Seismic Hazard Screening (SHS): Fault and data density

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Samenvatting

Introductie

Het Ministerie van Economische Zaken en Klimaat heeft EBN en TNO verzocht een nieuwe methode op te zetten om het risico op seismiciteit in te schatten voor geothermieprojecten in Nederland. Een van de onderdelen van deze nieuwe methode is het adequaat interpreten en karakteriseren van breuken binnen het invloedsgebied van een geothermie systeem (Mijnlieff & Jaarsma, 2021). De kwaliteit van deze interpretatie is sterk afhankelijk van de beschikbaarheid en kwaliteit van ondergrondse data (data positie) (Mijnlieff & Jaarsma, 2021).

De nieuwe Seismic Hazard Screening (SHS) methode zal bestaan uit een aantal kernelementen. Dit rapport beschrijft het voorgestelde ontwikkelingsproces, de methode en de resultaten voor één van deze kernelementen: beschikbaarheid en kwaliteit van de ondergrond-data. Uiteindelijk wordt dit kernelement gecombineerd met andere kernelementen en door EBN en TNO-AGE samengevoegd tot één nieuwe SHS-methode. In dit samenvoegingsproces kunnen wijzigingen worden aangebracht in de methoden, drempelwaarden en/of resultaten ten opzichte van de afzonderlijke kernelement rapporten. De methoden, waarden en resultaten die in het huidige rapport worden beschreven, moeten daarom als voorlopig worden beschouwd.

Werkwijze

De methode voor het relateren van geïnterpreteerde breuken aan de gebruikte data positie binnen een invloedsgebied werkt middels de volgende stappen (Figuur 0-1):

- Stap 1: Bepaal de score voor de dichtheid, het patroon en de kwaliteit van de gebruikte seismische - en putgegevens met behulp van aantal stappen, procedures en scoringssystemen (sectie 2.2).
- Stap 2: Bepaal of de gebruikte data voldoet aan minimum eisen met betrekking tot SHS (sectie 2.3).
- Stap 3: Bereken de breuken dichtheid met behulp van de seismische interpretatie en bepaal de breuken score binnen het invloedsgebied. De breuken score wordt bepaald middels de berekende dichtheid en variabelen die worden bepaald aan de hand van de breukgeometrie en putgegevens (sectie 2.4).
- Step 4: Evalueer de data score ten opzichte van de breuken score en verkrijg de aanbevelingen voor de vervolg stappen welke worden bepaald in de uiteindelijke, nieuwe SHS-methode (sectie 2.5).

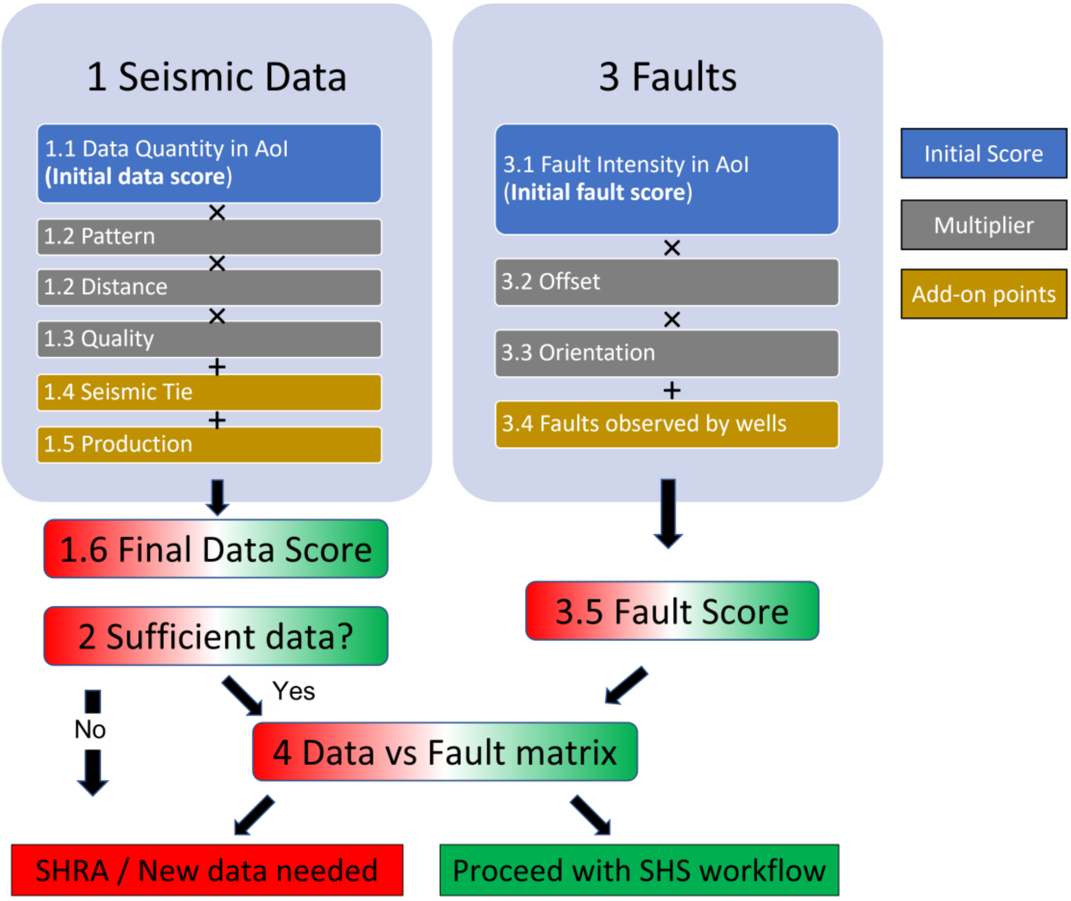
Het bepalen van de data score

De data score wordt bepaald middels de onderstaande vergelijking. De eerste score die wordt bepaald is de Intial data score, welke gebaseerd is op de seismische data dichtheid (3D: Coverage percentage, 2D: Hoeveelheid lijnen). De multipliers (M_{sp}, M_{d}, M_{r}, M_{q}) worden vervolgens bepaald door de kijken naar 1) het data patroon (grid, random, parallel), 2) de afstand van de seismische data tot de injectie put, 3) of het reservoir zichtbaar is en 4) de seismische data kwaliteit. Tot slot worden er punten toegevoegd op basis van offset well data en eventuele productie data.

$$\text{Data score} = \text{Intial data score} * \left(M_{\mathrm{sp}} * M_{\mathrm{d}} * M_{\mathrm{r}} * M_{\mathrm{q}}\right) + \left(\mathrm{DS}_{\text{offset well}} + \mathrm{DS}_{\mathrm{p}} + \mathrm{DS}_{\mathrm{l}}\right)$$

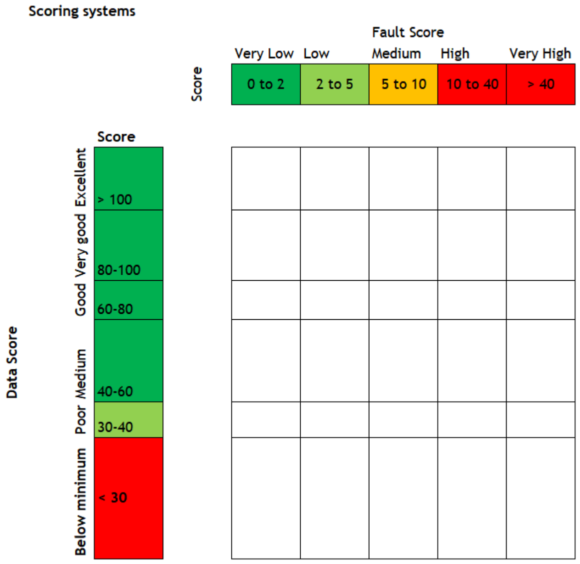
Het bepalen van de breuken score
De breuken score wordt bepaald middels de onderstaande vergelijking, waar als eerste de Intial fault score moet worden berekend. De Intial fault score wordt bepaald aan de hand van de gemeten breuken dichtheid binnen het invloedsgebied. De multipliers (M_{offset}, M_{orient}) zijn vervolgens bepaald door middel van het meten van 1) het verzet van de breuken en 2) de oriëntatie van de breuken ten opzichte van het lokale spanningsveld. Tot slot worden er punten toegevoegd op basis van breuken die zijn geobserveerd middels productie - en/of put gegevens.

$$\text{Fault score} = \text{Intial fault score} * (M_{\text{offset}} * M_{\text{orient}}) + (\text{FS}_{\text{p}} + \text{FS}_{\text{l}})$$



Figuur 0-1: Main workflow utilized for scoring the faults and utilized data within the Area of Influence. SHRA = Seismic Hazard and Risk Analysis. It should be noted that the final follow up steps are to be determined by EBN and TNO-AGE upon combining the individual key-elements into a single, new SHS-workflow, and can therefore change.

Evaluatie van data score ten opzichte van de breuken score
Het bepalen van de eventuele vervolgstappen wordt gedaan middels een evaluatie matrix (Figure 0-2), welke de berekende data en breuk score binnen het invloedsgebied met elkaar vergelijkt. De exacte vervolgstappen met betrekking tot de verkregen breuk en data score zullen nader worden bepaald tijdens het samenvoegen van alle kernelementen tot een nieuwe SHS-methodiek door EBN en TNO-AGE.



Data score vs Fault score matrix

Data Score	Fault Score: Very Low	Low	Medium	High	Very High
Excellent	Pass	Pass	SHRA	SHRA	SHRA
Very good	Pass	Pass	SHRA	SHRA	SHRA
Good	Pass	Pass	SHRA	SHRA	LSSE
Medium	Pass	Pass	SHRA	SHRA	SHRA
Poor	Pass	SHRA	SHRA	SHRA	SHRA
Below minimum	New data	New data	New data	New data	New data

Figure 0-2: Left) The construction of matrix using the data score and fault score. Right) The final scoring matrix and the potential follow up steps given the data and fault scores.

1 Introduction

The Ministry of Economic Affairs and Climate Policy has requested EBN and TNO to develop a new method to assess the seismic hazard for onshore geothermal projects of the Netherlands. The previous guideline by IF/Q-Con (2016) "Defining the Framework for Seismic Hazard Assessment in Geothermal Projects V0.1" (Q-con & IF Technology, 2016) was developed in 2016 and should be updated to the current state of the geothermal industry.

The new Seismic Hazard Screening (SHS) method will consist of a number of key-elements. This report describes the suggested development process, method and results for two of these key elements: the fault density in the area of influence of a geothermal project and the data density and quality available for a geothermal project. Eventually, these key-elements will be combined with other key-elements and merged into a single, new SHS method by EBN and TNO-AGE. In this merging process, changes may be made to the methods, values and results as described in the individual key-element reports. The methods, values and results described in the current report should therefore be regarded as preliminary.

An important part of the new SHS workflow is the adequate interpretation and characterisation of faults within the Area of Influence (AoI) of a geothermal system. The uncertainty of this interpretation is largely dependent on availability and quality of the seismic data (data position), which varies greatly across the Netherlands. Therefore, in order to better relate faults within an AoI to different data positions and the coinciding uncertainties, "fault density" and "data density and quality" were defined as two key elements of the SHS-workflow by TNO and EBN in 2021 (Mijnlieff & Jaarsma, 2021).

In this report, we present a workflow which evaluates faults within an AoI to the respective data position. This is done by 1) scoring the data density and data quality , 2) scoring the fault density and 3) evaluating the fault density vs data position.

The amount of possible geological details stored in subsurface models relevant to SHS (e.g. faults) is largely dependent on the type, amount and quality of relevant seismic - and (off-set) well data. Therefore, the first part of the workflow presented in this report is aimed at finding a classification system so that the uncertainties related to data availability and quality can be scored and quantified. Data scoring is done by assessment of data type, quantity, coverage, location, pattern and quality.

Once data density and data quality have been scored, faults within the AoI are characterised and scored in the second part of the proposed workflow. This is done by 1) measuring the quantity of faults in the AoI using seismic interpretation and/or well data and 2) by qualifying the faults in the context of seismic hazard screening (e.g. by measuring the fault offset and slip tendency).

The last step in the proposed workflow is to evaluate the data score against the fault score using a scoring matrix which gives recommendations for potential follow up steps given the respective data position and fault characteristics within the AoI. It should be noted that the exact details of these follow up steps are to be determined by EBN and TNO-AGE in the process of combining all the key-elements into a single new SHS-workflow.

The aim of this report is to describe and exemplify the above described methodology and is structured as follows: First, the workflow and different scoring systems for the data position within the AoI is comprehensively described and depicted. Second, the workflow and different scoring systems for characterising faults within the AoI is described and depicted. Third the scoring matrix for evaluating the data score vs fault score is explained. Fourth, different example projects are presented so that the data and fault scoring workflow is adequately exemplified. Finally, it should be noted that the workflow described in this report is optimized for projects where data is already interpreted and qualified.

2 Proposed scoring system

2.1 OVERALL WORKFLOW

To evaluate and score the faults and data within the Area of Influence of a geothermal project (which is defined in Borst et al., (2021) and hereafter referred to as **AoI**) in the context of SHS screening, several scoring matrixes have been developed which fit in a larger workflow (decision tree). This workflow consists of the following sequence of steps (Figure 2-1):

- Step 1: Determine and score the density, coverage and quality of the seismic and well data using a set of pre-defined steps, procedures and scoring systems (section 2.2).
- Step 2: Determine whether the data meets the minimum data requirements needed for SHS screening (section 2.3).
- Step 3: Compute the fault intensity (hereafter commonly referred to as P21) using the results of seismic interpretation and determine the fault score within the AoI using the measured fault intensity and fault multipliers determined by the fault characteristics and/or well test data (sections 2.4)
- Step 4: Evaluate the fault score vs utilized data score (seismic and well) and acquire recommendations for the next step (section 2.5). The possible next steps are determined by EBN and TNO-AGE upon combining the individual key-elements into a single, new SHS-workflow.

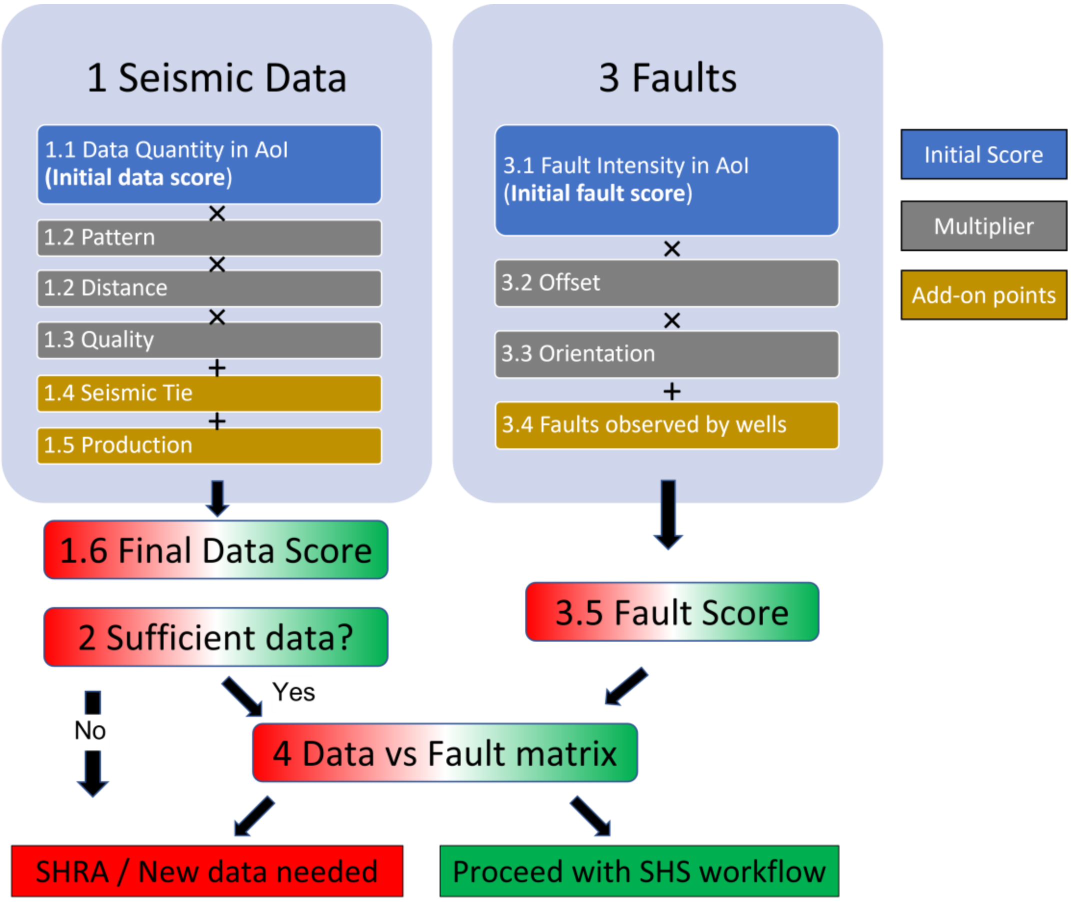


Figure 2-1: Main workflow utilized for scoring the faults and utilized data within the Area of Influence. SHRA = Seismic Hazard and Risk Analysis. It should be noted that the final follow up steps are to be determined by EBN and TNO-AGE upon combining the individual key-elements into a single, new SHS-workflow, and can therefore change.

2.2 STEP-1: SCORE DATA TYPE, QUANTITY, PATTERN AND QUALITY

The first step in the main workflow (Figure 2-1) is to score the data density, coverage and quality. The data score is calculated using an initial score based on seismic data type and quantity in or close to the AoI and a set of multipliers derived from data coverage and quality (Figure 2-2). When available and/or during the production phase, well data is also scored and the resulting points are added in order to make up the final score (Figure 2-2).

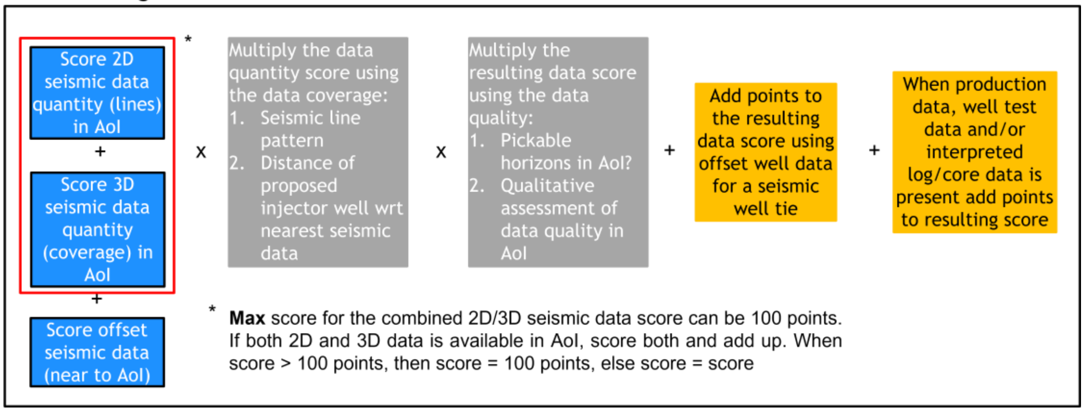


Figure 2-2: Workflow for scoring the data type, quantity, pattern and quality. The workflow consists of five main steps namely: 1.1) Determine an initial score based on seismic data type and quantity in and close to the AoI, 1.2) determine the multipliers based on data pattern and distance to the proposed injector well location, 1.3) determine the multipliers based on seismic data quality, 1.4) add points to the score when well data for a seismic to well tie for the reservoir is available near the AoI (within same geological basin) and 1.5) when production or well test data in or near to the AoI is available, add points to the determine the final data score.

2.2.1 Step 1.1: Determine the initial data score using the 2D/3D data quantity in the AoI and offset seismic data

The first step in the data-scoring methodology (Figure 2-2) is to determine the initial score, which is determined using seismic data in and close to the AoI (Table 2-1 and equation 1).

$$\text{Intial data score} = \text{Data score within AoI} + \text{Offset seismic data score}$$
$$\text{Data score within AoI} = \text{If: (3D score + 2D score)} \geq 100, \text{then: } 100, \text{else: (3D score + 2D score)}$$
(**Equation 1**)

If 3D data is present in the AoI the score is based on the data coverage, such that: when 3D seismic coverage of the AoI < 10 % = 0 Points, when 3D seismic coverage of the AoI is between 10 – 25 % = 10 points, when 3D seismic coverage of the AoI is between 26 – 50 % = 25 points, when 3D seismic coverage of the AoI is between 51-75 % = 50 points and when 3D seismic coverage of the AoI is > 75 % = 100 points.

If only 2D data is present in the AoI, the score is determined using the number of lines: 0 lines = 0 Points, 1-2 lines = 10 points, 3-4 lines = 30 points, 5-6 lines = 75 points and > 6 lines = 100 points.

Noted that the score for data (3D/2D) in the AoI cannot be higher than 100 points (equation 1 and Table 2-1).

Also nearby seismic data within 1.0 km of the AoI (offset seismic data) can add points to determine the initial data score (Table 2-1 and equation 1). The 1.0 km criteria is chosen such that only data which can be used for characterising faults within the AoI is scored.

The initial score is the starting point for determining the final data score (equation 2) (section 2.2.6).

Table 2-1: Tables for determining the initial data score using seismic data in or close the AoI.

Data within AoI (Combine) (Max score = 100)				
Score	**3D seismic data coverage in AoI**		**Score**	**Number of 2D seismic lines in AoI**
100	> 75 %		100	> 6
50	51 - 75 %		75	5 to 6
25	26 - 50 %		40	3 to 4
10	10 - 25 %		10	1 to 2
0	< 10 %		0	0

Offset Seismic data (data outside of AoI) (add)	
Score (add)	**Offset seismic data within 1.0 km of AoI)**
15	> 5 lines / 3D volume
10	3 - 5 lines
5	1 - 2 lines
0	0 lines

2.2.2 Step 1.2: Determine the multipliers for the data pattern and the distance to the injector well

The second step in the data-scoring methodology (Figure 2-2) is to derive the multipliers for 1) the seismic data pattern and 2) the distance of the nearest seismic data to the proposed injector location at reservoir depth (Table 2-2).

Firstly, the multiplier for the seismic pattern is derived from the arrangement of the seismic data within the AoI which is determined as follows: 1) For a data set consisting of 3D seismic data and/or of 2D lines arranged in a grid, the multiplier is set at 1.0, 2) for a dataset of 2D lines arranged randomly the multiplier is set at 0.75 and 3) for a dataset of 2D lines which are parallel oriented the multiplier is set at 0.5 (Figure 2-3, Table 2-2).

The second multiplier is determined by measuring the distance of the proposed injector well at target depth to the nearest seismic data, so that wells which are positioned at a relatively large distance from seismic data will receive a low multiplier (e.g. D > 500 m, multiplier = 0.25), whereas wells which are in close proximity to seismic data will receive a high multiplier (e.g. D = 0-100 m, multiplier = 1.0) (Figure 2-4, Table 2-2).

Both multipliers are implemented in equation 2 in order to compute the data score (section 2.2.6).

Table 2-2: Multipliers related to the seismic data pattern (Figure 2-3) and to the distance to the proposed injector well (Figure 2-4)

Score (multiplier)	Seismic pattern (see Figure 3)		Score (multiplier)	Distance of nearest seismic line/volume to injector well [m]? (see Figure 4)
1	grid pattern / 3D volume		1	0-100m / Within volume
0.75	Random lines		0.75	100-500m
0.5	Parallel lines		0.25	> 500m

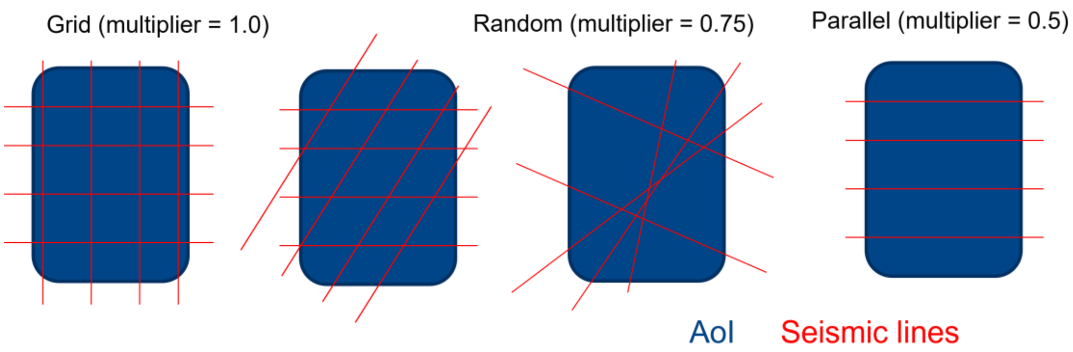


Figure 2-3: Multipliers based on the seismic data pattern. Left) Grid pattern provides the best coverage of the AoI. Therefore a multiplier off 1.0 is assigned. Middle) A random pattern provides a poorer coverage than a grid. However, lines are often at an angle and therefore a multiplier of 0.75. Right) a parallel pattern can provide relatively good coverage. However, faults aligned parallel to the line strike are difficult to detect. Therefore, a multiplier of 0.5 is assigned. Note that all figures are in map view. It should also be noted that the qualifications on what makes a grid pattern, what makes a random pattern, and what makes a parallel pattern and what is an appropriate multiplier, may be adjusted in the final SHS-workflow after integration of all key-elements by EBN and TNO-AGE.

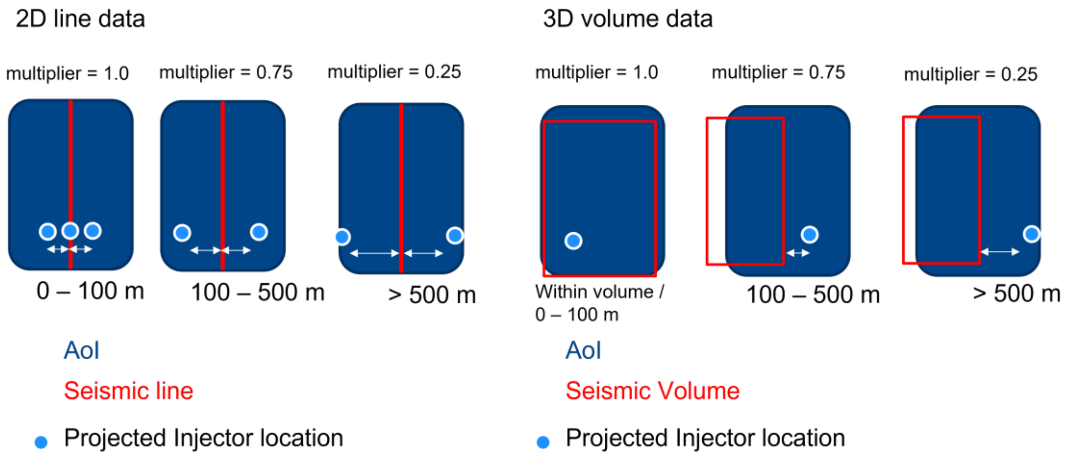


Figure 2-4: Multipliers based on the distance of the proposed injector well at reservoir depth to the nearest seismic data. Left) Examples for 2D line data. Right) Examples for 3D volume data. Note that all figures are in map view.

2.2.3 Step 1.3: Determine the multipliers for data quality in Area of Influence

The third step in the data-scoring methodology (Figure 2-2) is to derive the multipliers for the seismic data quality in the AoI and at reservoir depth (Table 2-3). This is done as follows:

1. Answer the question on whether horizons/reflections are pickable around reservoir depth within the targeted structural fault block (Table 2-3). This is an important question because when reflections are not clearly visible, faults are hard to detect. The answer to this question should be yes or no and will result in a multiplier of 0 or 1, respectively.
2. Determine the multiplier based on the seismic data quality in the AoI (Table 2-3). The quality of the seismic data should be qualitatively checked using Figure 2-5.
3. Implement the multipliers in equation 2 to compute the final data score (subsection 2.2.6).

Table 2-3: Multipliers related to data quality in the AoI. See Figure 2-5 for additional information and examples.

Score (multiplier)	Pickable horizons/reflections around reservoir depth within target structural block?		Score (multiplier)	Seismic data quality around reservoir depth (qualitative)
1	Yes		1	Excellent
[redacted]			1	Good
			0.75	Sufficient
0	No		0.25	Poor

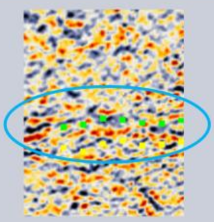
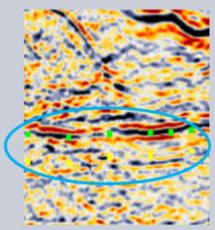
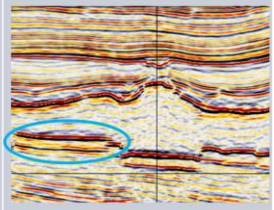
	Poor	Sufficient	Good to excellent
Data example			
Description	• Almost impossible to identify horizons and potential faults • Low signal/noise ratio	• Possible but difficult to identify horizons and larger potential faults • Medium signal/noise ratio	• Horizon identification is easy and faults up to seismic resolution can be identified • High signal/noise ratio

Figure 2-5: Qualifications for seismic data quality. Left) Poor quality seismic data where it is difficult to pick reservoir horizons and/or faults. Middle) Seismic data which of sufficient quality so that horizons and faults can be picked. However, smaller faults a difficult to identify. Right) Good to excellent quality seismic where horizons and fault can easily be characterised. Note that the targeted reservoir is encircled. It should be noted that the qualifications on what makes a poor, sufficient and good to excellent data quality may be adjusted in the final SHS-workflow after integration of all key-elements by EBN and TNO-AGE.

2.2.4 Step 1.4: Determine the score for offset well data for a seismic to well tie

The fourth step in the data-scoring methodology (Figure 2-2) is to derive the score for offset well data to be used for a seismic to well tie, which can provide relevant information in accurately determining the location of the targeted reservoir. For example, the Albasserdam and Delft

Members are often difficult to distinguish using seismic data, and interpretations are often supported by seismic well ties from offset well(s). The scoring of offset well data is described in Table 2-4 and Figure 2-6. The acquired score is implemented in equation 2 in order to compute the data score (subsection 2.2.6).

Table 2-4: Score acquired from offset well data which can be used for a seismic to well tie such that the reservoir can adequately be determined.

Score (add)	(Offset) well data for seismic well tie (see figure 6)
10	1 well in targeted structural fault block
5	1 well in a different structural fault block
0	No wells

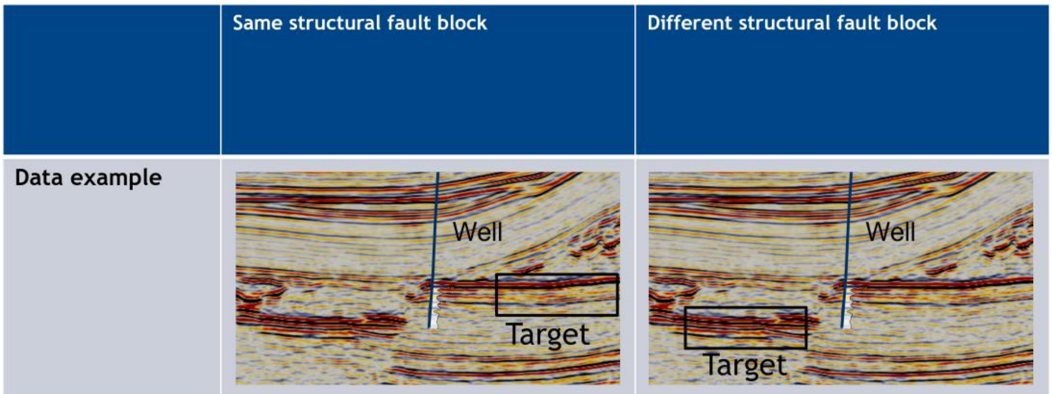


Figure 2-6: Discrimination of the offset well data using structural fault blocks. Left) The offset well is in the same structural fault block, thereby making the location of the reservoir well-known. Right) The offset well is in a different fault block, thereby making it more difficult to determine the location of the reservoir.

2.2.5 Step 1.5: Determine the score for available production and/or well data

At this step, the score related to well tests -, production - or log data in or around the AoI is derived (

Table 2-5). Such data can provide relevant information on the presence of faults within the AoI (i.e. faults can directly be encountered by the well or can be observed as fluid flow baffles during well testing or production). The scoring of production data is done as follows:

1. Derive the score for interpreted well tests / production data in or close to the AoI (i.e. within the AoI = 10 points, 0.01 – 1.0 km from the AoI = 5 points and > 1.0 km from the AoI = 0 points).
2. Derive the score for interpreted mudlog -, FMI (borehole image log) - or core data present in or close to the AoI (i.e. within the AoI = 5 points, 0.1 – 1.0 km from the AoI = 2.5 points and > 1.0 km from the AoI = 0 points). Again the 1.0 km is chosen so that only data which help in characterising faults within the AoI is scored (see subsection 2.2.1).
3. Implement the scores in equation 2 to compute the final data score (subsection 2.2.6).

Table 2-5: Scores related to production and previously drilled geothermal wells and acquired from interpreted well tests, production data, mudlog data, core data and/or FMI data, all of which can give relevant information for the presence of faults within or close to the AoI.

Score (add)	Interpreted well test data / Production data
10	In the AoI
5	0.01 - 1.0 km from the AoI
0	> 1.0 km from the AoI

Score (add)	Interpreted Mudlog / Core / FMI data
5	In the AoI
2.5	0.01 - 1.0 km from the AoI
0	> 1.0 km from the AoI

2.2.6 Step 1.6: Compute the data score using the results from steps 1.1 to 1.5

The final data score is a combination of the acquired scores and multipliers from steps 1.1 to 1.5 and can be derived using equation 2:

$$\text{Data score} = \text{Intial data score} * (M_{\text{sp}} * M_{\text{d}} * M_{\text{r}} * M_{\text{q}}) + (\text{DS}_{\text{offset well}} + \text{DS}_{\text{p}} + \text{DS}_{\text{l}}) \quad \textbf{(Equation 2)}$$

Where Intial data score is the score related to seismic data in or close to the AoI (equation 1), M_{sp} is the multiplier related to the data pattern, M_{d} is the multiplier related to the distance between the nearest seismic data and the proposed injection well at reservoir depth, M_{r} is the multiplier related to the pickable reflectors question, M_{q} is the multiplier related to the seismic data quality, $\text{DS}_{\text{offset well}}$ is the score related to offset well data for a seismic to well tie, DS_{p} the score related to production and/or well test data and DS_{l} is the score related to mudlog, FMI or core data.

Equation 2 will give the final data score, which is a value between 0 and more than 100 points, with higher scores (e.g. 110 points) being representative of excellent data for the purpose of Seismic Hazard Screening, whereas low scores are regarded as insufficient. For the interpretation of the final data score see paragraph 2.3.

2.3 STEP-2: DETERMINE WHETHER SUFFICIENT DATA IS AVAILABLE

The second step in the main workflow (Figure 2-1) is to determine whether sufficient data is available. Based on the scoring system of paragraph 2.2.6, a scoring matrix has been defined (Figure 2-7) which gives the threshold data score to pass. When the computed data score is below 30 points then the utilized data is regarded as insufficient for the purpose of Seismic Hazard Screening and subsequent steps (e.g. new data or a Seismic Hazard and Risk Analysis (SHRA)) to be determined in the final SHS-workflow that includes all key-elements are needed. When data score is above 30 points you can proceed with the main workflow (Figure 2-1).

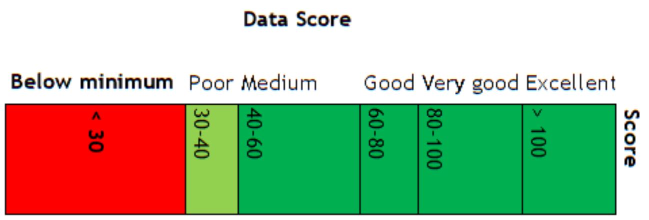


Figure 2-7: Final data score. Scores below 30 points are regarded as insufficient.

As an example for determining the minimum data requirements for the purpose of Seismic Hazard Screening, a dummy project with 3 seismic lines of decent quality has been created in Table 2-6. Given the utilized project set up, the final data score is 30 points and is therefore equal to the minimum requirements. It should be noted that there are other possible data arrangements which can pass the minimum data requirements (e.g. 2 lines with offset seismic data and available production data in the AoI). Other hypothetical and real world examples will be given in chapter 3.

Table 2-6: Hypothetical test case which is representative of the minimum data requirements for the purpose of seismic hazards screening.

Data score	**Minimum data example**	**Score**	
Number of 2D lines in AoI	3 lines	40	add
3D seismic coverage percentage in AoI	0 percent	0	add
Seismic data score in AoI		40	2D+3D
Offset seismic data (within 1 km)	0 lines	0	add
Pattern	Random	0.75	multiplier
Distance to injector well	0-100 m	1	multiplier
pickable horizon?	yes	1	multiplier
quality	good	1	multiplier
well for seismic well tie	No wells	0	add
Interpreted well test / production data	No	0	add
Interpreted Mudlog / FMI / Core	No	0	add
		30	

2.4 STEP-3: DETERMINE THE FAULT SCORE IN THE AOI

The third step in the proposed workflow is to determine the fault score using 1) the computed fault intensity (P21), 2) the measured fault offset, 3) the measured fault orientation with respect the largest horizontal stress component, and 4) faults detected by production data and/or previously drilled wells within the AoI (Figure 2-8). The utilized methodology is similar to the data scoring system (Figure 2-2), such that an initial score is computed (fault intensity) which is amended using multipliers dependent on the fault characteristics (fault offset and orientation). Lasty, points related to faults detected in the production phase are added to acquire the final fault score (Figure 2-8).

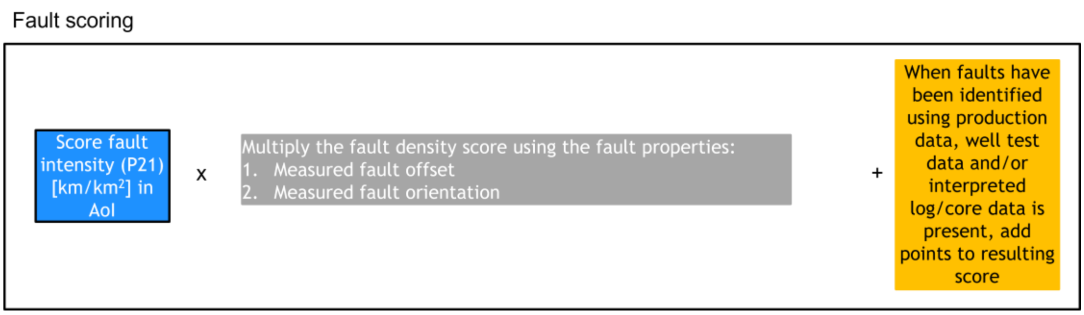


Figure 2-8: Workflow for scoring the faults within the AoI, which consists of four main steps, namely: Step 4.1) determine the initial score using the computed fault intensity (P21 [km/km²]), step 4.2) determine the multipliers related to fault offset and fault orientation, step 4.3) determine the score related to faults observed from production - and other well data and step 4.4) calculate the fault score using equation 3 (section 2.4.4).

2.4.1 Step-3.1: Compute and score the fault intensity (P21) in the AoI

The first step in the fault scoring methodology is to compute the fault intensity (P21) (Dershowitz, 1984; Dershowitz & Herda, 1992) for the AoI at reservoir level. This implies that a full seismic interpretation of the target area (AoI and surroundings) should be finished. Once the interpretation is finished, the fault intensity should ideally be computed using the following sequence of steps:

1. Make fault map at reservoir level using industry standard methodologies for fault mapping (e.g. Figure 2-9). When 2D data is used, interpolate the faults between the 2D lines, again using industry standard practices.
2. Measure the length of each fault within the AoI and compute the fault intensity (P21) which is total length of faults per defined area. For the purpose of this workflow, P21 can be computed using the following equation: $\mathrm{P21} = \sum_{i=0}^{i=n}(L_i\ [\mathrm{km}])\ /\ \mathrm{AoI}\ [\mathrm{km}^2]$ (e.g. *Figure 2-8*). Where L_i is the length of fault i [km] and AoI is Area of Influence [km^2]
3. The computed fault intensity for the AoI is subsequently qualified as follows (*Figure 2-8*):
   - Fault intensity is high when: P21 = > 1.0 [km/km^2]
   - Fault intensity is medium when: P21 = 0.5 – 1.0 [km/km^2]
   - Fault intensity is low when: P21 = 0.01 – 0.5 [km/km^2]
   - Fault intensity is none when P21 = < 0.01 [km/km^2]
4. It should be noted that for the purpose of this workflow the P21 should be calculated using km and expressed as km/km^2.

Fault Map Top Slochteren

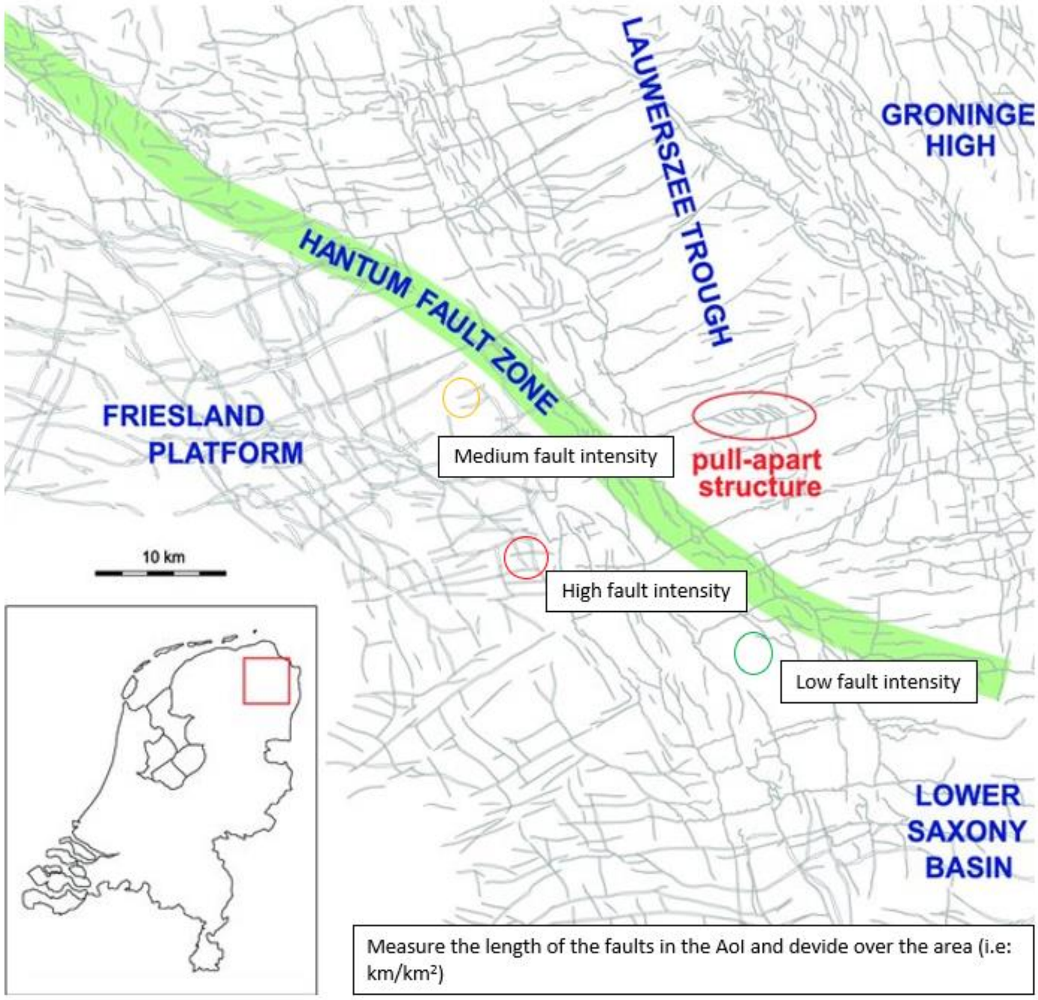


Figure 2-9: Fault map for Top Slochteren in the Drenthe-Groningen Area modified after De Jager, (2007). On the map three locations are highlighted having different fault intensities. Note that clear examples on how to compute the fault intensity within the AoI will be given in chapter 3.

Once the fault intensity in the AoI is computed, determine the initial fault score as follows:

1. The initial fault score is **0 Points** when the calculated P21 = 0.0 [km/km^2].
2. The initial fault score is **3 Points** when the calculated P21 = 0.01 – 0.5 [km/km^2].
3. The initial fault score is **7 Points** when the calculated P21 = 0.51 – 1.0 [km/km^2].
4. The initial fault score is **10 Points** when the calculated P21 > 1.0 [km/km^2].

See Table 2-7 for more information. The initial fault score will form the basis in determining the final fault score (equation 3).

Table 2-7: The initial fault score acquired from the derived fault intensity. See section 2.4 for information on calculating the fault intensity in the AoI.

Score (initial)	Derived fault intensity (in AoI) (P21) [km/km^2]
10	High (P21: > 1.0)
7	Medium (P21: 0.51 - 1.0)
3	Low (P21: 0.01 - 0.5)
0	none (P21: 0.0)

2.4.2 Step 3.2-3.3: Determine the multipliers for fault offset and fault orientation

The second and third steps in the fault-scoring methodology are to determine multipliers for fault offset and fault strike within the AoI, both of which can have a significant impact on the overall stress conditions and potential fault reactivation in the subsurface (e.g. (van den Hoek et al., 2021; Q-con, 2018; Q-con & IF Technology, 2016). For example, faults which have a offset equalling the reservoir thickness and a strike which is sub-parallel to the maximum horizontal stress (σ_H) direction have high probability to be reactivated by changing reservoir conditions, whereas faults which have a small offset and a large angle with the σ_H orientation have a much lower probability (see results of van den Hoek et al., 2021). Therefore, the fault offset and orientation multipliers have been constructed as follows:

*The fault offset multiplier is based on the **max** fault displacement measured in the AoI (*

1. Table 2-8 and Figure 2-10):
    - Offset = > 1.5 reservoir thickness: Multiplier = 0.5
    - Offset = 1.26 – 1.5 reservoir thickness: Multiplier = 1.0
    - Offset = 1.06 – 1.25 reservoir thickness: Multiplier = 1.5
    - Offset = 0.91 – 1.05 reservoir thickness: Multiplier = 2.0
    - Offset = 0.51 – 0.9 reservoir thickness: Multiplier = 1.5
    - Offset = 0.26 – 0.5 reservoir thickness: Multiplier = 1.0
    - Offset = 0 – 0.25 reservoir thickness: Multiplier = 0.5
    - Offset = < 0 reservoir thickness (reverse fault): Multiplier = 0.5

The fault orientation multiplier is determined by measuring the angle between the fault strike and the maximum horizontal stress (σ_H) direction. Take the minimum angle between the orientation of the faults and the σ_H direction within the AoI (

2. Table 2-8 and Figure 2-11):
    - Angle = 0 – 25° / not measurable due to data limitations: Multiplier = 2 (high / unknown slip tendency)
    - Angle = 26 – 40° / : Multiplier = 1.5 (Medium slip tendency)
    - Angle = 41 - 70° / : Multiplier = 1.0 (Low slip tendency)
    - Angle = 71 - 90° / : Multiplier = 0.5 (Locked)
3. Implement the two multipliers in equation 3 in order to compute the final fault score

Table 2-8: The multipliers determined from fault offset (Figure 2-10) and fault orientation with respect to the current maximum horizontal stress (Figure 2-11)

Score (multiplier)	Fault offset (m or twt)
0.5	> 1.5 reservoir thickness
1.0	1.26 – 1.5 reservoir thickness
1.5	1.05 - 1.25 reservoir thickness
2	0.91 – 1.05 reservoir thickness
1.5	0.51 – 0.9 reservoir thickness
1.0	0.26 - 0.5 reservoir thickness
0.5	0.0 – 0.25 reservoir thickness
0.5	< 0.0 reservoir thickness (reverse fault)

Score (multiplier)	Orientation wrt the current stress field (°)
2	0-25° / not measurable
1.5	26-40°
1.0	41-70°
0.5	71-90°

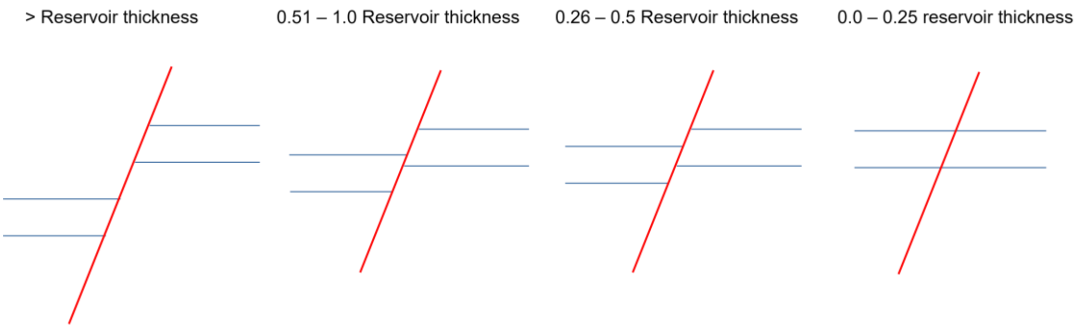


Figure 2-10: Cartoon depicting the different fault offset conditions. Left) Fault offset > 1.5 reservoir thickness which is related to a multiplier of 0.5. Centre left) Fault offset is 0.51 - 1.0 reservoir thickness which is related to a multiplier ranging between 1.5-2.0. Centre right) Fault offset is 0.26 - 0.50 reservoir thickness which is related to a multiplier of 1.0. Right) Fault offset is not observed - 0.25 reservoir thickness which is related to a multiplier of 0.5. Reverse faults (negative displacement) get a multiplier of 0.5. Note that all figures are in cross-section view. See table

Table 2-8 for additional details.

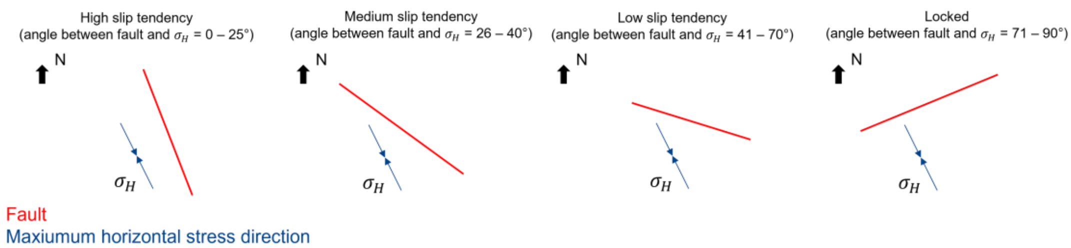


Figure 2-11: Cartoon depicting the different fault orientation conditions. Left) High slip tendency which is related to a multiplier of 2.0. Centre left) Medium slip tendency which is related to a multiplier of 1.5. Centre right) Low slip tendency

which is related to a multiplier of 1.0. Right) Locked which is related to a multiplier of 0.5. Note that all figures are in map view. See table

Table 2-8 for additional details.

Note that for the multiplier derived from the angle with the local stress field, we assume normal faulting conditions where σ_1 is vertical.

2.4.3 Step 3.4: When in the production phase: determine the score for faults observed on production data

The fourth step in the fault-scoring methodology is only applicable to projects which are already in the production phase. At this step, the score related to faults observed by well tests -, production - or log data in the AoI is derived (Table 2-9). Faults can for example be observed as fluid flow baffles by production and/or well test data. In addition, faults can directly be observed by log and/or core data when they are directly drilled by wells. The scoring of faults observed during the production data is done as follows:

1. Determine whether faults are observed by well tests / production data in the AoI. If yes then the score is 2.5 points. If not, then the score is 0 points.
2. Determine whether faults are observed by mudlog, FMI or core data in the AoI. If yes then the score is 2.5 points. If not, then the score is 0 points.
3. Implement the scores in equation 3 in order to compute the final data score.

Table 2-9: The scores determined by faults observed during the production phase.

Score (add)	Fault identified in the AoI by well tests / production data		Score (add)	Fault identified in the AoI by mudlog, FMI or core data
2.5	yes		2.5	yes
[redacted]			[redacted]	
0	No		0	No

2.4.4 Step 3.5: Compute the fault score using the results from steps 3.1 to 3.4

The final fault score is a combination of the acquired scores and multipliers from steps 3.1 to 3.4 and can be derived using equation 2:

$$\text{Fault score} = \text{Intial fault score} * (M_{\text{offset}} * M_{\text{orient}}) + (\text{FS}_{\text{p}} + \text{FS}_{\text{l}})$$ **(Equation 3)**

Where $\text{Intial fault score}$ is the score related to fault intensity (P21) in the AoI (section 2.4), M_{offset} is the multiplier related measured fault offset in the AoI, M_{orient} is the multiplier related to fault orientation with respect to the σ_{H} direction, FS_{p} the score related to faults observed by production and/or well test data and FS_{l} is the score related to faults observed by mudlog, FMI or core data.

The final data score is a value between 0 and more than 40 points, with higher scores (e.g. 40 points) being representative of a high fault density, large measured offsets and/or favourable strikes for fault reactivation, whereas low scores (e.g. 2 points) being regarded as low hazard in the context of seismic hazard screening (Figure 2-12). See Table 2-10 below for example on how to score the faults within the AoI.

	Very Low	Low	Medium	High	Very High
			Fault Score		
Score	0 to 2	2 to 5	5 to 10	10 to 40	> 40

Figure 2-12: Final fault score. In general scores below 5 points are regarded as low hazard in the context of seismic hazard screening given that adequate data is present (score is medium or higher).

Table 2-10: Hypothetical test case of a very low fault score

Fault score	Example	Score	
Fault intensity (in AoI) [km/km2]	Low (0.23 [km/km^2])	3	add
Fault offset	0 – 0.25 reservoir	0.5	multiplier
Orientation in the current stress field	41-80°	1	multiplier
Fault interpreted on well test / production data	N/A	0	add
Fault interpreted on mudlog / FMI / core data	N/A	0	add
		1.5	

2.5 STEP-4: FAULT SCORE VS DATA SCORE

The last step in the proposed workflow is to evaluate the final fault score vs final data score using scoring matrix which is constructed using Figure 2-7 and Figure 2-12 (Figure 2-13). With this matrix an operator can determine whether the project receives a pass or whether further action is required (i.e. SHRA / new data or proceed with SHS workflow) (Figure 2-13).

As an example, projects which have sufficient data score (> 30 points) and a very low fault score (< 2 points) receive a pass and can proceed with the SHS workflow (i.e. with the assessment of the fault reactivation potential). Projects which a low fault score (2 – 5 points) will only receive a pass when the acquired data score is medium or higher (i.e. > 40 points). All other possible combinations will require further action and are redirected to a SHRA / New data recommendation either due to a too high fault score or due to insufficient data. That being said, it should be noted that the exact follow-up steps are to be determined by EBN and TNO-AGE upon combining the individual key-elements into a single, new SHS-Workflow.

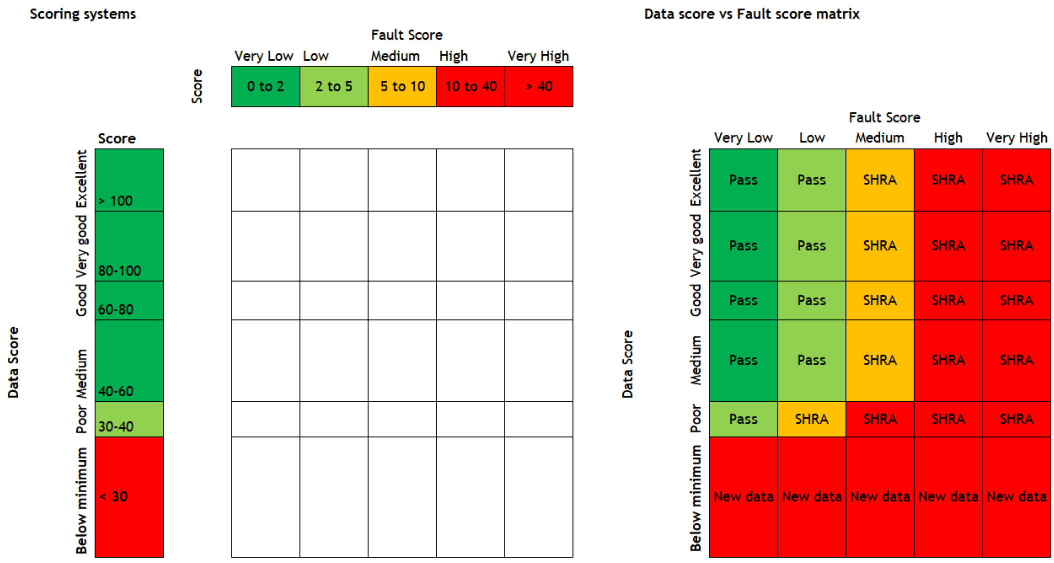


Figure 2-13: Left) The construction of matrix using the data score and fault score. Right) The final scoring matrix and the potential follow up steps given the data and fault scores.

3 Example projects and hypothetical test cases

To demonstrate how the proposed workflow operates in real world and hypothetical test cases two example projects and five test cases have been constructed. It should be noted that presented dummy projects should be seen as examples and do not directly represent actual sub-surface conditions.

3.1 HYPOTHETICAL EXAMPLE PROJECT 1: NOORDOOSTPOLDER

The first hypothetical project is located in the Noordoostpolder and the target is the Slochteren reservoir at approximately 2.5 km depth (Figure 3-1). In this area, the Slochteren formation is believed to have good potential for geothermal energy exploitation. The Area of Influence has been computed using the French Method (Figure 3-2). However, it should be noted that the French Method is different from the methodology presented in Borst et al., (2021), which should be always be used for SHS in future projects.

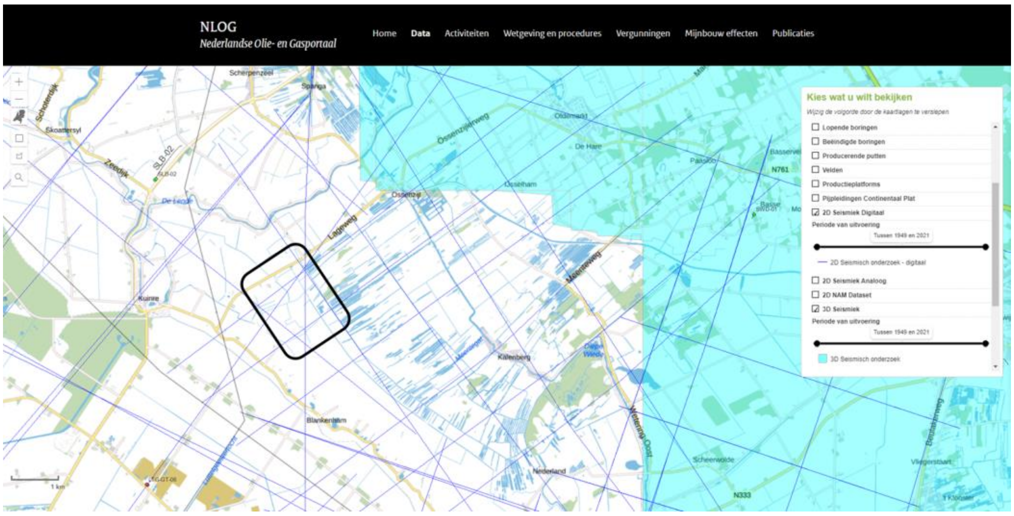


Figure 3-1: Location of the Noordoostpolder example project.

3.1.1 Data scoring

No 3D seismic data exists in the area. However 2D seismic lines are present which are mostly organised in a grid pattern and are of sufficient quality (Figure 3-2). In total 6 lines were used for the interpretation within the AoI. The 2D seismic lines surrounding the AoI were also used for the interpretation, two of which were within 1.0 km of the AoI (Figure 3-2). One previously drilled exploration well (SLB-01) was used for conducting a seismic to well tie and the top and base Slochteren FM (Base ZE and BPU) could adequately be traced across the region (Figure 3-2). The location of injector well was chosen in to be within 0-100m of the seismic line at reservoir depth (Figure 3-2). Finally, no production data was available in or around the AoI. Given the utilized project settings, the final data score was calculated to be 85 points (Table 3-1), thereby making the data position within the AoI good.

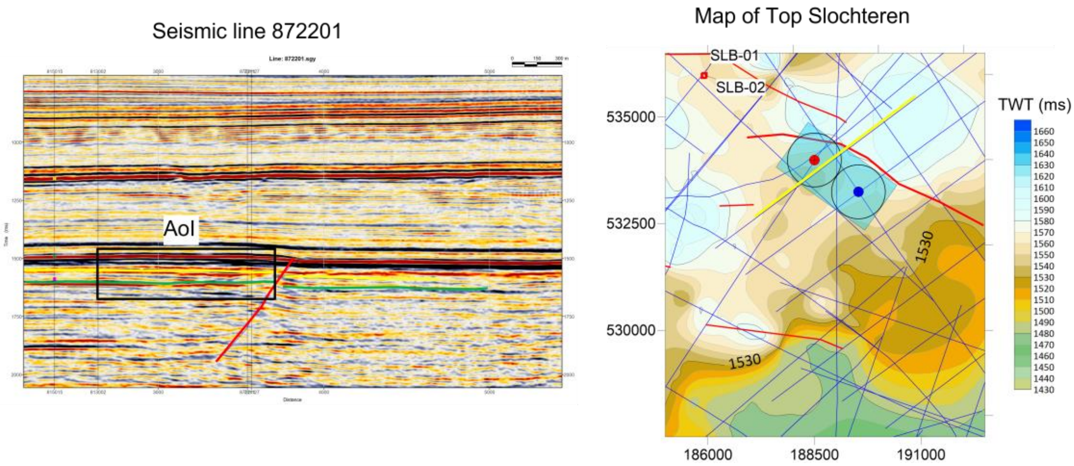


Figure 3-2: Left) Interpretation of the seismic line 872201 (Top Slochteren: Yellow, Base Slochteren: Green). The fault is highlighted in red. The location of the seismic line is highlighted in yellow on the map (right figure). Map of the Top Slochteren in TWT (ms). The AoI is constructed using the French method and is highlighted as a light blue shade. The location of the injector and producer wells are indicated by the blue and red dots, respectively. Interpreted faults are highlighted as red lines.

Table 3-1: Data score table for the Noordoostpolder project

Data score	Noordoostpolder	Score	
Number of 2D lines in AoI	6 lines	75	add
3D seismic coverage percentage in AoI	0 percent	0	add
Seismic data score in AoI		75	2D+3D
Offset seismic data (within 1 km)	2 lines	5	add
Pattern	Grid	1	multiplier
Distance to injector well	0-100 m	1	multiplier
pickable horizon?	yes	1	multiplier
quality	sufficient	0.75	multiplier
well for seismic well tie	1 well different block	5	add
Interpreted well test / production data	No	0	add
Interpreted Mudlog / FMI / Core	No	0	add
		65	

3.1.2 Fault scoring

During the seismic interpretation one fault crossing the AoI was observed, resulting in a calculated fault intensity (P21) within the AoI of 0.31 [km/km^2] (Figure 3-2). Fault offset is relatively constant throughout the region and is observed to range between 0.26 – 0.50 reservoir thickness (Figure 3-2). The maximum horizontal stress direction was taken from Mechelse, (2017) and was set at 326°. The angle between maximum horizontal stress direction and the observed fault strike is approximately 38° making the slip tendency medium. Finally, since no production data was used, the scores related to the production phase were set at 0.0. Given above described fault density and characteristics a final fault score is 4.5 which is considered low (Table 3-2).

Table 3-2: Fault score table for the Noordoostpolder project

Fault score	Noordoostpolder	Score	
Scaled fault density (in AoI) [km/km^2]	Low (0.31 [km/km^2])	3	add
Fault offset	0.26-0.5 reservoir	1	multiplier
Orientation in the current stress field	25-40°	1.5	multiplier
Fault interpreted on well test / production data	N/A	0	add
Fault interpreted on mudlog / FMI / core data	N/A	0	add
		4.5	

3.1.3 Fault score vs data score

Given a data score of 65 points and fault score of 4.5 points this project passes the seismic hazard screening for this key element (Figure 3-3).

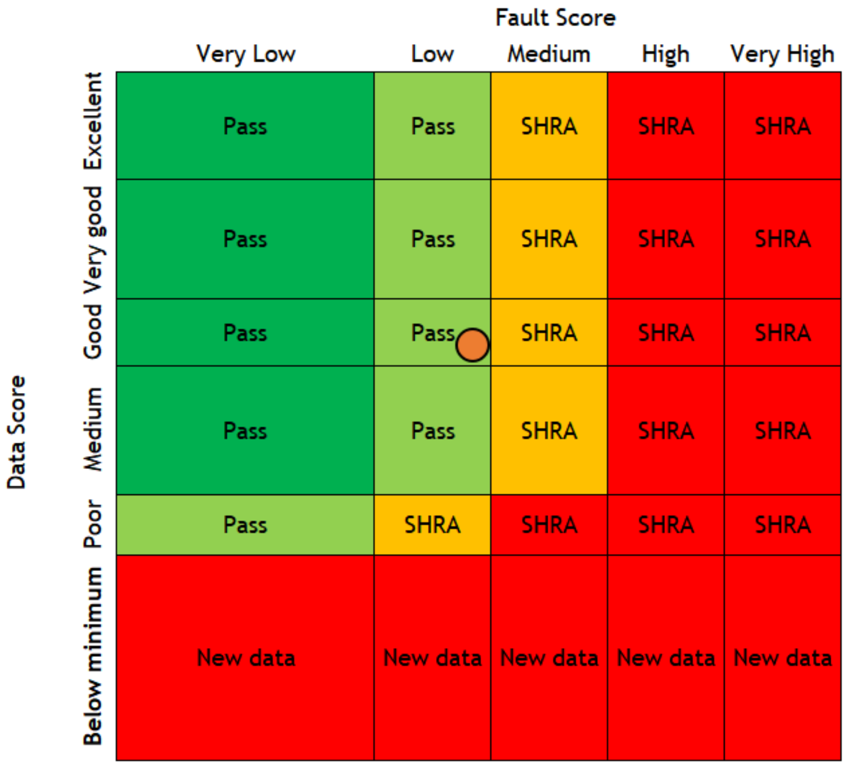


Figure 3-3: Data vs Fault score evaluation matrix for the Noordoostpolder project

3.2 HYPOTHETICAL EXAMPLE PROJECT 2: APPELSCHA & NORG-ZUID

The second hypothetical project is located in the province of Drenthe and the target is the Slochteren reservoir at approximately 3.0 km depth (Figure 3-4). In this area, the Slochteren formation is believed to have good potential for geothermal energy exploitation. The Area of Influence has been computed using the French Method (Figure 3-5). Again, it should be noted that the French Method is different from the methodology presented in Borst et al., (2021), which should be always be used for SHS in future projects.

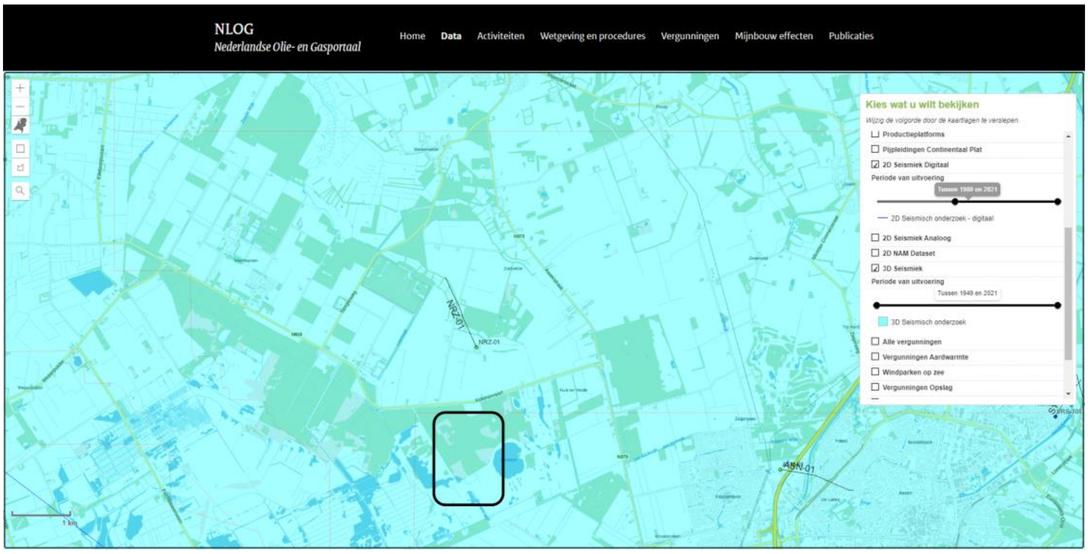


Figure 3-4: Location of the Appelscha Norg Zuid example project.

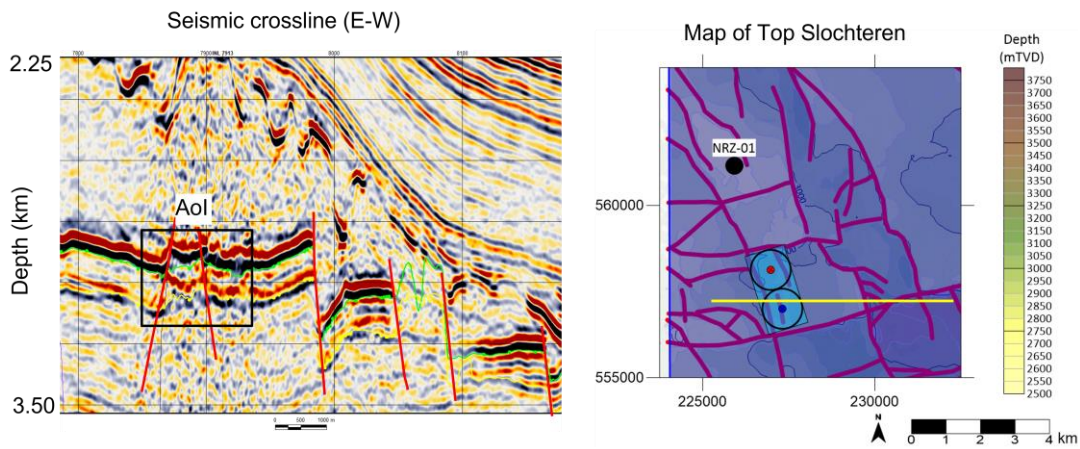


Figure 3-5: Left) Interpretation of a seismic crossline E-W (Top Slochteren: Green, Base Slochteren: Yellow). Faults are highlighted in red. The location of the seismic line is highlighted in yellow on the map (right figure). Map of the Top Slochteren in depth (m). The coverage of the 3D seismic data is shown by the dark blue overlay. The AoI is constructed using the French method and is highlighted as a light blue shade. The location of the injector and producer wells are indicated by the blue and red dots, respectively. Interpreted faults are highlighted as red lines.

3.2.1 Data scoring

The project location is fully covered by depth converted and reprocessed 3D seismic data which is good to excellent quality in the AoI (Figure 3-5). One previously drilled exploration well (NRZ-01) was used for conducting a seismic to well tie and top and base Slochteren FM (Base ZE and BPU) could adequately be traced across the region. The location of injector well is within the seismic volume at reservoir depth (Figure 3-5). Finally, no production data was available in or around the AoI. Given the utilized project settings, the final data score was calculated to be 120 points (Table 3-3), thereby making the data position within the AoI excellent.

Table 3-3: Data score table for the Appelscha Norg Zuid project

Data score	APS-NRZ	Score	
Number of 2D lines in AoI	0	0	add
3D seismic coverage percentage in AoI	100 percent	100	add
Seismic data score in AoI		100	2D+3D
Offset seismic data (within 1 km)	3D Seismic	15	add
Pattern	random	1	multiplier
Distance to injector well	Within volume	1	multiplier
pickable horizon?	yes	1	multiplier
quality	Good	1	multiplier
well for seismic well tie	1 well different block	5	add
Interpreted well test / production data	No	0	add
Interpreted Mudlog / FMI / Core	No	0	add
		120	

3.2.2 Fault scoring

During the seismic interpretation multiple fault crossings the AoI were observed, resulting in a calculated fault intensity (P21) within the AoI of 1.63 [km/km^2] (Figure 3-5). Maximum fault offset is relatively constant throughout the region and is observed to range between 1/4 – 1/2 reservoir thickness (Figure 3-5). The maximum horizontal stress direction was taken from Mechelse, (2017) and was set at 326°. The angle between maximum horizontal stress direction and the observed fault is approximately 0-25° making the slip tendency high. Finally, since no production data was used, the scores related to the production phase were set at 0.0. Given above described fault density and characteristics a final fault score is 20 points which is considered high (Table 3-4).

Table 3-4: Fault score table for the Appelscha Norg Zuid project

Fault score	APS-NRZ	Score	
Scaled fault density (in AoI) [km/km2]	High (1.63 [km/km^2])	10	add
Fault offset	0.26-0.5 reservoir	1	multiplier
Orientation in the current stress field	0-25°	2	multiplier
Fault interpreted on well test / production data	N/A	0	add
Fault interpreted on mudlog / FMI / core data	N/A	0	add
		20	

3.2.3 Fault score vs data score

Given a data score of 120 points and fault score of 20 points this project does not pass the seismic hazard screening (Figure 3-6) and a SHRA or a new project location are recommended.

Data Score	Fault Score: Very Low	Low	Medium	High	Very High
Excellent	Pass	Pass	SHRA	SHRA	SHRA
Very good	Pass	Pass	SHRA	SHRA	SHRA
Good	Pass	Pass	SHRA	SHRA	SHRA
Medium	Pass	Pass	SHRA	SHRA	SHRA
Poor	Pass	SHRA	SHRA	SHRA	SHRA
Below minimum	New data	New data	New data	New data	New data

Figure 3-6: Data vs Fault score evaluation matrix for the Appelscha Norg Zuid project

3.3 OTHER HYPHOTHETICAL EXAMPLES

Lastly, to further exemplify the scoring methodology and different data / fault configurations, five additional test project are shown by Figure 3-7. The utilized excel sheets are provided as an attachment to this report which can be used to create other potential test cases.

Data score	Test case 1	Score	Test case 2	Score	Test case 3	Score	Test case 4	Score	Test case 3	Score	
Number of 2D lines in AoI	3 lines	40	3 lines	40	3 lines	40	0 lines	0	0 lines	0	add
3D seismic coverage percentage in AoI	0 percent	0	0 percent	0	0 percent	0	> 75 percent	100	> 75 percent	100	add
Seismic data score in AoI		40		40		40		100		100	2D+3D
Offset seismic data (within 1 km)	1 line	5	0 lines	0	1 line	5	3D seismic	15	3D seismic	15	add
Pattern	Grid	1	random	0.75	random	0.75	Grid (3D)	1	Grid (3D)	1	multiplier
Distance to injector well	0-100 m	1	0-100 m	1	0-100 m	1	Within volume	1	Within volume	1	multiplier
pickable horizon?	yes	1	yes	1	yes	1	yes	1	yes	1	multiplier
quality	good	1	sufficient	0.75	Good	0.75	good	1	sufficient	0.75	multiplier
well for seismic well tie	1 well same block	10	no	0	No	0	1 well different block	5	1 well different block	5	add
Interpreted well test / production data	No	0		0	No	0	0.1-1.0 km from AoI	5	0.1-1.0 km from AoI	5	add
Interpreted Mudlog / FMI / Core	No	0		0	No	0	no	0	no	0	add
		55		22.5		33.75		125		96.25	

Fault score	Test case 1	Score	Test case 2	Score	Test case 3	Score	Test case 4	Score	Test case 3	Score	
Scaled fault density (in AoI) [km/km2]	Low	3	Medium	7	none	0	None	0	High	10	add
Fault offset	0.26-0.5	1	0.26-0.5	1	N/A	0	N/A	0	0.51-0.9	1.5	multiplier
Orientation in the current stress field	25-40°	1.5	25-40°	1.5	N/A	0	N/A	0	0-25°	2	multiplier
Fault interpreted on well test / production data	N/A	0	N/A	0	N/A	0	None	0	No	0	add
Fault interpreted on mudlog / FMI / core data	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	add
		4.5		10.5		0		0		30	

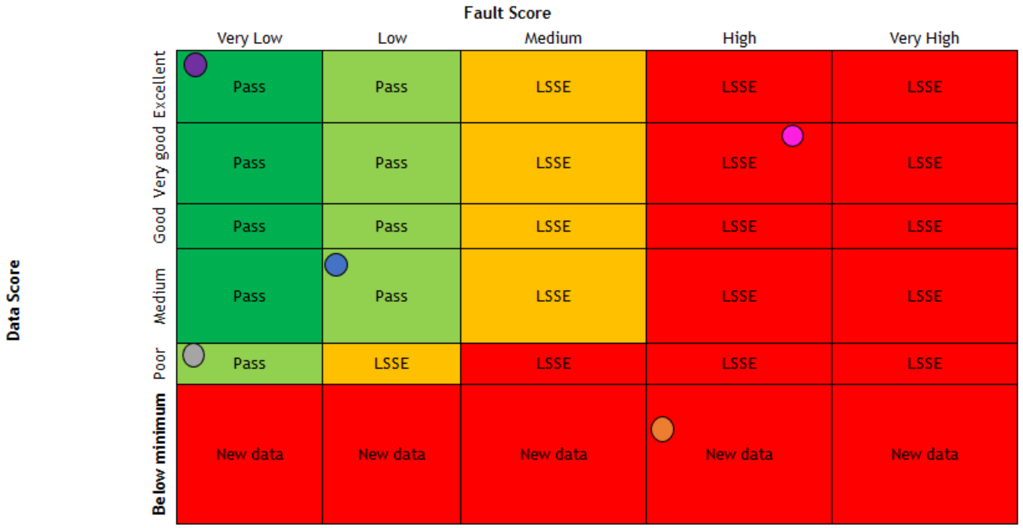


Figure 3-7: Top) Potential test cases and the computed data and fault scores. Bottom) Data vs Fault score evaluation matrix for the different test cases.

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