hypocenter method (*Lienert et al.*, 1986). This fast solution uses an average 1D model for the north of the Netherlands (*Kraaijpoel and Dost*, 2013). In the following, the epicenter is improved by using a best-fitting traveltime versus distance model based on the P-wave traveltime picks for this event. An error estimate is derived from the spread in picking times from the best-fitting model. This error incorporates both the local variations of the velocity field as well as picking errors. These errors are propagated further into an epicentral probability density function (PDF). This results into an updated epicenter and its 95% confidence region.

The initial picks were made with the operational system SeisComp3 using only the sensor at 200 m depth. This picking is redone using depth-consistent picking over all 5 borehole

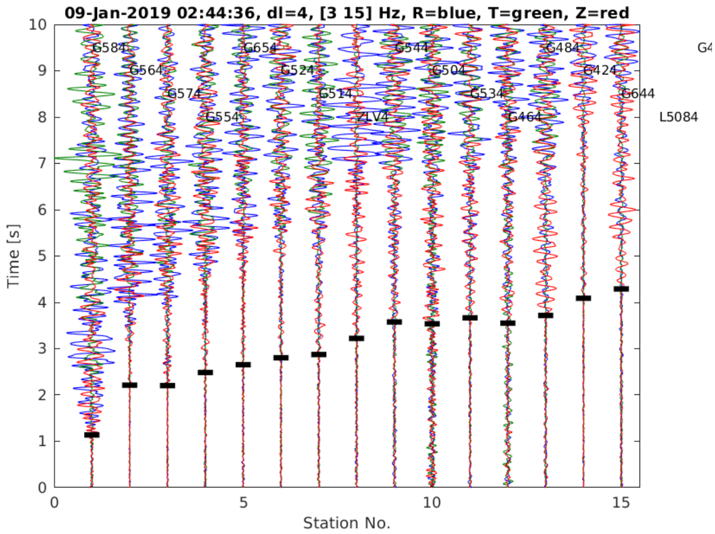

Figure 5: Event gather for Veendam event for the 13 nearest 200-m depth stations from the KNMI network. The 3 colours show recordings over 3 orthogonal components: radial (blue), transverse (green) and vertical (red). P-wave onset picks are indicated with black bars. The underlying waveform data is publicly available and can be obtained through http://rdsa.knmi.nl/dataportal/ or http://rdsa.knmi.nl/fdsnws/dataselect/1/.

levels as in *Ruigrok et al.* (2018). Fig. 5 shows the recordings for the 13 nearest 200-m depth sensors. The refined picks are shown as black bars.

Fig. 6 shows the seismic sensors where refined P-wave picks are available for this event. A grid search is done for a region around the Hypocenter solution, as indicated by the red box in Fig. 6. In the first step, equal differential time (EDT, *Zhou*, 1994) residuals are computed. That is, for each grid point and for each station combination, the traveltime differences are forward modelled and tabulated. From these values, the observed traveltime differences are subtracted to obtain the EDT residuals. In the second step, the PDF (*Tarantola*, 2005) is derived from the EDT residuals, using a L1 norm. Fig. 7(a) shows the 95% confidence area of the resulting PDF.

Next, the 3D EDT method is implemented (*Spetzler et al.*, 2018). The local 3D velocity model (*Romijn*, 2017) well incorporates the different salt domes. Hence, also the picks for the stations on top of the Heiligerlee salt dome are used. From all the picks as shown in Fig. 5 only the pick at geophone G584 is left out, due to suspicious raytracing times. Over the top 1 km in depth, there are only minimal changes in the misfit. Fig. 7(b) shows the 95% confidence area for a slice at 1000 m depth. The location with the maximum probability is assigned to be the new epicenter. In the Dutch triangulation grid the epicenter reads [x,y]=[258.9, 566.2] km. In WGS84 the epicenter is [lon,lat]=[6.94, 53.07] degrees.

On Fig. 8(a) the location results from 1D EDT (black 95% confidence contour), 3D EDT (white 95% confidence) and P-S delay times (grey contour, see next section) are combined. The 3D EDT epicenter with the highest probability is depicted with a white dot. It maps on top of the Zuidwending salt dome. The outline of 3D EDT 95% confidence area covers the southern part and flanks of the salt dome. Fig. 8(b) shows that the most likely hypocenter maps to the southern flank of the Zuidwending salt dome.

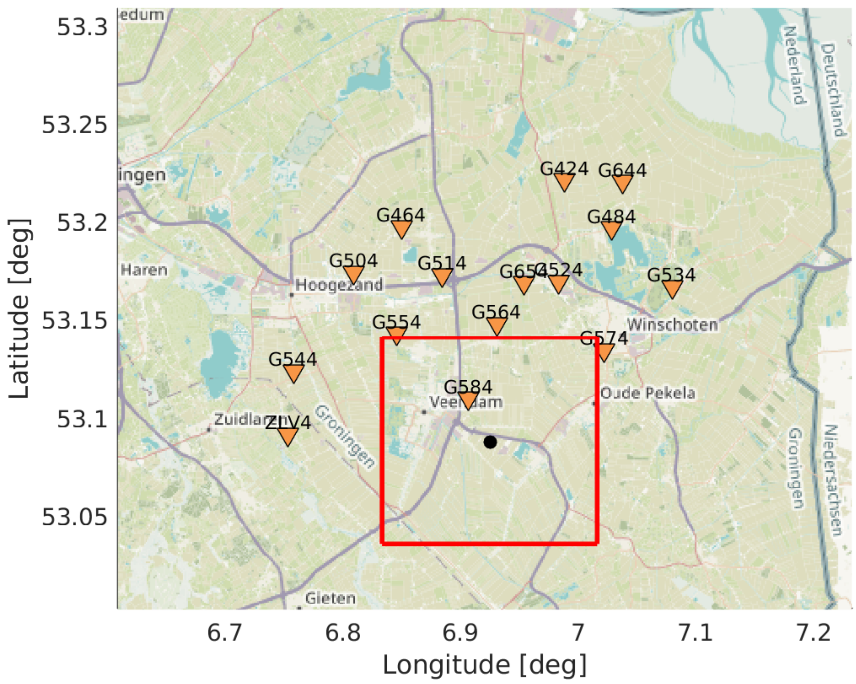

Figure 6: Overview map with locations of stations (yellow triangles) where P-wave onsets were picked, the fast Hypocenter solution (black dot) and the boundary line of the area in which a grid search is done (red box). Background map is from www.openstreetmap.org.

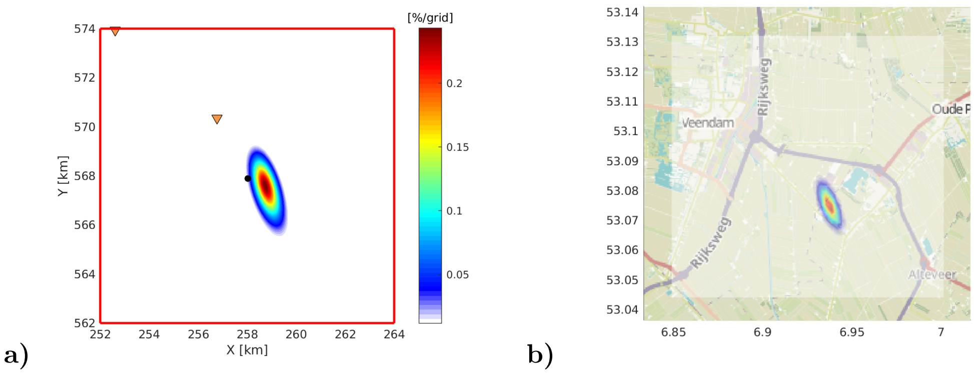

Figure 7: Maps showing the 95% confidence areas for (a) 1D and (b) 3D EDT (for a slice at 1000 m depth). (a) also depicts the initial Hypocenter solution (black dot) and the two nearest stations (orange triangles). (b) has, as a background, an Open Street Map of the Veendam Oude Pekela region. The white transparent region in (b) corresponds with the geographical area depicted in (a), (a) is in Rijksdriehoekstelsel whereas (b) is in wgs84.

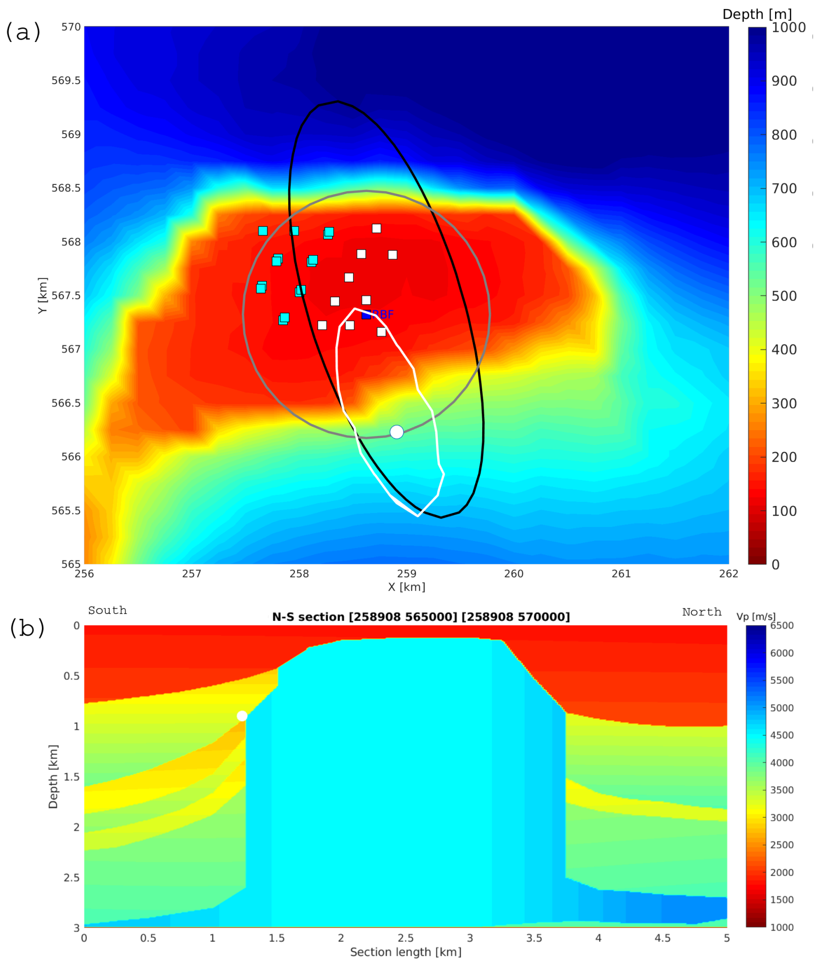

Figure 8: (a) Map view with location confidence areas (bounded by ellipses), locations of salt caverns (white squares) and gas-storage cavernes (cyan squares) in the Zuidwending salt dome and a depth map of the North Sea Group (colour map). The salt dome can be recognized as the red area, i.e., the area where the North-Sea-Group bottom is shallow (with a minimum of about 125 m depth). The outline of the 1D and 3D EDT 95% confidence area are plotted with a black and white line, respectively. The maximum distance contour with respect to station RBF is plotted as a grey circle. The white dot denotes the most likely 3D EDT location. (b) The 3D EDT location (white dot) on top of a vertical south-north slice through the 3D P-wave velocity model (*Van Dalfsen et al.*, 2006). The Zuidwending salt dome corresponds with P-wave velocities of 4400 m/s and up (*Romijn*, 2017), which are shown in cyan.

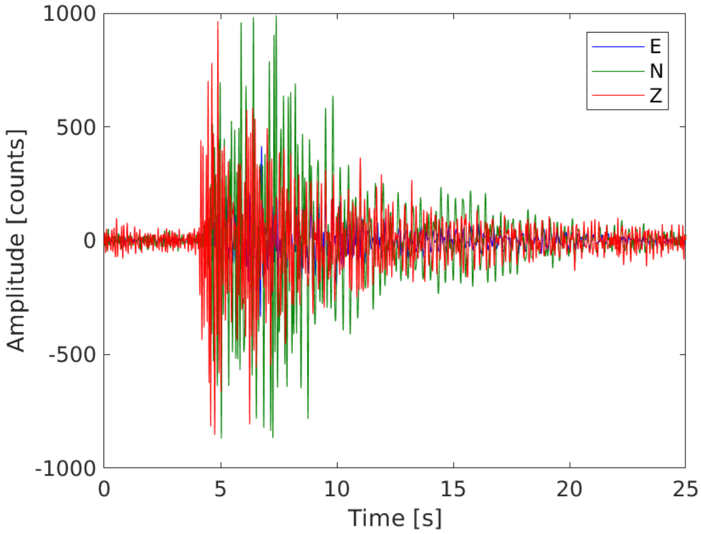

Figure 9: 3-component response at accelerometer RBF, which is located at [lat, lon]=[53.08274 6.9337]. The 3 colours show recordings over 3 orthogonal components: east (blue), north (green) and vertical (red).

4 Maximum depth

The Zuidwending salt caverns are included in the epicentral 95% confidence area (Fig. 8a). At a Gasunie office at the Zuidwending plant, a SIG accelerometer is present which is labeled as RBF. Fig. 9 shows the 3-component waveforms, without restoration of the instrument response. This recording can not readily be incorporated in the KNMI-network event gather (Fig. 1). The waveforms and the epicenter (previous section) show that this instrument is closer to the source then any of the KNMI instruments. However, the first onset is not untill after 4 seconds with respect to the Hypocenter earthquake origin time. Note that the first onset at G584 is already at about 1.1 seconds (Fig. 5). The timing error on RBF would be a value between 3 and 4 seconds. We use the recording at RBF to estimate the maximum depth or distance to the source.

The guided wave only becomes apparent after a few kilometers. At shorter ranges, an S-wave is the first clear 'slow' wave. On Fig. 10(a) it can be seen that at the nearest KNMI station the first slow arrival has an S-wave velocity over the borehole array, with consistent polarization over the different sensor levels. On most other stations, like on Fig. 10(b), the slow wave arrives simultaneously at the receivers, with a particle polarization that is mostly radial on the deeper sensors and vertical on the shallow sensors. This can be explained by a guided wave.

As a consequence, the first slow wave at RBF is most likely an S-wave. Fig. 11 shows the 3-component waveforms around the onsets of the first two arrivals and the traveltime picks for P and S. The resulting P-S delay time is 0.47 s. From this delay time we compute the corresponding maximum distance or depth.

From the deep version of the digital geological model (DGM-deep, *Van Dalfsen et al.*, 2006) we find that the North Sea Group extends to 125 m depth below RBF. Taking the harmoni-

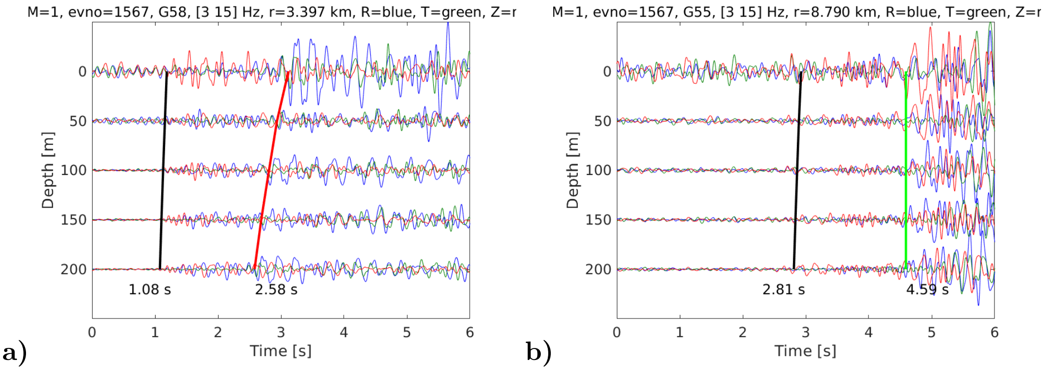

Figure 10: 3-component response at 5 depth levels in boreholes (a) G58 and (b) G55. The red, blue and green seismograms denote the vertical, radial and transverse particle velocity recordings. Thick black and red lines denote depth-consistent picks of the first P- and S-wave onset, respectively. The green line shows the simultaenous arrival time of the guided wave at the different sensor levels.

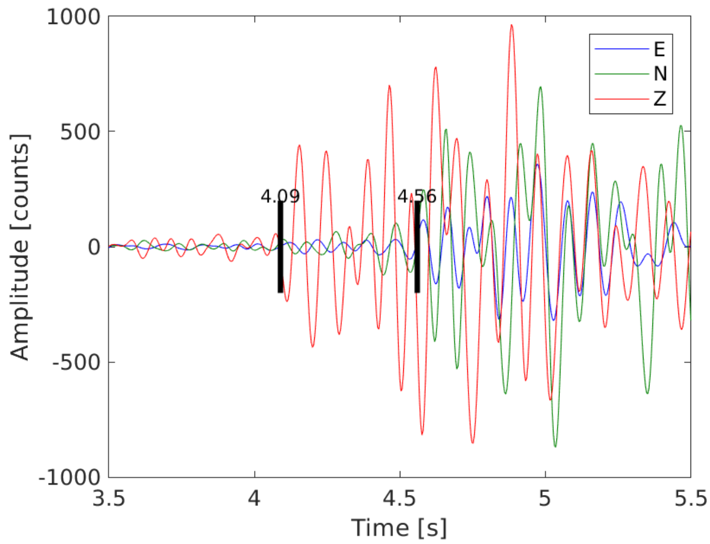

Figure 11: 3-component response at accelerometer RBF, at a time window around the first P- and S-wave. The black bars denote the picked onset times of the first P- and S-wave, at 4.09 and 4.56 s, respectively.

cally averaged P- and S-wave velocities from the nearest G station (G58, *Hofman et al.*, 2017) of 1826 and 371 m/s, respectively, we find that 0.27 s of the delay time is consumed in the soft sediments. Below 125 m depth, halite from the Zechstein is present. The fastest wave would take a trajectory over this high-velocity salt body. Using the velocities of halite from *Romijn* (2017) we find that the leftover P-S delay time corresponds to a distance or depth of 1150 m. Thus, the maximum depth of the event is 1150+125=1275 m. This depth would be reached if the source is directly below RBF. Any lateral offset of the source with respect to RBF would result in a shallower depth. The maximum distance would be 1150 m from RBF.

Added to Fig. 8(a) is the location of instrument RBF and the maximum distance of the event from this instrument based upon the recorded P-S delay time. combining the 3 epicentral surfaces (black ellipse, white epplipse and grey round) results in a further narrowing of the likely source region. Most likely, the event took place at the southern flank of the Zuidwending salt dome (Fig. 8b).

Conclusion

The Veendam 09-01-2019 event took place within, or at the flanks of, the Zuidwending salt dome at a maximum depth of 1275 m. Most likely, the event was located at the southern flank of the salt dome and lasted multiple seconds. This event was compared with recordings of an explosion, an earthquake due to gas extraction and an earlier event near a salt dome. It was concluded to be akin the previous salt-dome event. The signal characteristics from this event and the previous event near a salt dome (Winschoten events, 19-11-2017) clearly differ from the others. The occurrence of both guided waves and long signal durations are features specific to near salt dome events. The mechanism by which the seismic energy is generated remains to be investigated. It is hypothesized that the brittle rock overlying the salt might have moved due to salt creep.

5 Acknowledgements

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