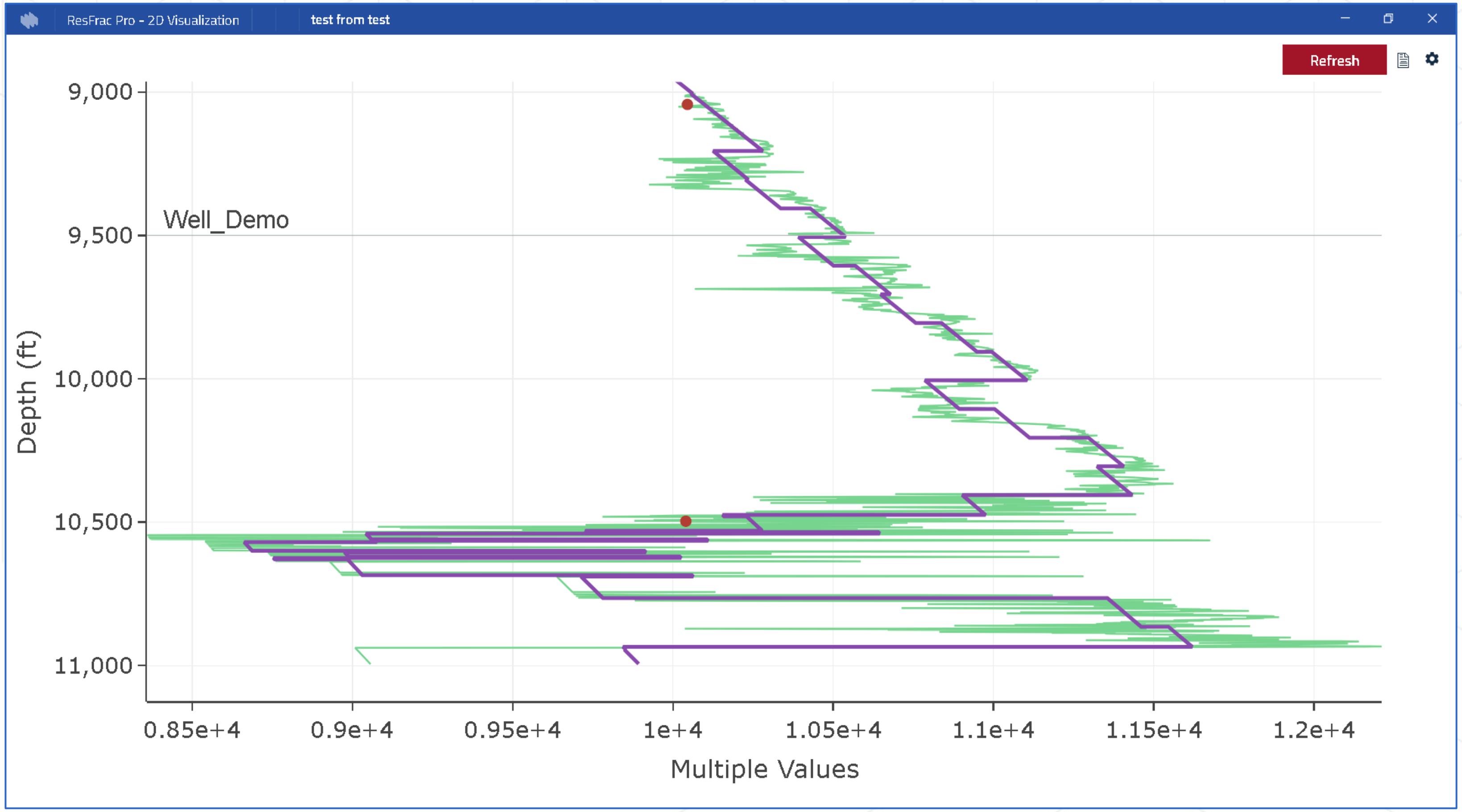
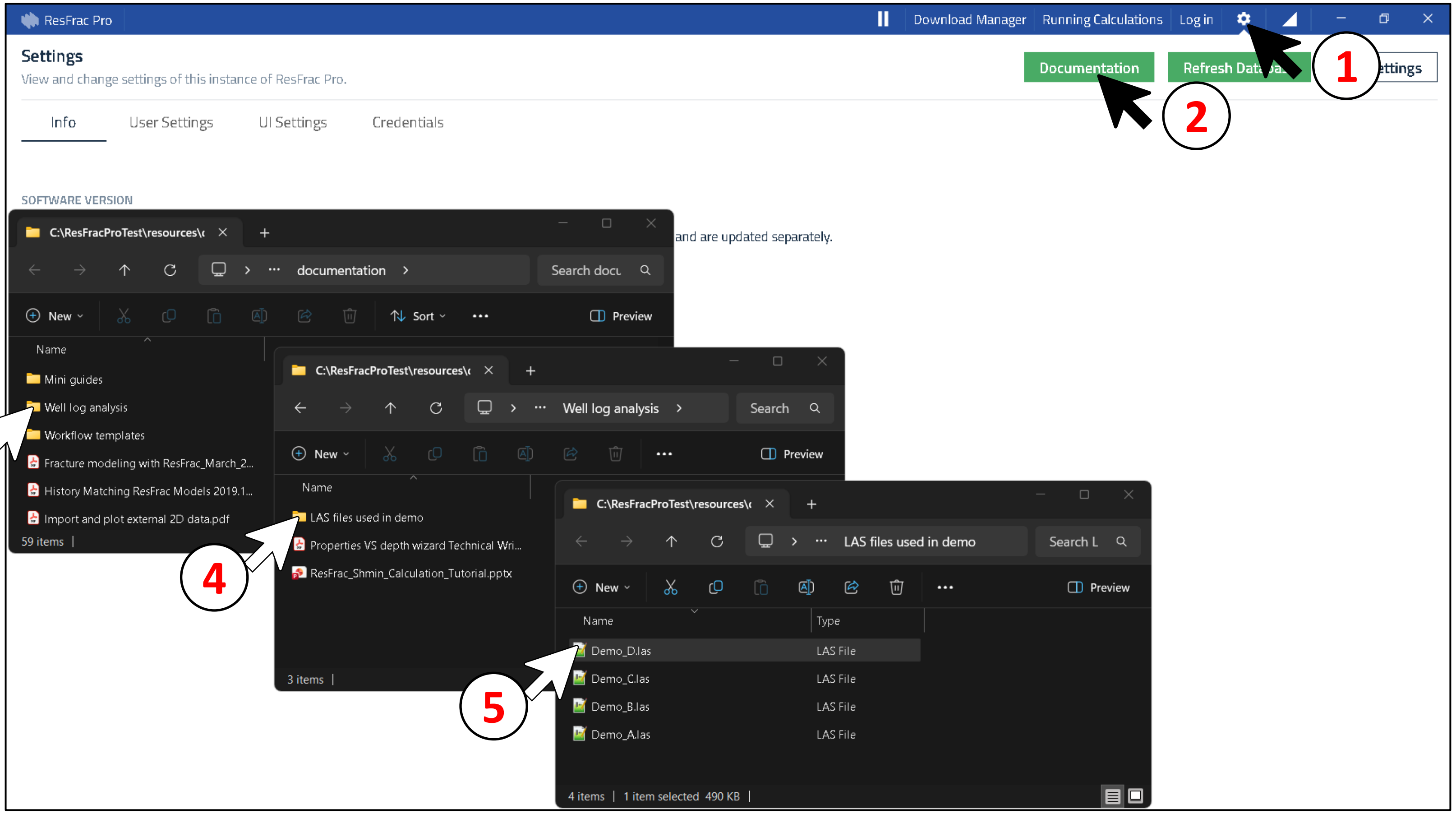


ResFrac Shmin Calculation Tutorial

A Step-by-Step Guide to Calculating Shmin with the Properties vs. Depth Wizard

Introduction

- In this tutorial we will use the Properties vs. depth wizard to calculate Shmin and visualize the results.
- The synthetic LAS file is available in the Documentation folder:



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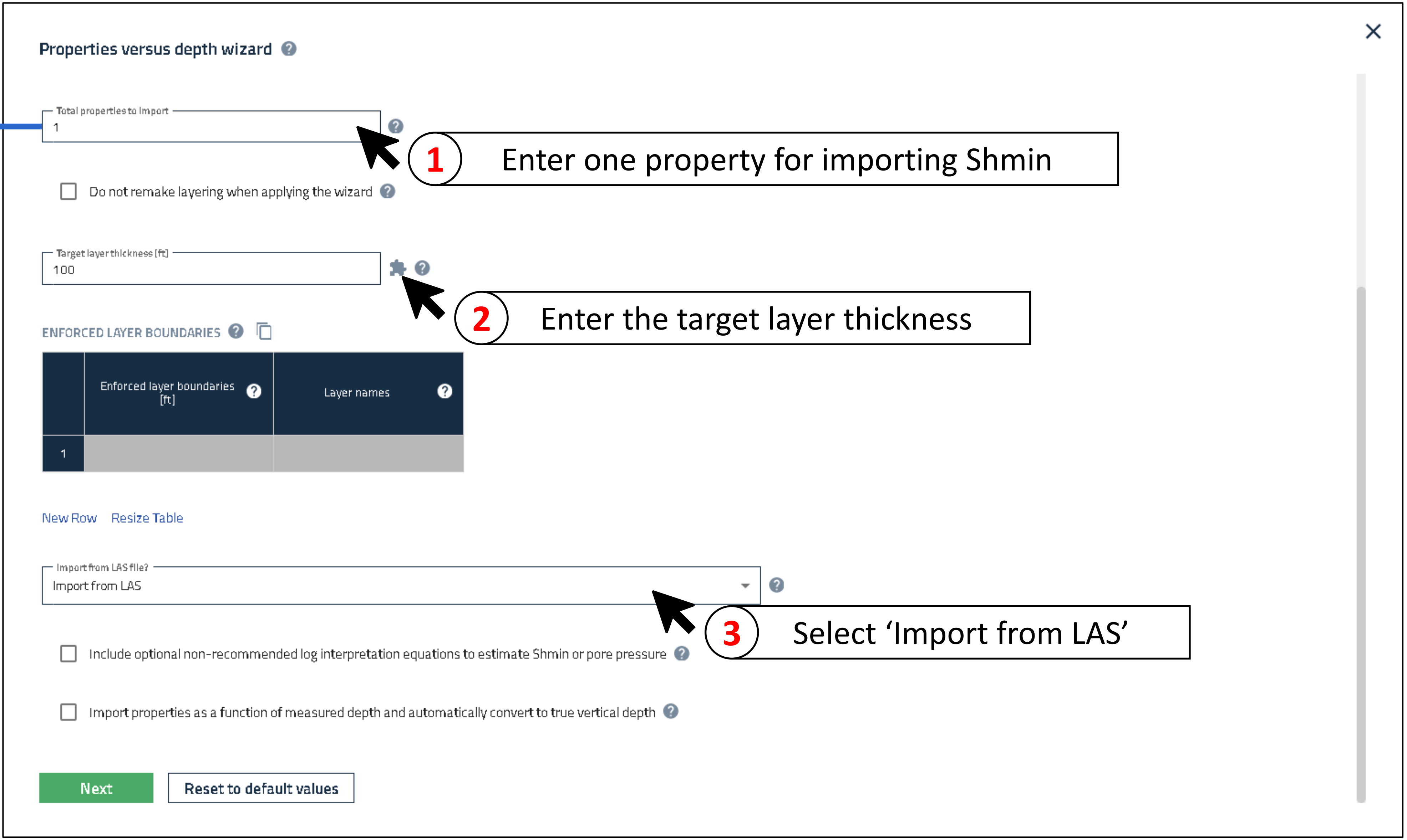
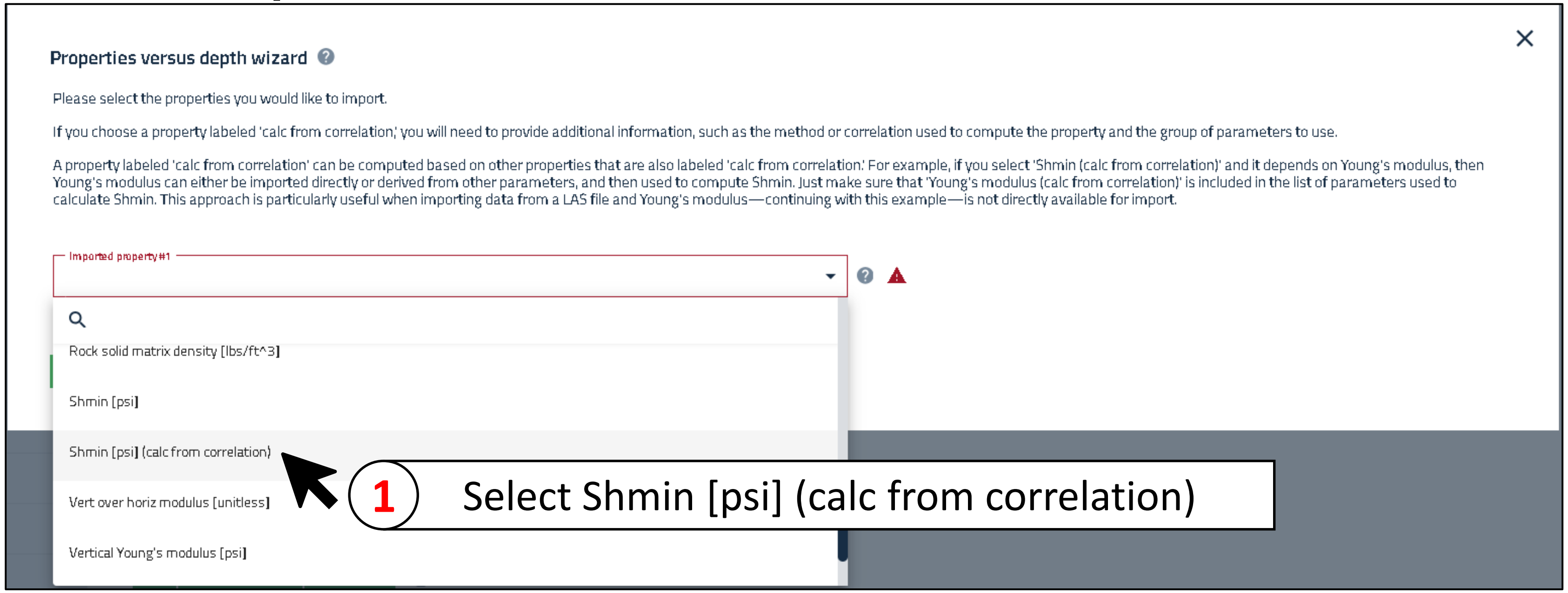
1st panel: general inputs

CLARIFICATION NOTE: This is the number of properties that will be imported into the "Geological Units (Facies List)" table.

For example, if you want to use the wizard to estimate a property (Shmin, in this case), and during the process the wizard asks you to import *pore pressure vs. depth*, but you **ALSO** want *pore pressure vs. depth* to be imported into the Geological Units table, then you must enter 2 for "Total properties to import."

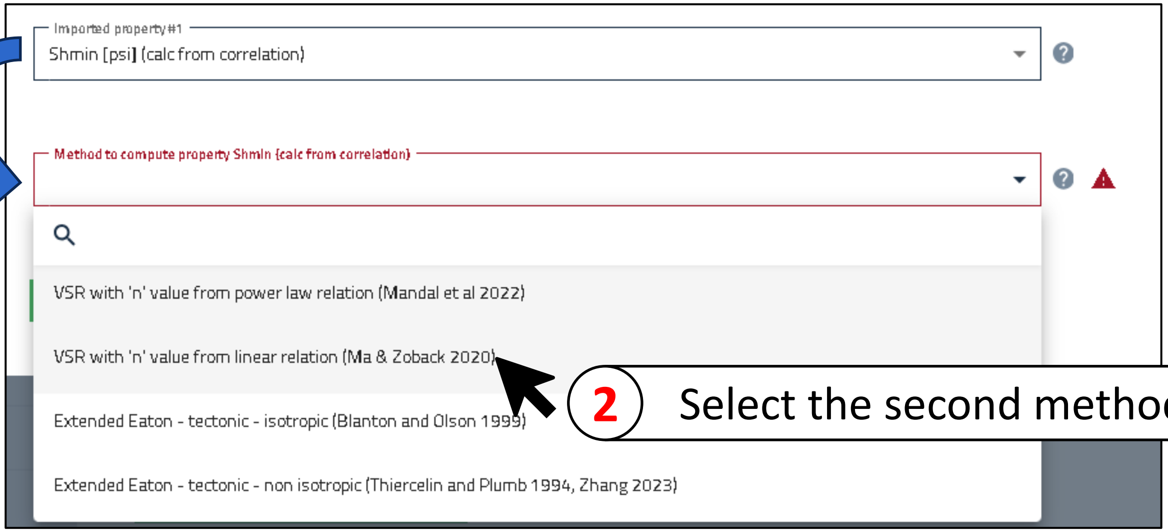


2nd panel: properties to be imported



1 Select Shmin [psi] (calc from correlation)

Once you have selected the property to be imported a new input will be displayed



2 Select the second method from the list

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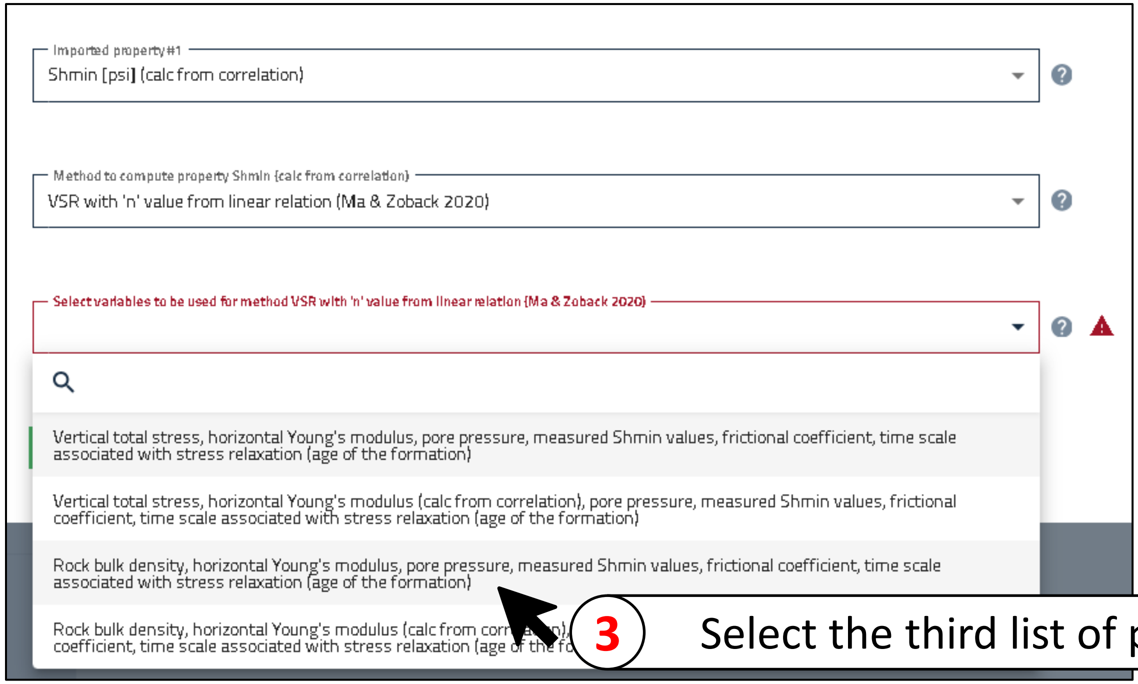
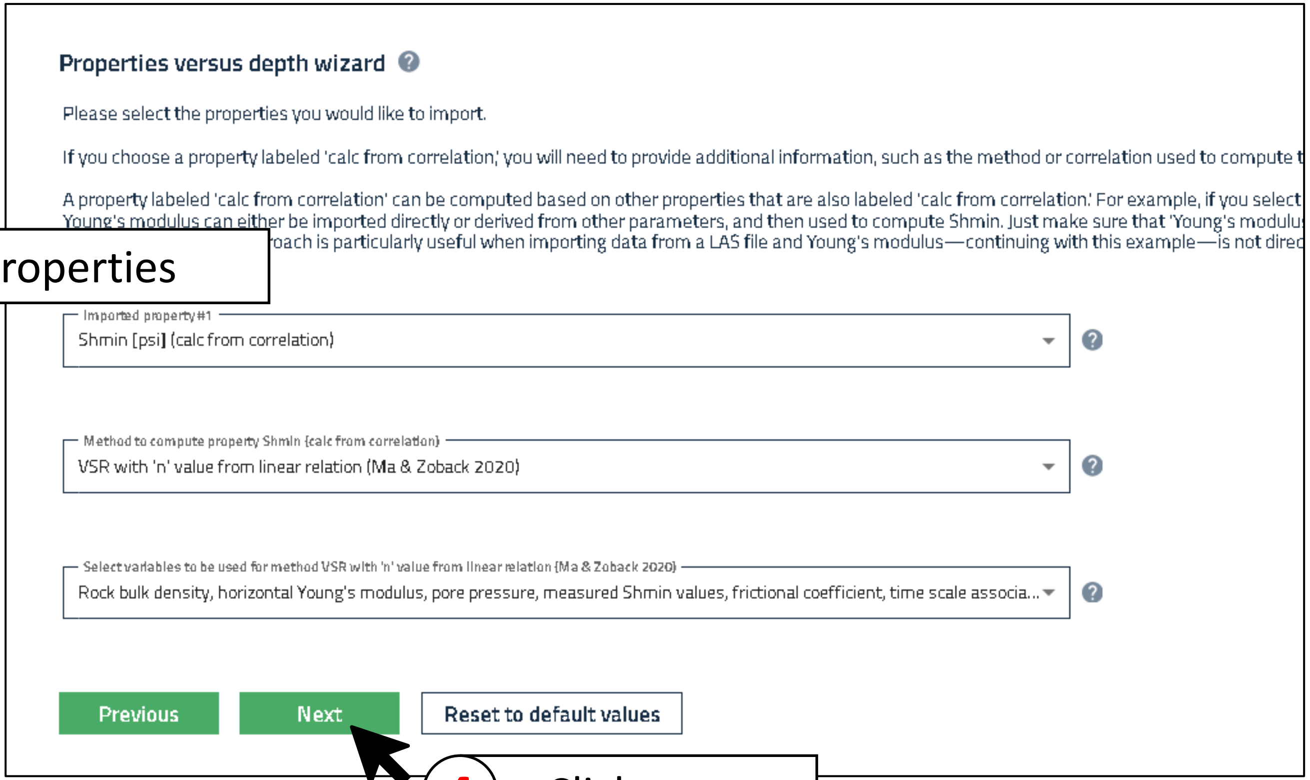
2nd panel (continued)



3 Select the third list of properties



4 Click next

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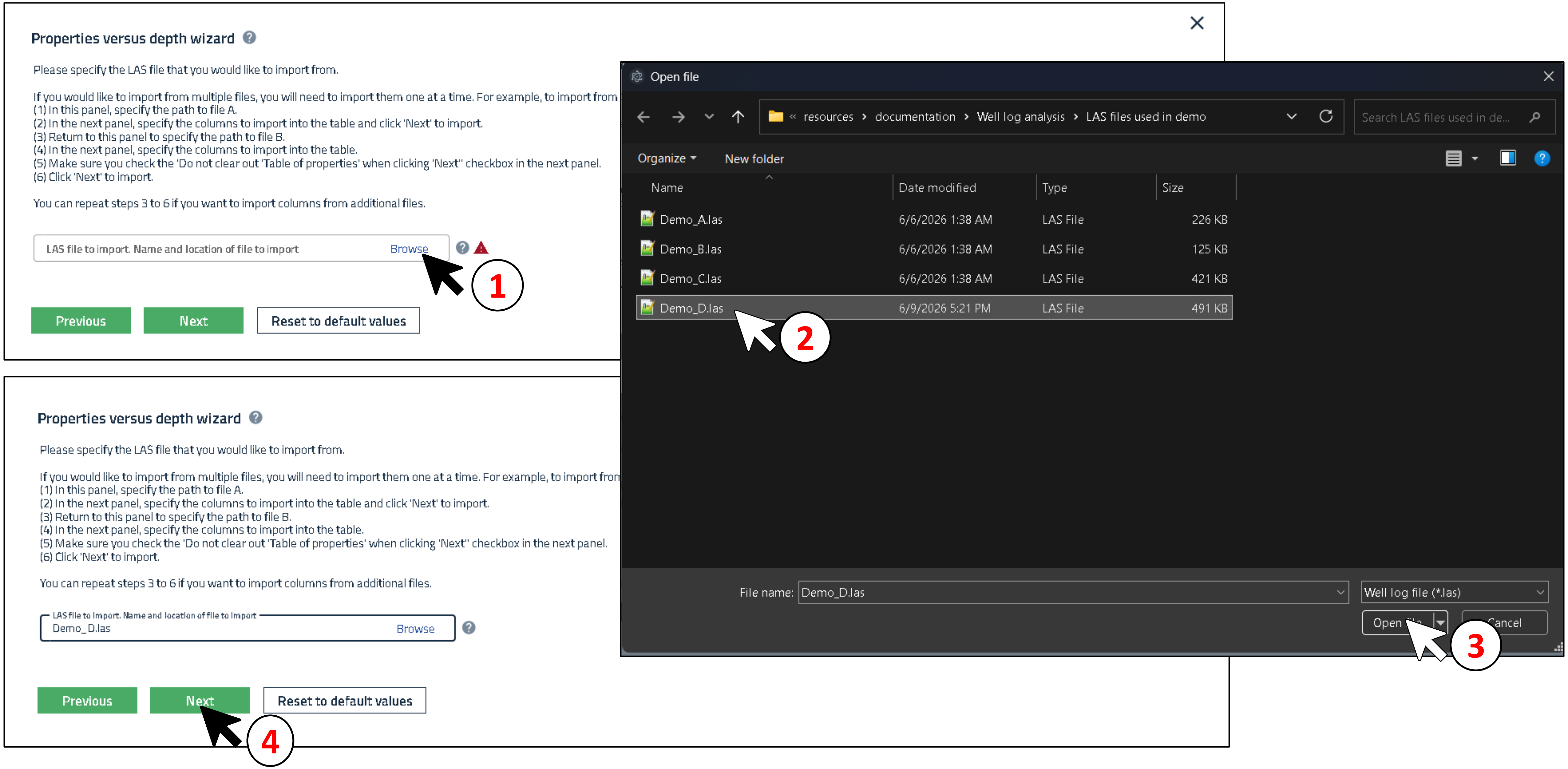
3rd panel: path to the LAS file



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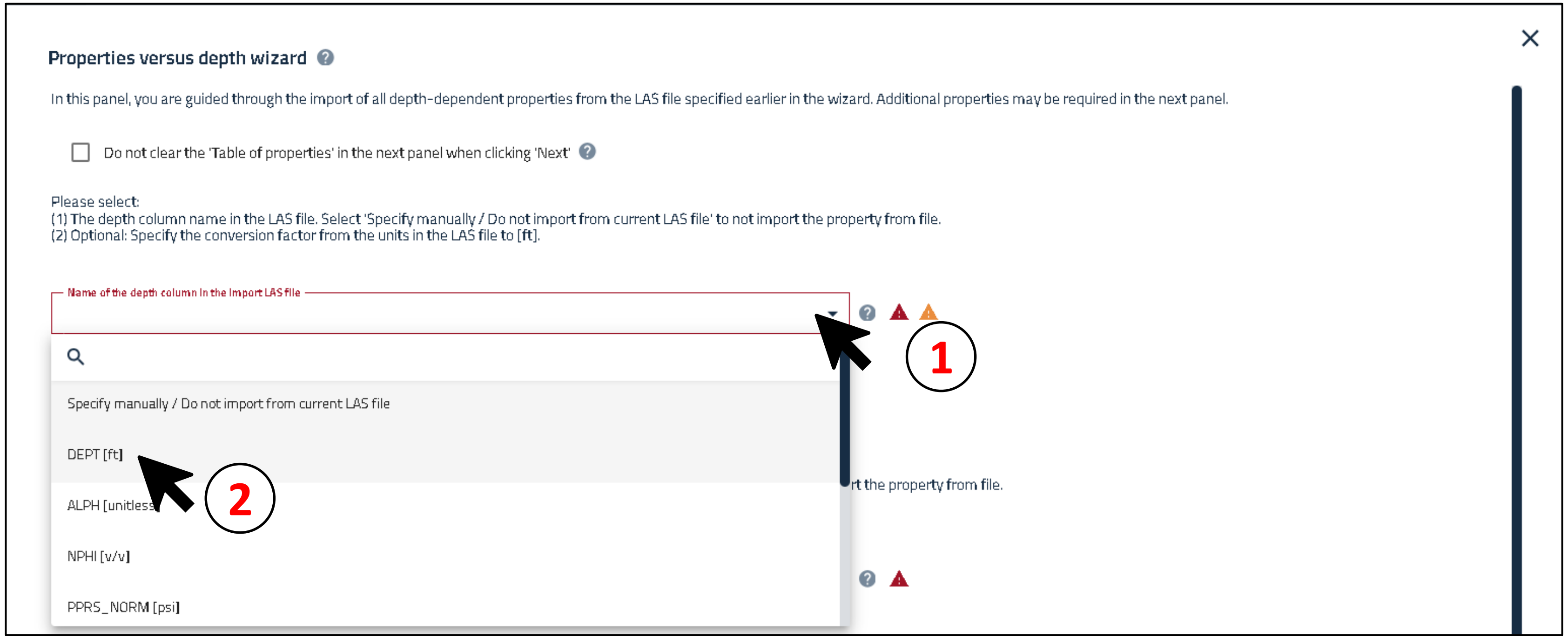
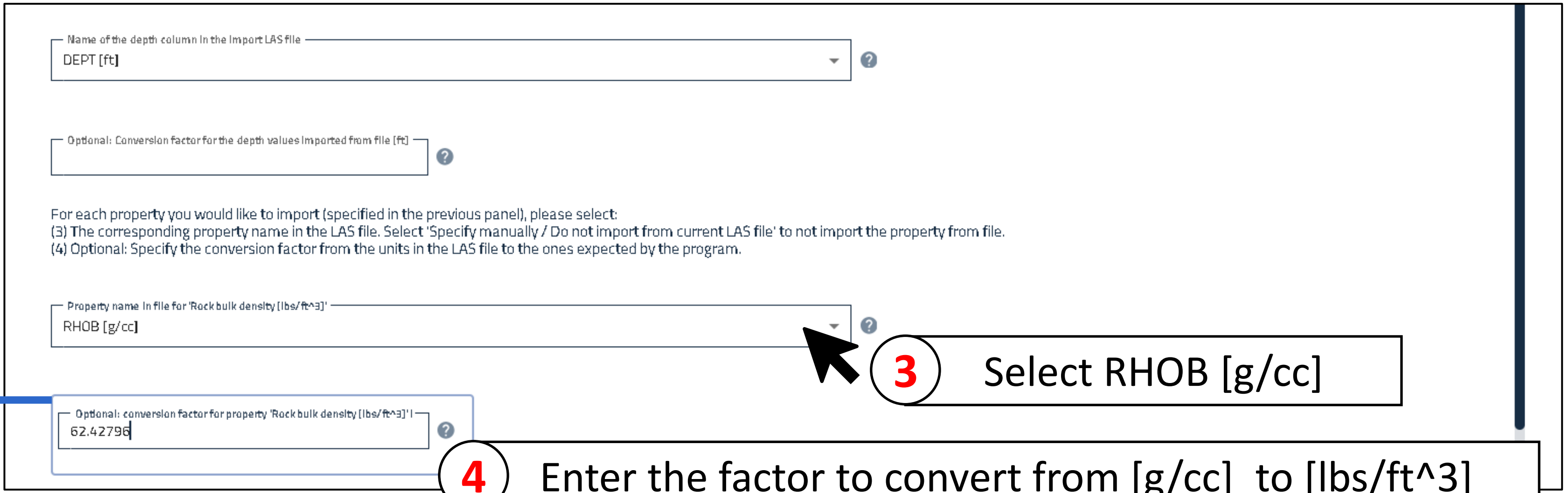
4th panel: column to be imported from the LAS file





3 Select RHOB [g/cc]

4 Enter the factor to convert from [g/cc] to [lbs/ft^3]

CLARIFICATION NOTE:
In this example, the units in the LAS file are [g/cc], while the units required by the wizard are indicated in the title of the input field for the property. In this case, the wizard expects [lbs/ft^3]. Therefore, the user must provide a conversion factor. The code will multiply the values from the LAS file by this factor, and the resulting values are expected to be in the units required by the wizard.

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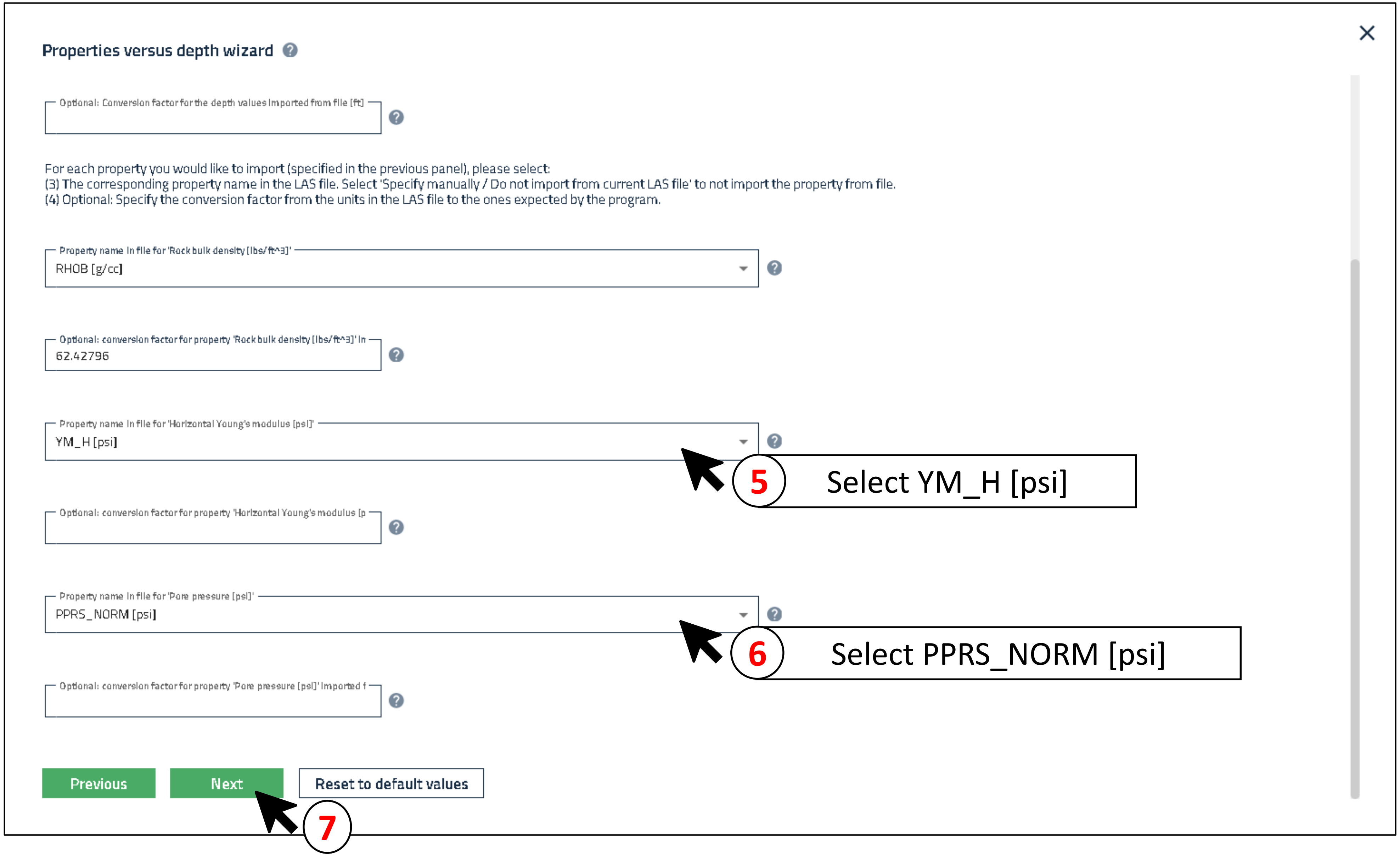
4th panel (continued)



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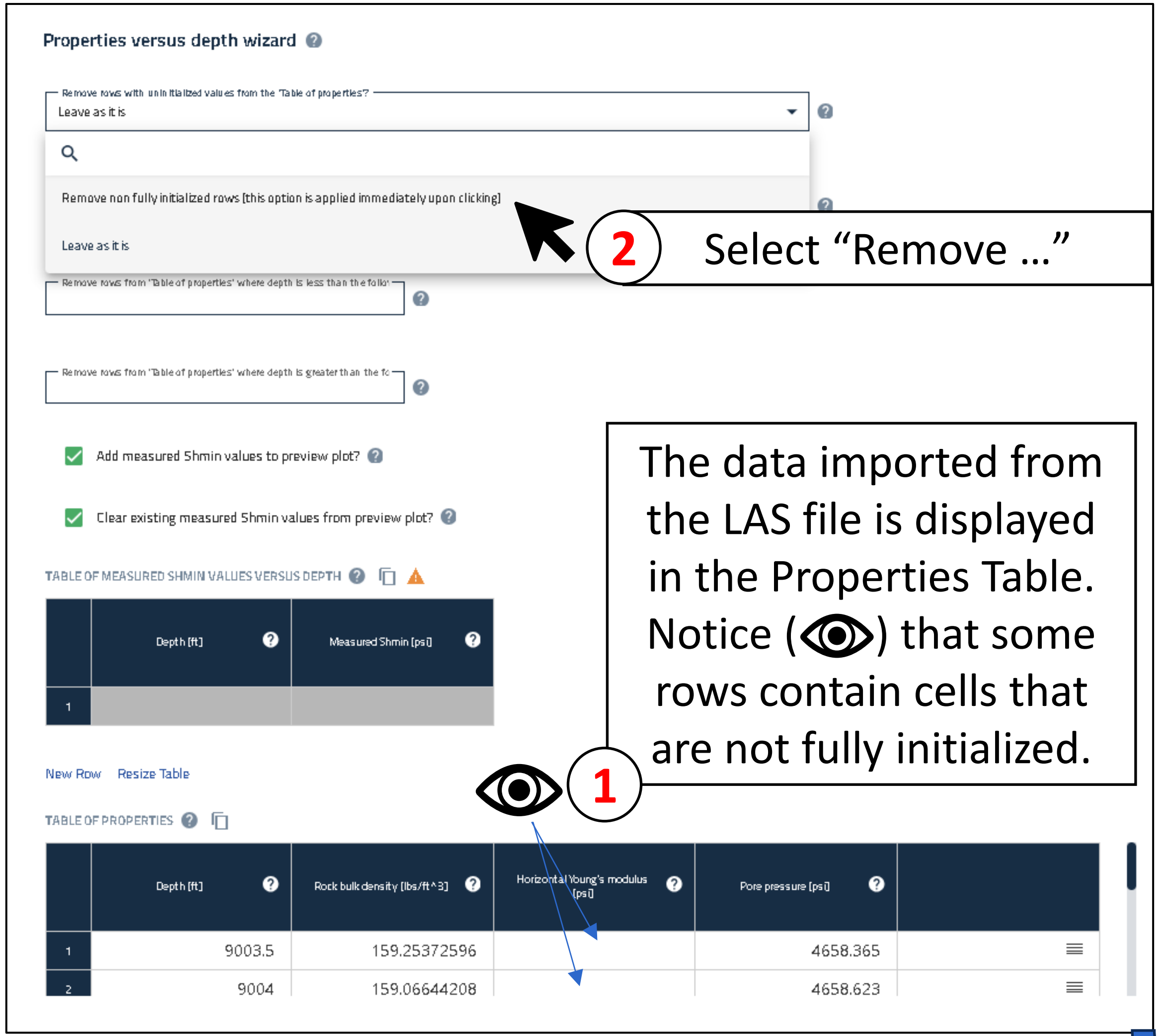
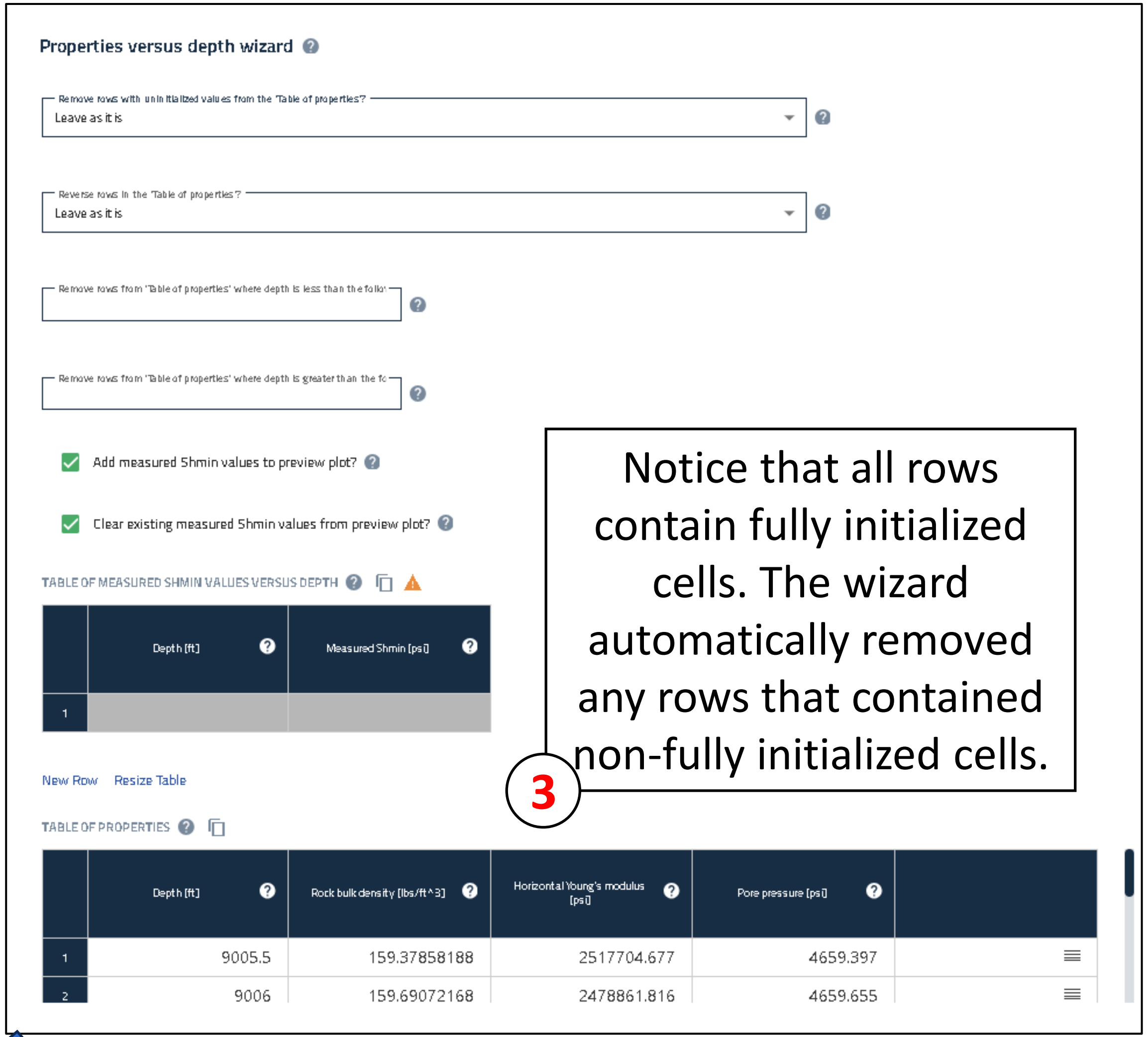
5th panel: summary of the imported data & additional inputs





Once you have clicked "Remove...", the Table of Properties is updated immediately

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5th panel (continued)

Properties versus depth wizard

Remove rows from 'Table of properties' where depth is less than the foll

Remove rows from 'Table of properties' where depth is greater than the

- [x] Add measured Shmin values to preview plot?
- [x] Clear existing measured Shmin values from preview plot?

TABLE OF MEASURED SHMIN VALUES VERSUS DEPTH

	Depth [ft]	Measured Shmin [psi]
1	9043	10045
2	10496	10040

New Row Resize Table

ABLE OF PROPERTIES

	Depth [ft]	Rock bulk density [lbs/ft^3]	Horizontal Young's modulus [psi]	Pore pressure [psi]
1	9005.5	159.37858188	2517704.677	4659.397
2	9006	159.69072168	2478861.816	4659.655
3	9006.5	159.69072168	2477681.088	4659.913

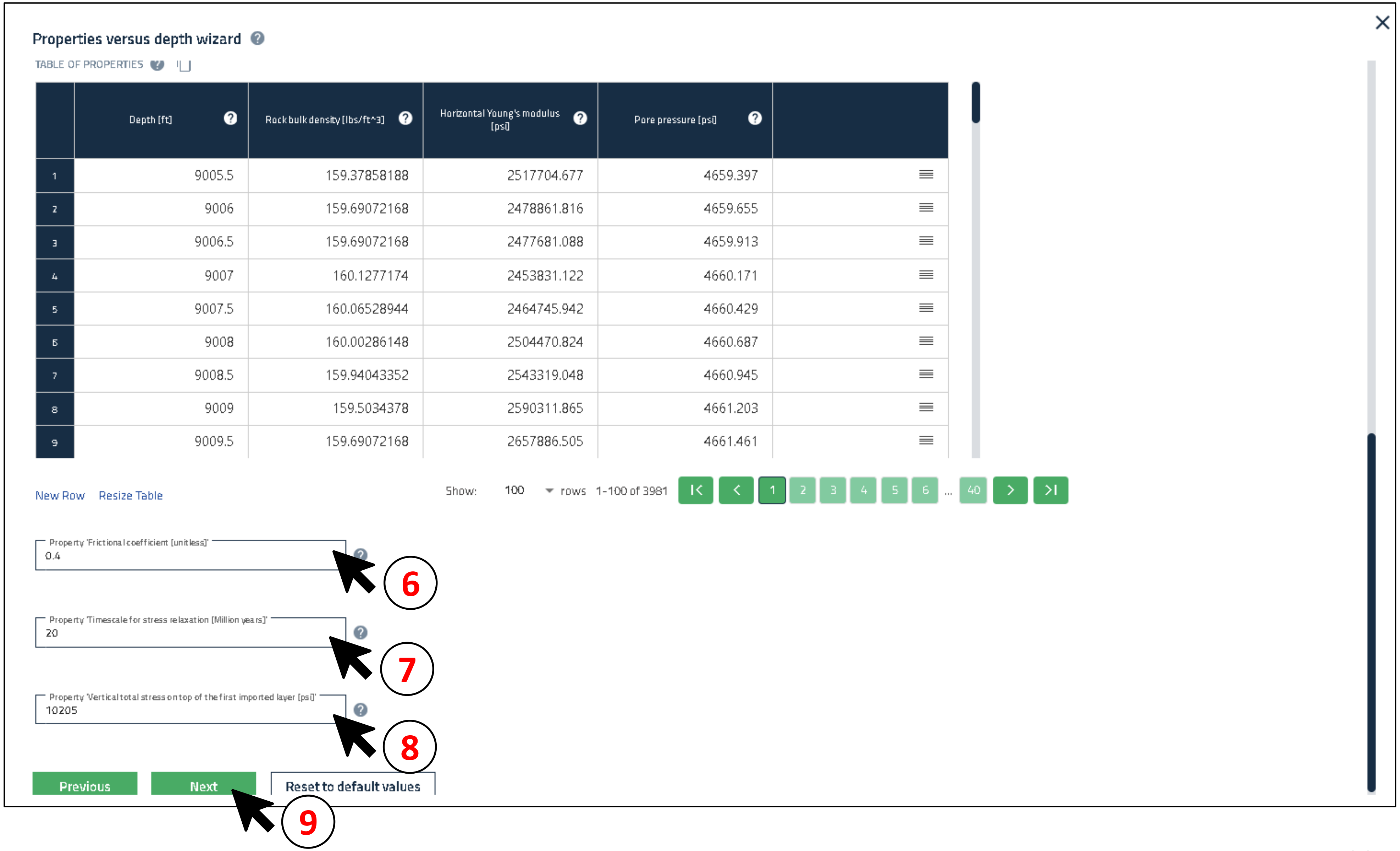
Add the measured Shmin values to the table

5

Add two rows

4

5th panel (continued)



	Depth [ft]	Rock bulk density [lbs/ft^3]	Horizontal Young's modulus [psi]	Pore pressure [psi]
1	9005.5	159.37858188	2517704.677	4659.397
2	9006	159.69072168	2478861.816	4659.655
3	9006.5	159.69072168	2477681.088	4659.913
4	9007	160.1277174	2453831.122	4660.171
5	9007.5	160.06528944	2464745.942	4660.429
6	9008	160.00286148	2504470.824	4660.687
7	9008.5	159.94043352	2543319.048	4660.945
8	9009	159.5034378	2590311.865	4661.203
9	9009.5	159.69072168	2657886.505	4661.461

6th panel: estimated properties (before upscaling)

Properties versus depth wizard

The table of values to be upscaled import is below. Please manually modify, as needed, and then press 'Next' to complete the import/upscaling in the next step.

TABLE OF PROPERTIES TO BE UPSCALED

	Depth [ft]	Shmin [psi] [calc from correlation]	
1	9005.5	10061.7068868579	
2	9006	10066.2408280787	
3	9006.5	10066.9150905811	
4	9007	10069.8738279323	
5	9007.5	10069.3331283566	
6	9008	10065.8459788019	
7	9008.5	10062.3687171692	
8	9009	10057.9392480259	
9	9009.5	10051.1159652535	

New Row Resize Table Show: 100 rows 1-100 of 3981

1 2 3 4 5 6 ... 40

Previous Next Reset to default values

1

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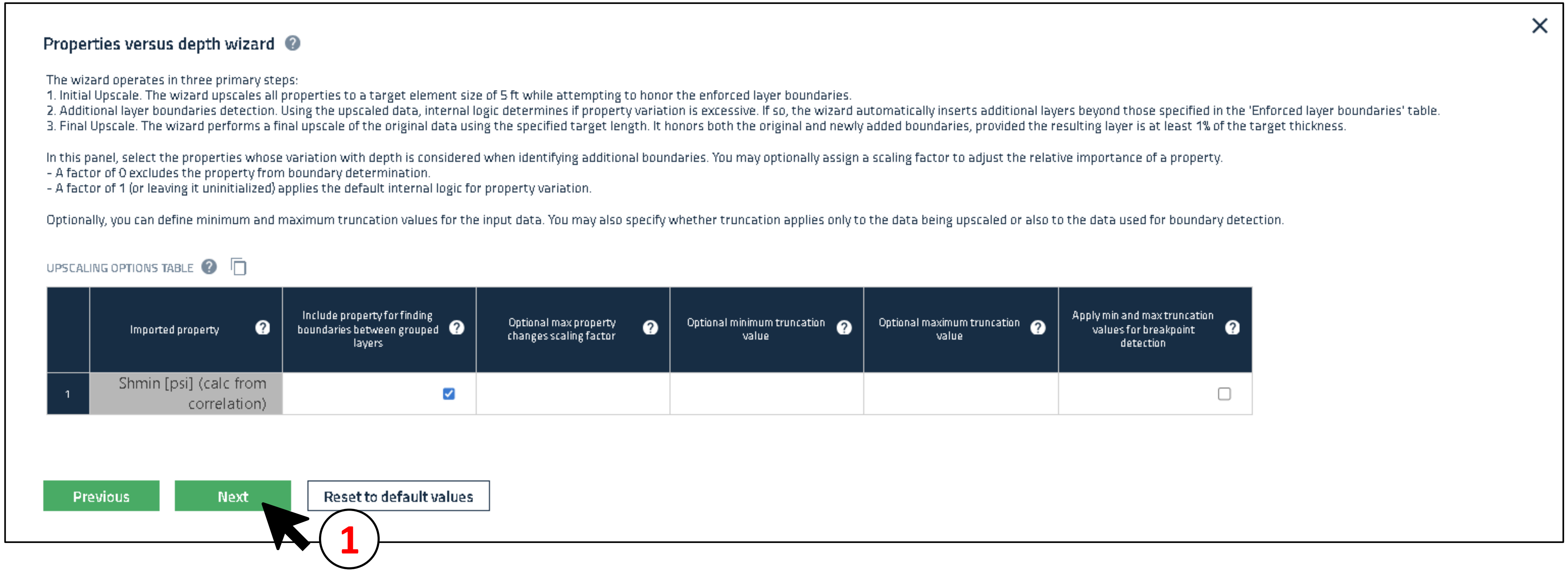
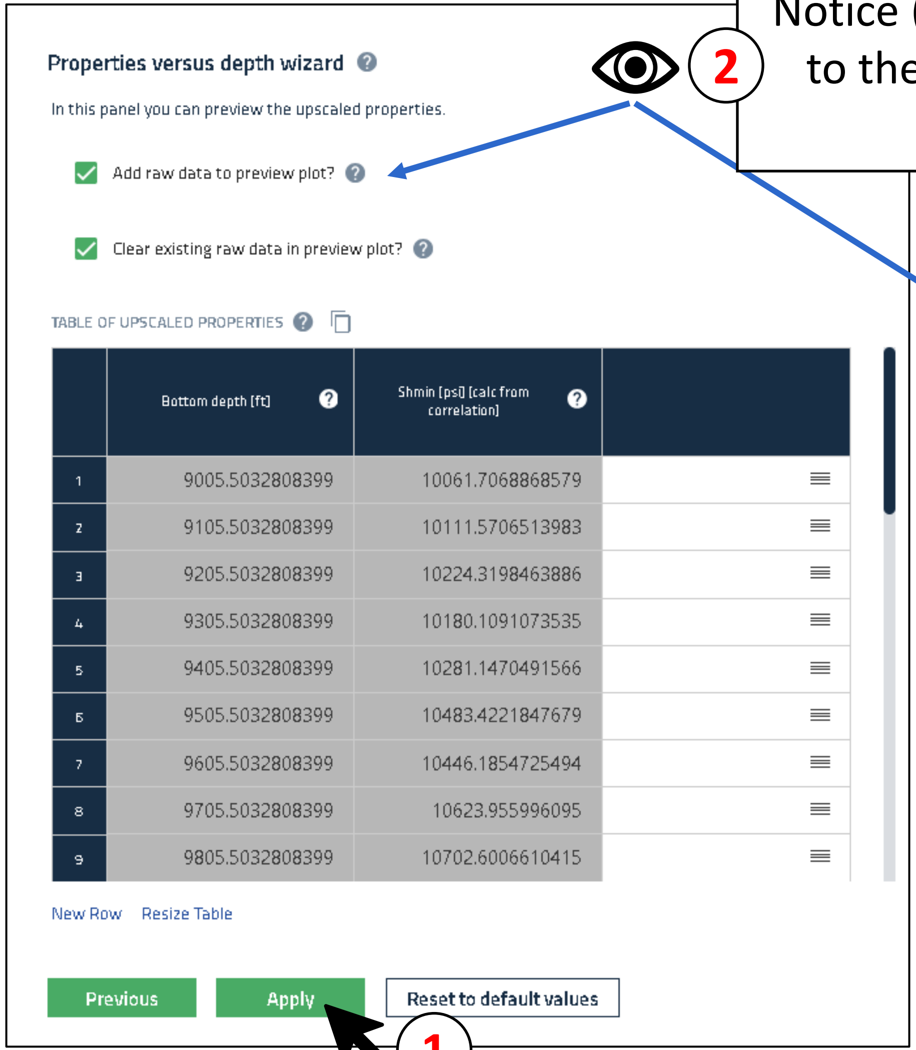
7th panel: upscaling options (before upscaling)



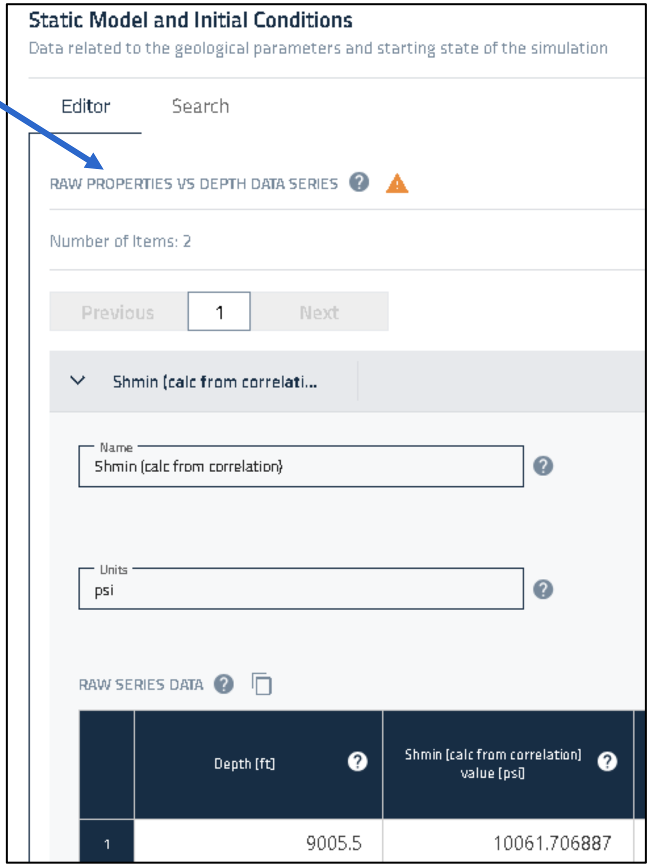
8th panel: preview of the upscaled properties

Notice (👁) that the raw data is added to the Raw properties vs depth data series.

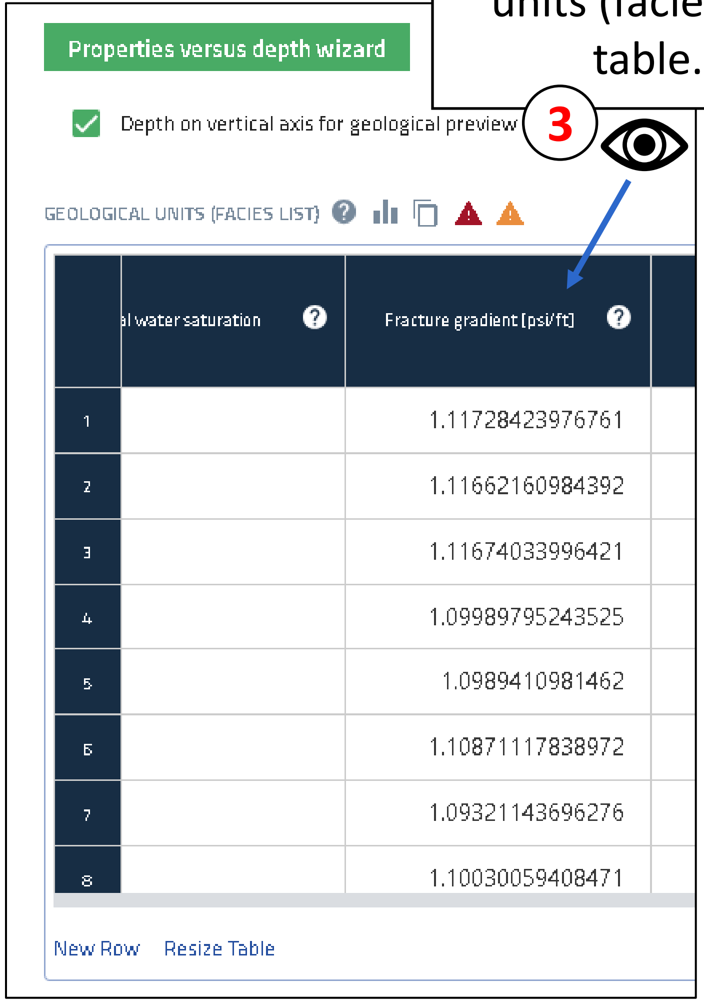
Notice (👁) that Shmin is imported as Fracture gradient in the Geological units (facies list) table.



	Bottom depth [ft]	Shmin [psi] (calc from correlation)	
1	9005.5032808399	10061.7068868579	
2	9105.5032808399	10111.5706513983	
3	9205.5032808399	10224.3198463886	
4	9305.5032808399	10180.1091073535	
5	9405.5032808399	10281.1470491566	
6	9505.5032808399	10483.4221847679	
7	9605.5032808399	10446.1854725494	
8	9705.5032808399	10623.955996095	
9	9805.5032808399	10702.6006610415	



	Depth [ft]	Shmin (calc from correlation) value [psi]
1	9005.5	10061.706887



	...l water saturation	Fracture gradient [psi/ft]
1		1.11728423976761
2		1.11662160984392
3		1.11674033996421
4		1.09989795243525
5		1.0989410981462
6		1.10871117838972
7		1.09321143696276
8		1.10030059408471

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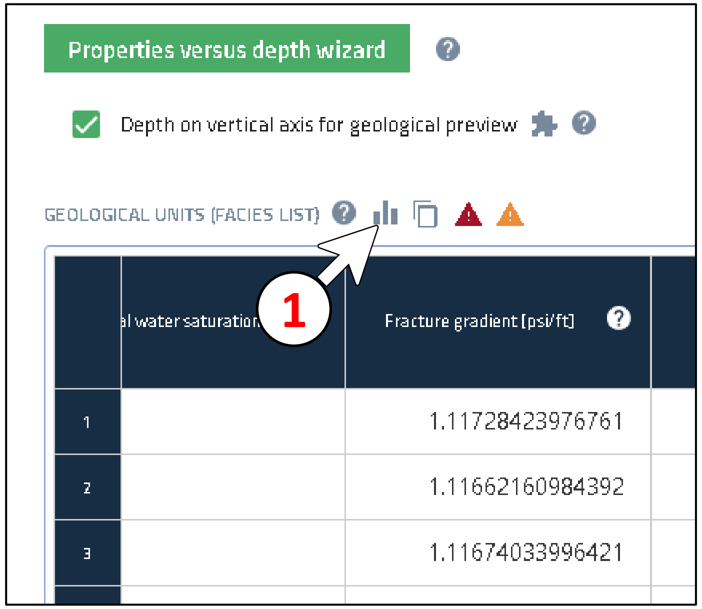
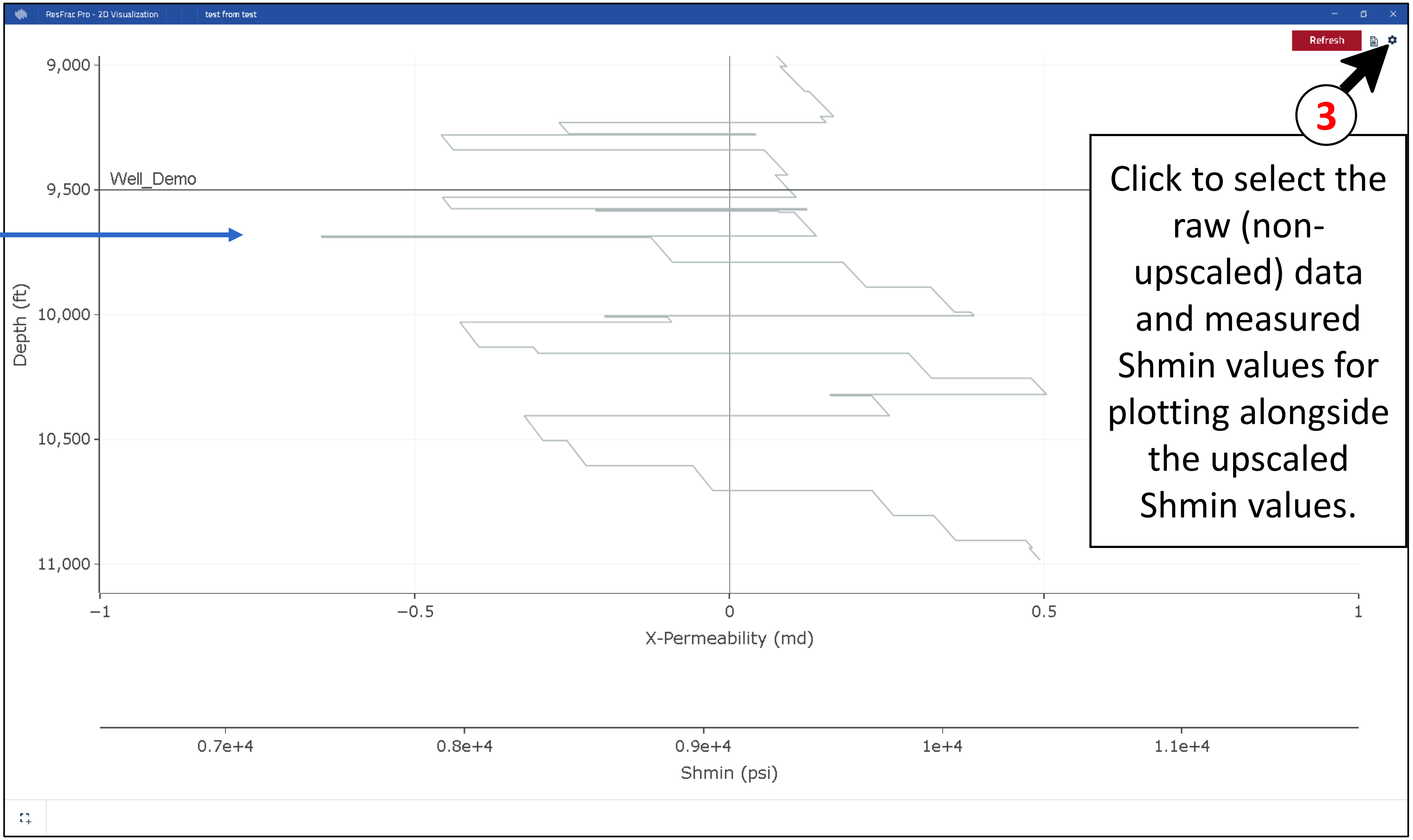
Plotting the upscaled properties and the raw (non upscaled) data

Notice (👁) that the raw (non upscaled data is not immediately visible).

2

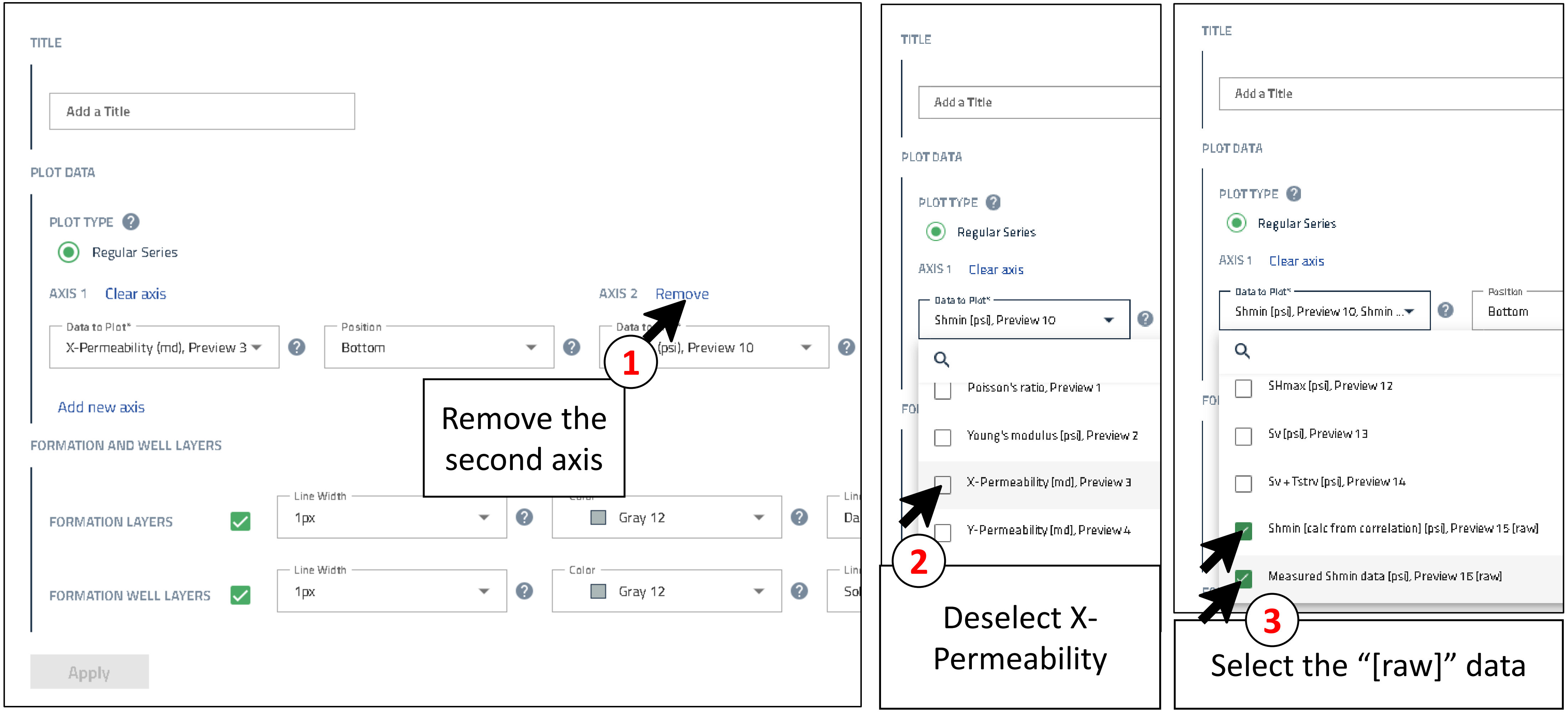




3

Click to select the raw (non-upscaled) data and measured Shmin values for plotting alongside the upscaled Shmin values.

Plotting the upscaled properties and the raw (non upscaled) data (continued)



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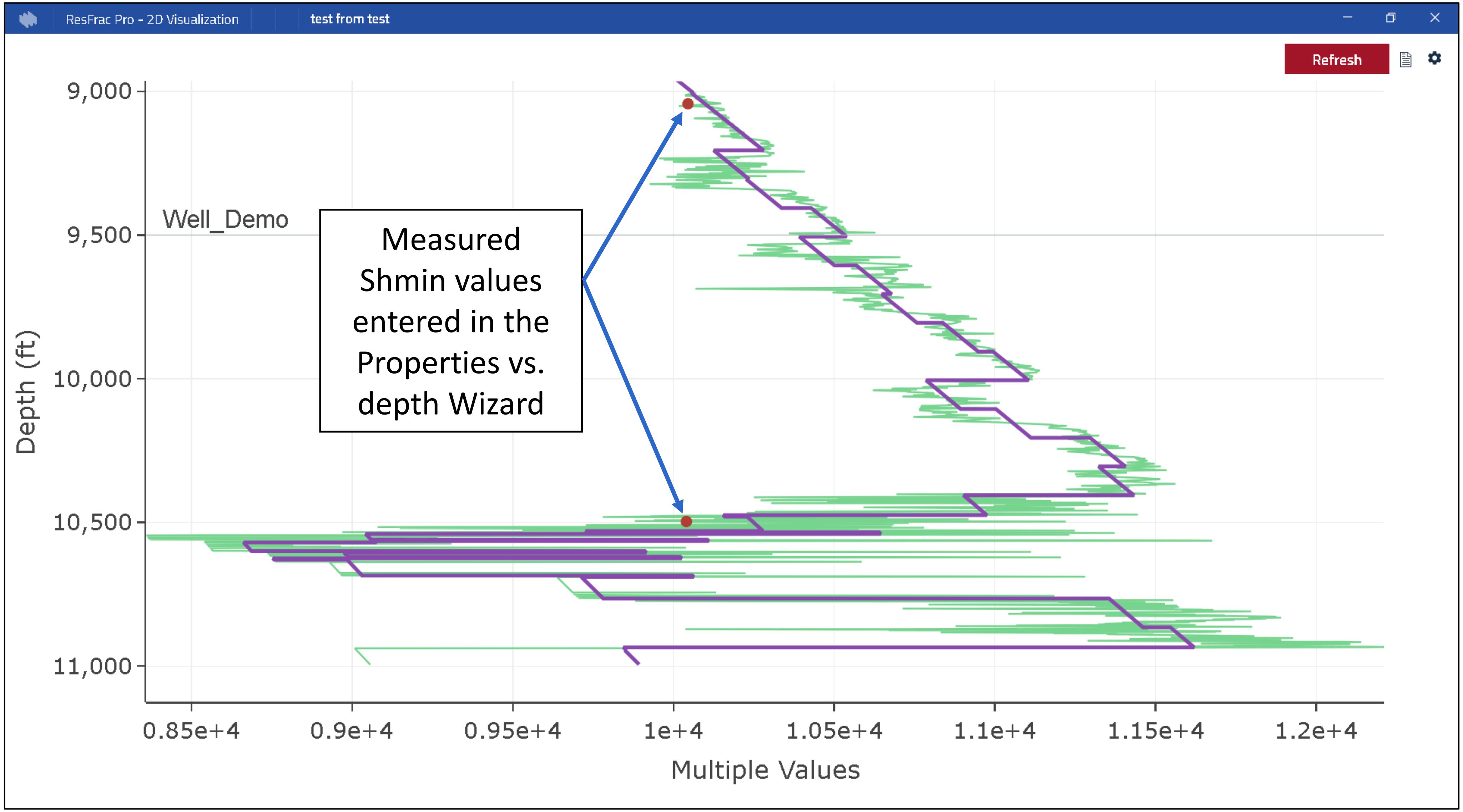
Plotting the upscaled properties and the raw (non upscaled) data (continued)



The following presentation is a quick review of common methodologies for calculating Shmin

S_{hmin} profile estimation methods: Quick look

Ankush Singh, ankush@resfrac.com

Abstract

Various methods are used in the industry to compute S_{hmin} profiles from log data

The methods can be based in two broad categories:

- Eaton and Extended Eaton methods: Based on the assumption that the stress/strain is applied instantaneously, and the rock is perfectly elastic. The original Eaton equation assumes uniaxial application of stress, extended Eaton modifications relax this assumption by using tectonic strain terms. All these methods require information about the pore pressure. Even though these methods are widely used in the industry, they are limited by the somewhat unreasonable geological assumptions and often fail to capture the stress variaitons.
- Viscoelastic stress relaxation (VSR) methods: Based on the principle that time dependent deformation in sedimentary rocks decreases the differential stress (i.e., increases S_{hmin} towards S_V) in more ductile rocks, such as shale formations rich in clay and organic matter. Pore pressure is not an input for the VSR methods. . Unlike the Extended Eaton methods, VSR utilizes geologically more reasonable assumptions for areas with low strain rate, which are typical of nearly all unconventional plays in the US. The VSR method has been developed very recently and the workflow will develop as it is tested on datasets across different formations.

The frictional faulting limit can be used to calculate a the lower bound for the stress profiles

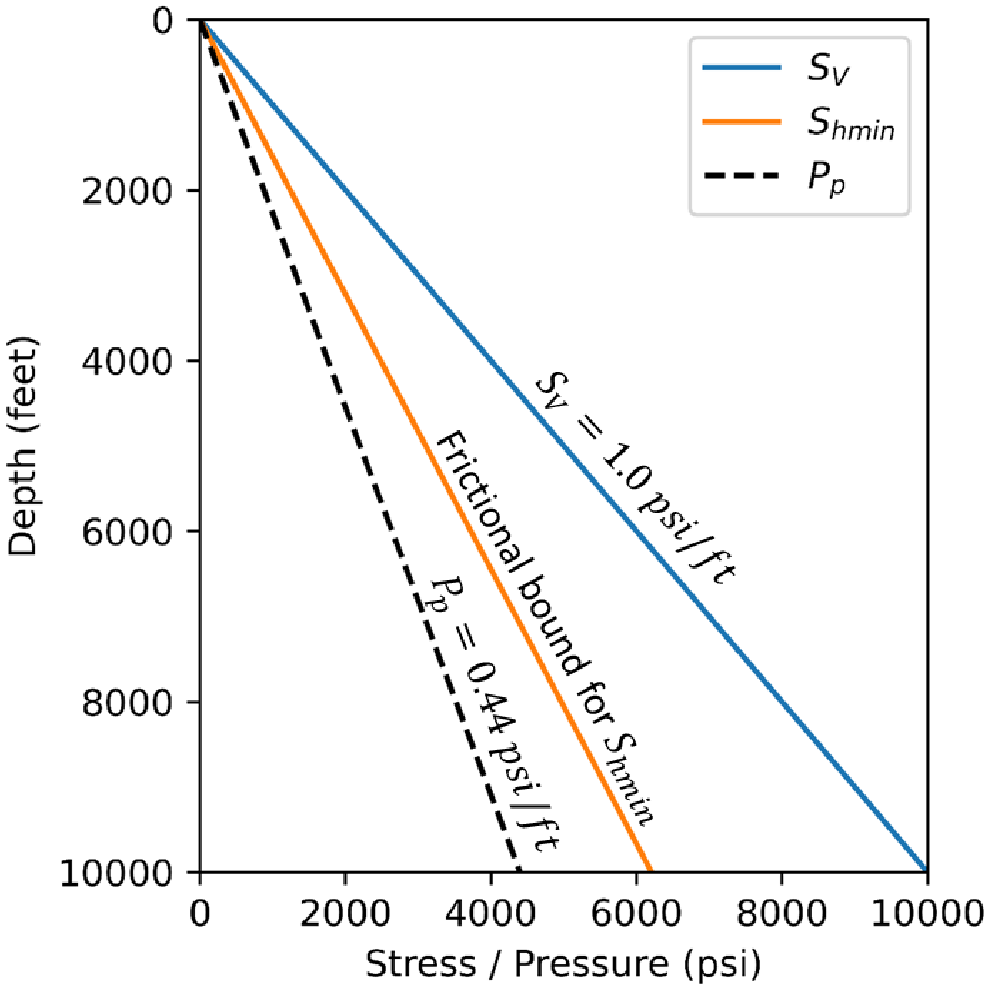
We compare the methods in terms of the applications and the number of parameters required

1. Frictional faulting equilibrium

Use: This method gives a lower bound for S_{hmin} magnitudes at any given depth if the pore pressure and overburden stress are known. For brittle rocks (especially basement), this method usually agrees well with the measured S_{hmin} magnitudes. For more ductile rocks, this can be used to constrain a lower bound.

Theory: This is based on the principal that the maximum possible difference between the highest and least principal stress is governed by the presence of critically stressed faults. Higher difference between the two principal stresses will lead to slip along these pre-existing fault planes.

Limitations: For strike slip faulting areas, since the highest principal stress S_{Hmax} is uncertain and higher than S_V, it can be hard to obtain reasonable lower bounds.



Jaeger & Cook (1979), Zoback (2007)

1. Frictional faulting equilibrium

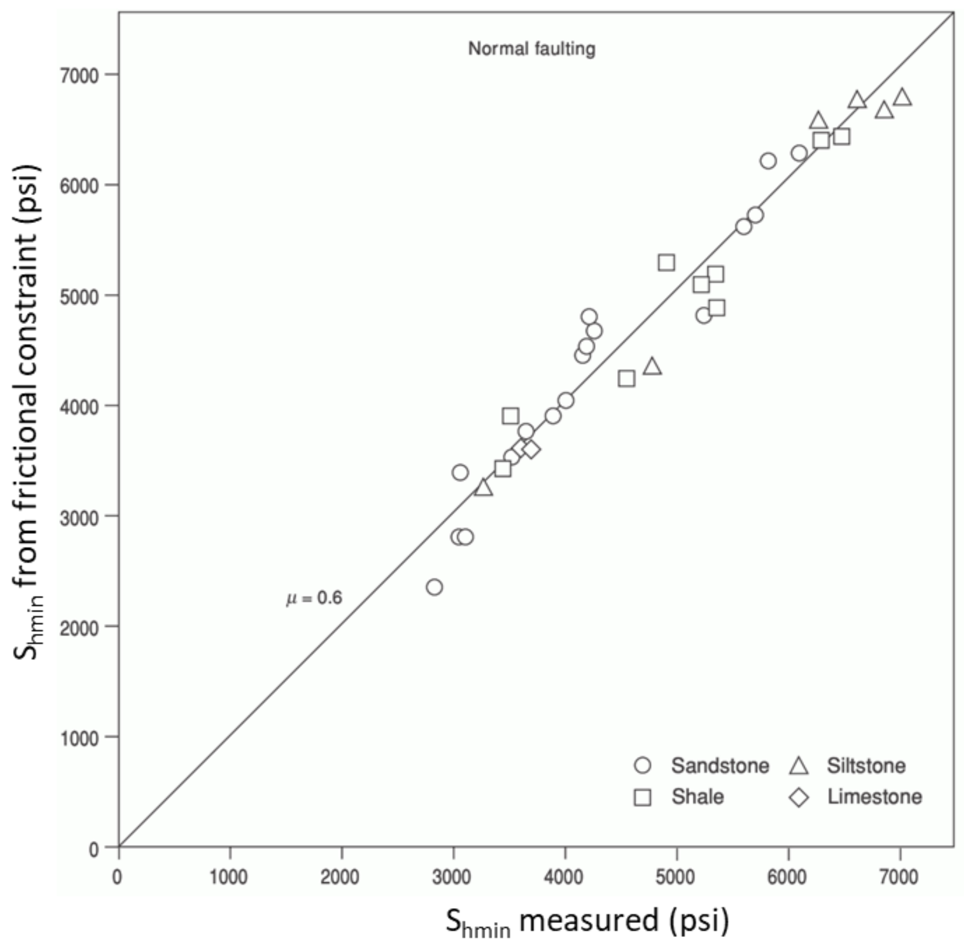
Expression: $\frac{S_V - P_p}{S_{hmin} - P_p} = \left[\sqrt{\mu^2 + 1} + \mu\right]^2$

μ is the friction coefficient. Zoback and Kohli, 2019 found that it varies between 0.4-0.8 for all major unconventional reservoir formations and 0.6 is usually a good value to assume.

For $\mu = 0.6$ and $P_p = P_{hydrostatic}$, this equation given $S_{hmin} = 0.6 S_V$

- For strike slip, the S_{hmin} would be significantly higher than this estimate

The figure shows data from the Travis Peak formation in East Texas showing how the frictional constraint agrees well with the S_{hmin} measurements



Zoback (2007)

2. Bilateral constraint or Eaton's method

Use: This method is widely used in the industry to compute Shmin profiles.

Theory: This method assumes that there is only source of horizontal stress is the overburden and solves the problem of instantaneous application of uniaxial vertical stress to a rock mass in poroelastic half-space. This leads to the rock wanting to expand laterally (Poisson effect) which induces the horizontal stresses. Modifications of this method involve adding on tectonic stress/strain calibration terms to shift the computed stress profiles and using the Biot coefficient as a scaling parameter.

Expression: $S_{hmin} = \frac{\nu}{1-\nu}\left(S_V - \alpha P_p\right) + \alpha P_p + \sigma_{tect}$

where ν is the Poisson's ratio, α is the biot's coefficient (used calibration scaling term) and σ_{tect} is referred to as the tectonic stress term (calibration term used to bulk shift the stress profile). This equation has a few different forms. The one above is equation 2 from Blanton and Olson, 2000.

2. Bilateral constraint or Eaton’s method

Limitations: Despite being widely used in the industry, this method has a lot of limitations. The original method assumes that the only source of stress is the overburden, which is incorrect, as shown by the existence of strike-slip faulting! Also, this method and all subsequent modifications assumes instantaneous application of stress or strain (or equivalently perfectly elastic behaviour). This might be OK for relatively brittle rocks, but for clay rich unconventional rocks, time dependent deformation has a significant effect of on the stress state even at the time scale of week- or month-long laboratory experiments.

Note: If we assume $\nu = 0.25, \alpha = 1 \; and \; \sigma_{tect} = 0$, for hydrostatic pore pressure, the computed Shmin from this method is close to the Frictional faulting equilibrium. Due to this equivalence, this method works well for some locations in the GOM.

2.1. Thiercelin and Plumb Extended Eaton Model

Use: This method is a modified version of the Eaton model derived by Thiercelin and Plumb 1995.

Theory: This method uses anisotropic tectonic strain terms relaxing the uniaxial strain assumption. This can be used assuming isotropic elastic properties or using a Transverse Isotropy assumption (typically VTI for shales) .

Expression for Isotropic medium: $S_{hmin} - \alpha P_p = \frac{\nu}{1-\nu}\left(S_V - \alpha P_p\right) + \frac{E}{1-\nu^2}\epsilon_{hmin} + \frac{E\nu}{1-\nu^2}\epsilon_{Hmax}$

where E is the Young's Modulus, ϵ_{hmin} and ϵ_{Hmax} are the tectonic strain terms in the S_{hmin} and S_{Hmax} directions (used as calibration terms).

Expression for Anisotropic medium: $S_{hmin} - \alpha P_p = \frac{E_h}{E_v}\frac{\nu_v}{1-\nu_h}\left(S_v - \alpha P_p\right) + \frac{E_h}{1-\nu_h^2}\epsilon_{hmin} + \frac{E_h\nu_h}{1-\nu_h^2}\epsilon_{Hmax}$

where E_h and E_v are the horizontal and vertical Young's modulus,ν_h, ν_v are the horizontal and vertical Poisson's ratios

Note that S_{hmin} increases with an increase in horizontal Young's Modulus

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2.1. Thiercelin and Plumb or Extended Eaton Model

Strengths: This method is an improvement over the Eaton model by relaxing the uniaxial stress assumptions.

Limitations: This method also does not account for time dependent behavior assuming instantaneous application of stress or strain. Also, a large number of parameters (both measured and calibration) are required in this. To apply the isotropic formulation, we need to estimate Young's Modulus, Poisson ratio and pore pressure from the logs in addition to fixing biot coefficient and the two tectonic strain terms in the calibration process. The number of parameters are even higher in the anisotropic formulation!

2.2 Blanton and Olson Extended Eaton Model

Use: This method is a modified version of the Eaton model derived by Blanton and Olson 2000.

Theory: This study modified the terms from Thiercelin and Plumb, 1995 by adding temperature terms and using the assumption that the horizontal strain in one direction is zero to reduce the adjustable parameters. The temperature term estimates the thermoelastic strain to take the effect of burial history into account.

Expression: $S_{hmin} = C_1\epsilon_{tect} + C_2$, if tectonic strain terms is negative,$S_{hmin} = \nu C_1\epsilon_{tect} + C_2$, if tectonic strain term is positive

- $C_1 = \frac{E}{1-\nu^2}$; $C_2 = \frac{\nu S_V + (1-2\nu)\alpha P_p + E\alpha_T \Delta T}{1-\nu}$

where α_T is the thermal coefficient of expansion in $°F^{-1}$, ΔT is the temperature at depth minus the surface temperature in $°F$

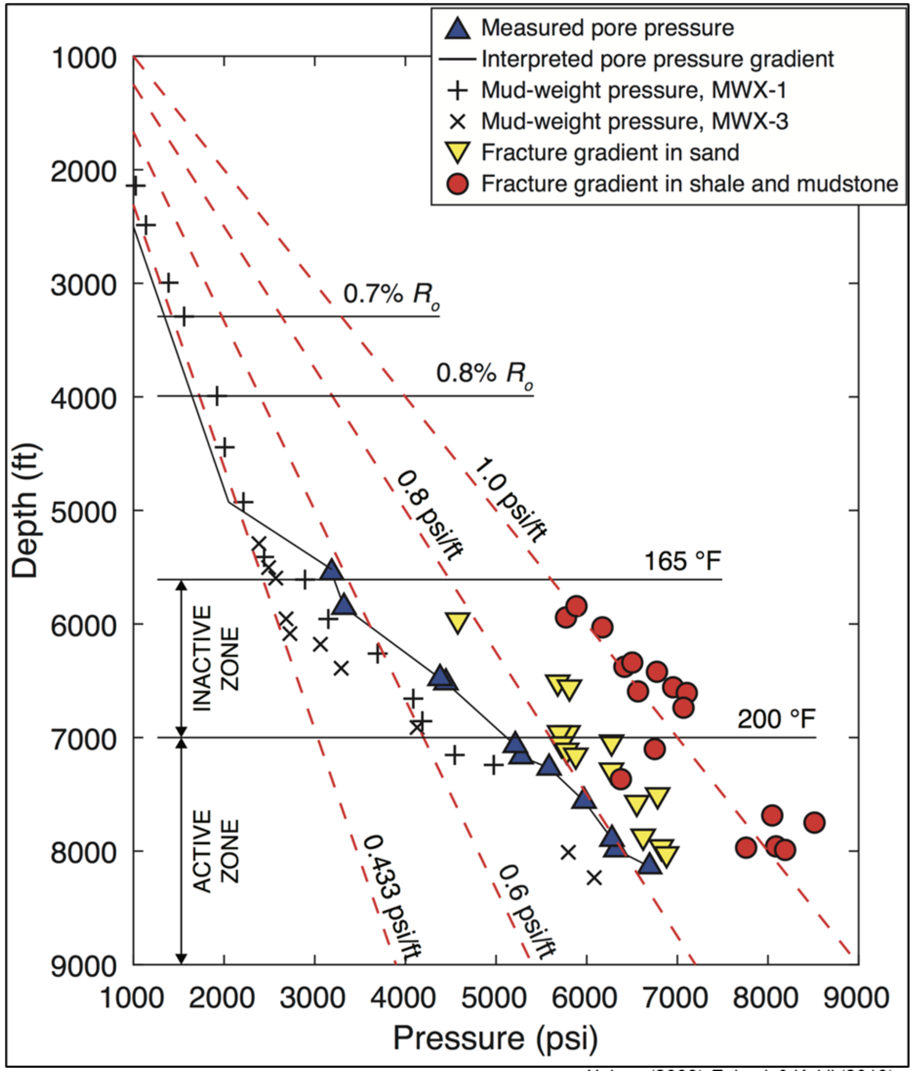
Limitations: Same as method 2.1

3. Viscoelastic stress relaxation (VSR)

Use: Constrain stress profile using log data or creep experiments performed on core data

Theory: More a rock tends to deform as a function of time (viscous deformation), the lower the difference between the principal stresses become. Thus, in rocks exhibiting more viscous deformation (more ductile) the S_{hmin} would be expected to increase, thus lowering the difference between S_V and S_{hmin} in normal and strike-slip faulting areas (Sone and Zoback, 2013, 2014). Thus, generally more ductile clay rich rock will have a higher S_{hmin} than more brittle clay poor clastics. Laboratory studies by Rassouli and Zoback, 2018 showed that carbonate rich unconventional reservoir formations also exhibit a significant amount of viscous deformation. Compared to the extended Eaton methods, VSR is based on realistic geological assumptions in areas with low strain rate, which is typical of nearly all unconventional formations.

Field example: The data from the Piceance basin in Colorado in the figure shows that the Shmin measured in the higher clay shales is consistently higher than the Shmin in the more brittle sandstones.



Nelson (2003), Zoback & Kohli (2019)

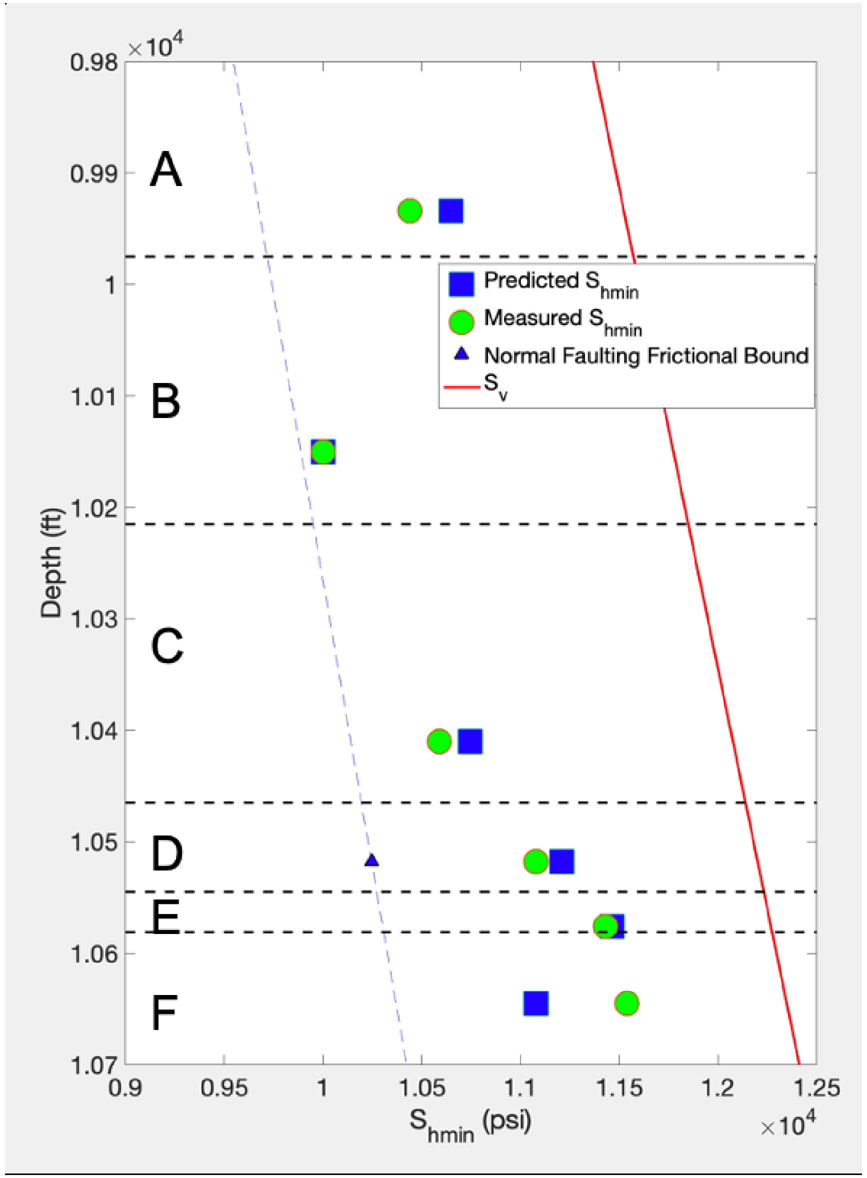
3.1. VSR using laboratory experiments

Equation: $S_V - S_{hmin} = \frac{\epsilon_0}{\kappa}\frac{t^{-n}}{1-n}\frac{1}{B}$

where ϵ is the total strain, κ is a factor to account for normal and strike slip faulting ($\kappa = 1$ for normal faulting and <1 for strike slip faulting). ϵ_0/κ is used a calibration terms to match the Shmin measurements. B and n are experimentally measured rock properties from creep experiment data (slope and intercept from log-log plot of time vs creep compliance (Sone and Zoback, 2014; Xu, Singh and Zoback, 2019).

Example: The figure on the right shows the application of the core based VSR method for an unconventional play in the NE US. The calibration is done using formation B and the predicted S_{hmin} agrees well with the S_{hmin} measurements from a vertical pilot well.

Limitations: This method requires core samples for creep experiments and can give stress estimates only at those discrete points.



Singh, Xu and Zoback , 2021

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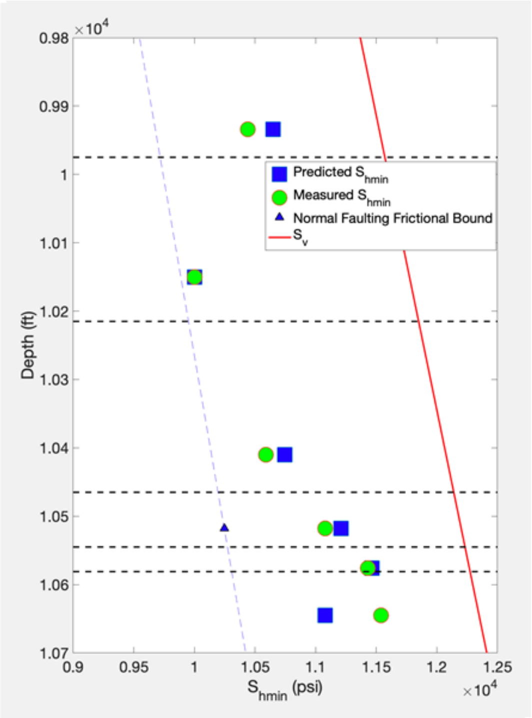
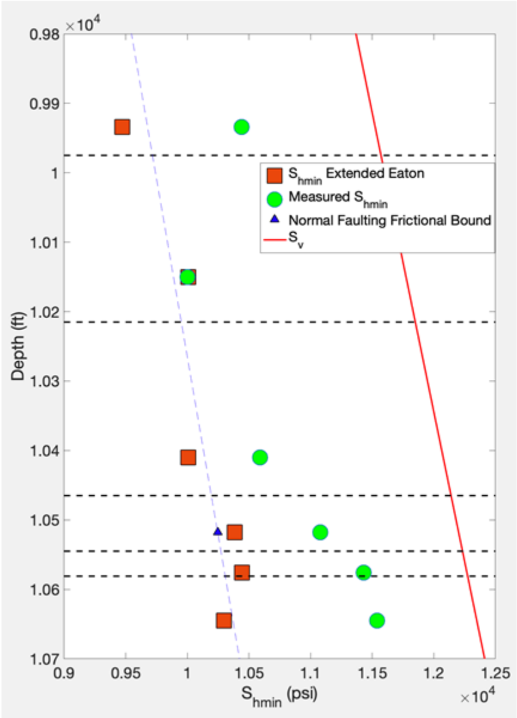
Comparison: VSR and Extended Eaton (2.1.) for laboratory data

In this example from the same dataset as the previous slide, the VSR method performs much better than the extended Eaton

The VSR method requires fewer fitting parameters than the extended Eaton.



Singh & Zoback (2021) *in prep.*



Calculations from Xu (2020)

VSR

$$S_{hmin} = S_v - \frac{1}{\kappa}\epsilon_0 \frac{1}{B}\frac{t^{-n}}{1-n}$$

Extended Eaton method

$$S_{hmin} - \alpha P_p = \frac{E_h}{E_v}\frac{V_v}{1-V_h}(S_v - \alpha P_p) + \frac{E_h}{1-V_h^2}\epsilon_h + \frac{E_h \nu_h}{1-\nu_h^2}\epsilon_H$$

Thiercelin & Plumb (1994)

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3.2. VSR from log data

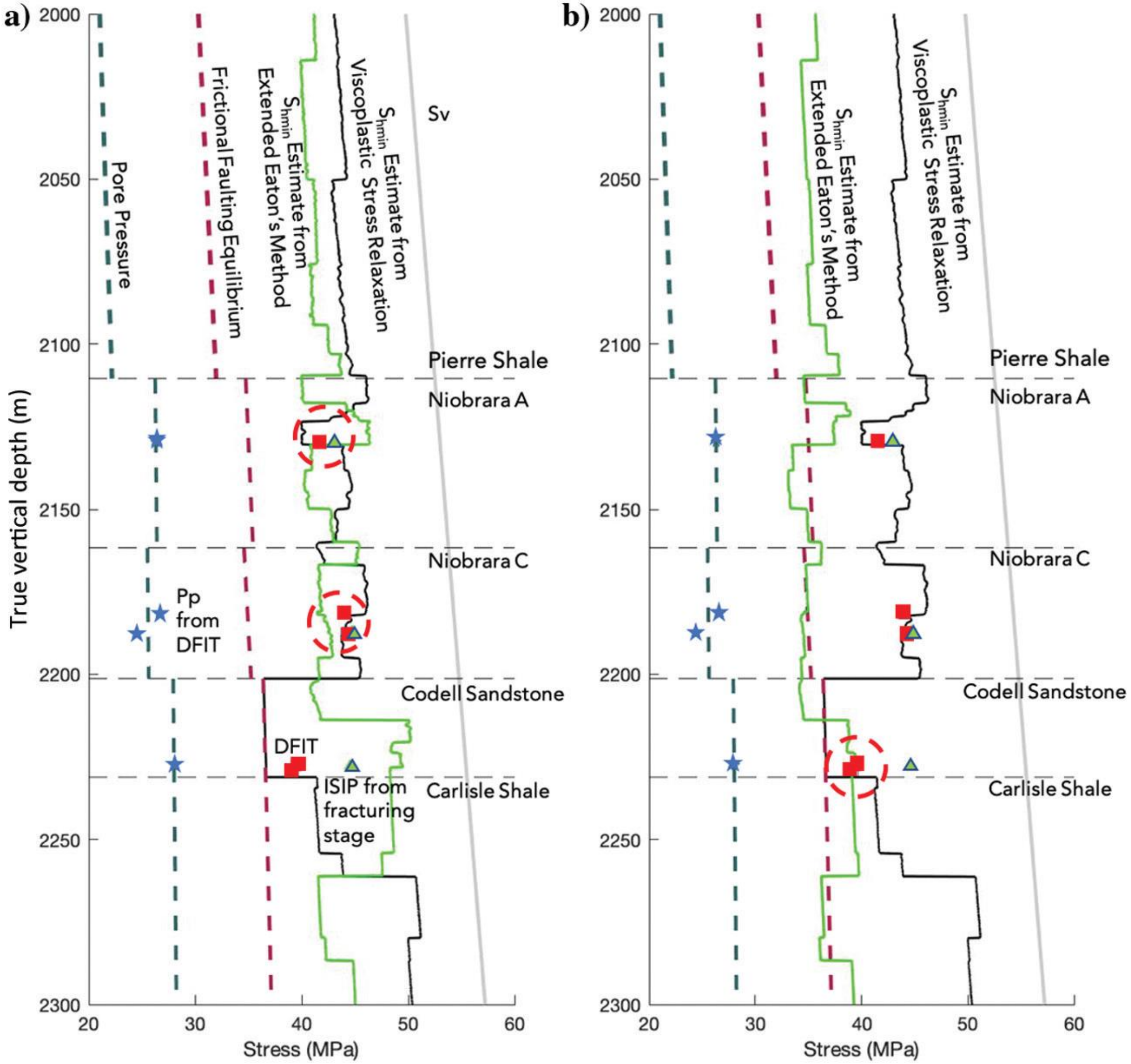
Equations: $S_{hmin} = S_V - \epsilon_0 E_{horiz} \frac{t^{-n}}{1-n}$

$$n = \frac{70 - E_{horiz}}{700}$$

Where E_{horiz} is the log computed horizontal Young's Modulus and has been found to be a good estimate the $\frac{1}{B}$ parameter. Vertical Young's modulus can also be used if it can be assumed reasonably that the ratio between vertical to horizontal Young's modulus is nearly constant for the entire log interval. The n parameter is derived in this formulation by using an empirical correlation derived using published laboratory data by Ma and Zoback, 2020. This method is simple to implement and does not require knowledge of pore pressure or Poisson's ratio. In this method, the frictional faulting bound should be used to constrain a lower bound for the Shmin profile.

Limitations: The empirical expression for the creep parameter n is based on a limited laboratory dataset and can be a significant reason for uncertainty.

Field example: The figure on the right shows the implementation of the method for the Niobrara shale and comparison with the Extended Eaton (2.1).



McCormack, Kuang and Zoback, 2021

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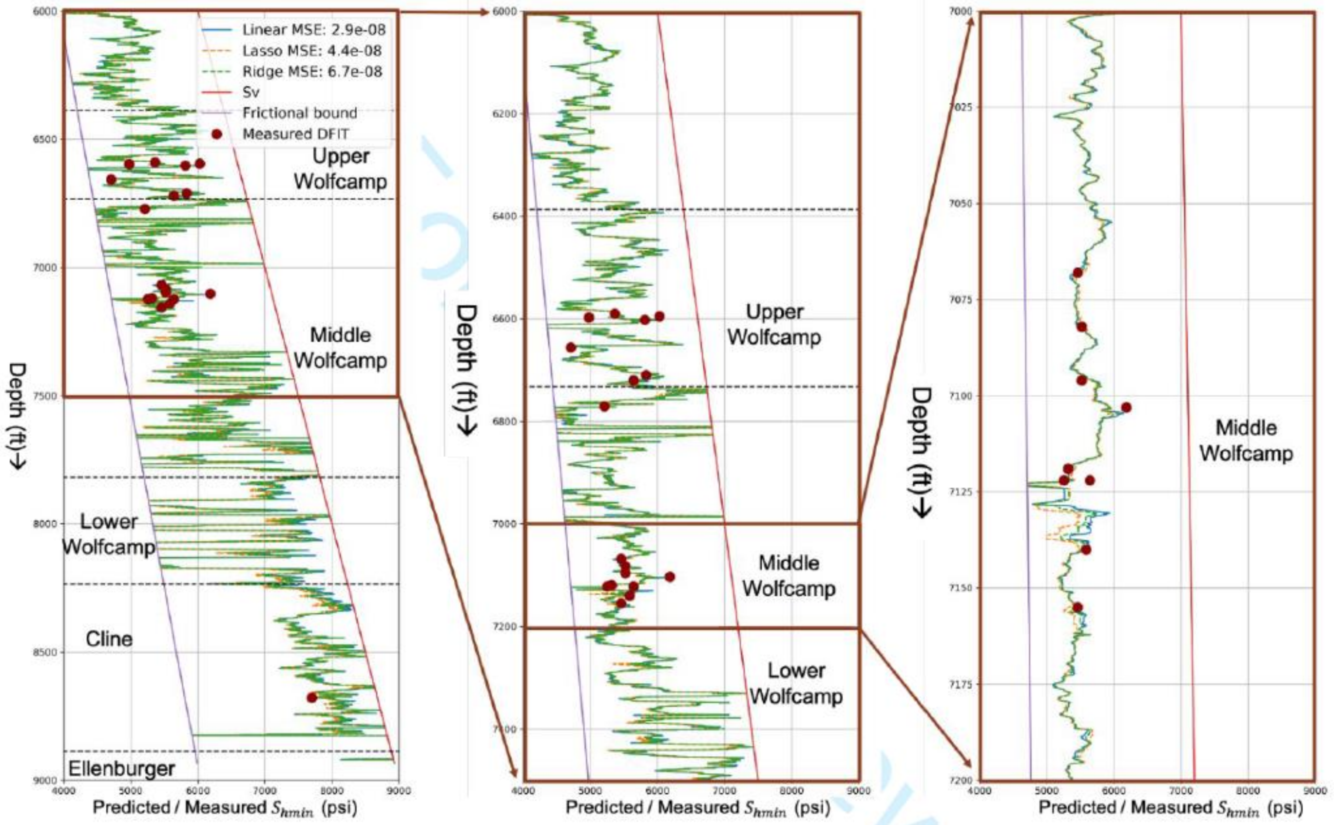
3.3. VSR from log data with a several DFIT calibration methods available.

Theory: In this method, the VSR equation is modified slightly to be of the form:

$S_V - S_{hmin} = n^*_{\epsilon t} E_{horiz}$ and $n^*_{\epsilon t}$ is fit as a function of the log data using the available DFITs. This method is based on Singh and Zoback, 2021 (accepted in Geophysics). The resultant stress profile is lower bound using the frictional faulting equilibrium.

- This method has been developed using a Wolfcamp case study. The figure on the right shows an example from the Wolfcamp case study.



Singh and Zoback, 2021

ResFrac

Abstract

Various methods are used in the industry to compute S_{hmin} profiles from log data

The methods can be based in two broad categories:

- Eaton and Extended Eaton methods: Based on the assumption that the stress/strain is applied instantaneously, and the rock is perfectly elastic. The original Eaton equation assumes uniaxial application of stress, extended Eaton modifications relax this assumption by using tectonic strain terms. All these methods require information about the pore pressure. Even though these methods are widely used in the industry, they are limited by the somewhat unreasonable geological assumptions and often fail to capture the stress variaitons.
- Viscoelastic stress relaxation (VSR) methods: Based on the principle that time dependent deformation in sedimentary rocks decreases the differential stress (i.e., increases S_{hmin} towards S_V) in more ductile rocks, such as shale formations rich in clay and organic matter. Pore pressure is not an input for the VSR methods. . Unlike the Extended Eaton methods, VSR utilizes geologically more reasonable assumptions for areas with low strain rate, which are typical of nearly all unconventional plays in the US. The VSR method has been developed very recently and the workflow will develop as it is tested on datasets across different formations.

The frictional faulting limit can be used to calculate a the lower bound for the stress profiles

We compare the methods in terms of the applications and the number of parameters required

Thank You!

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